# EXTREME EVENTS IN THE DEVELOPING WORLD

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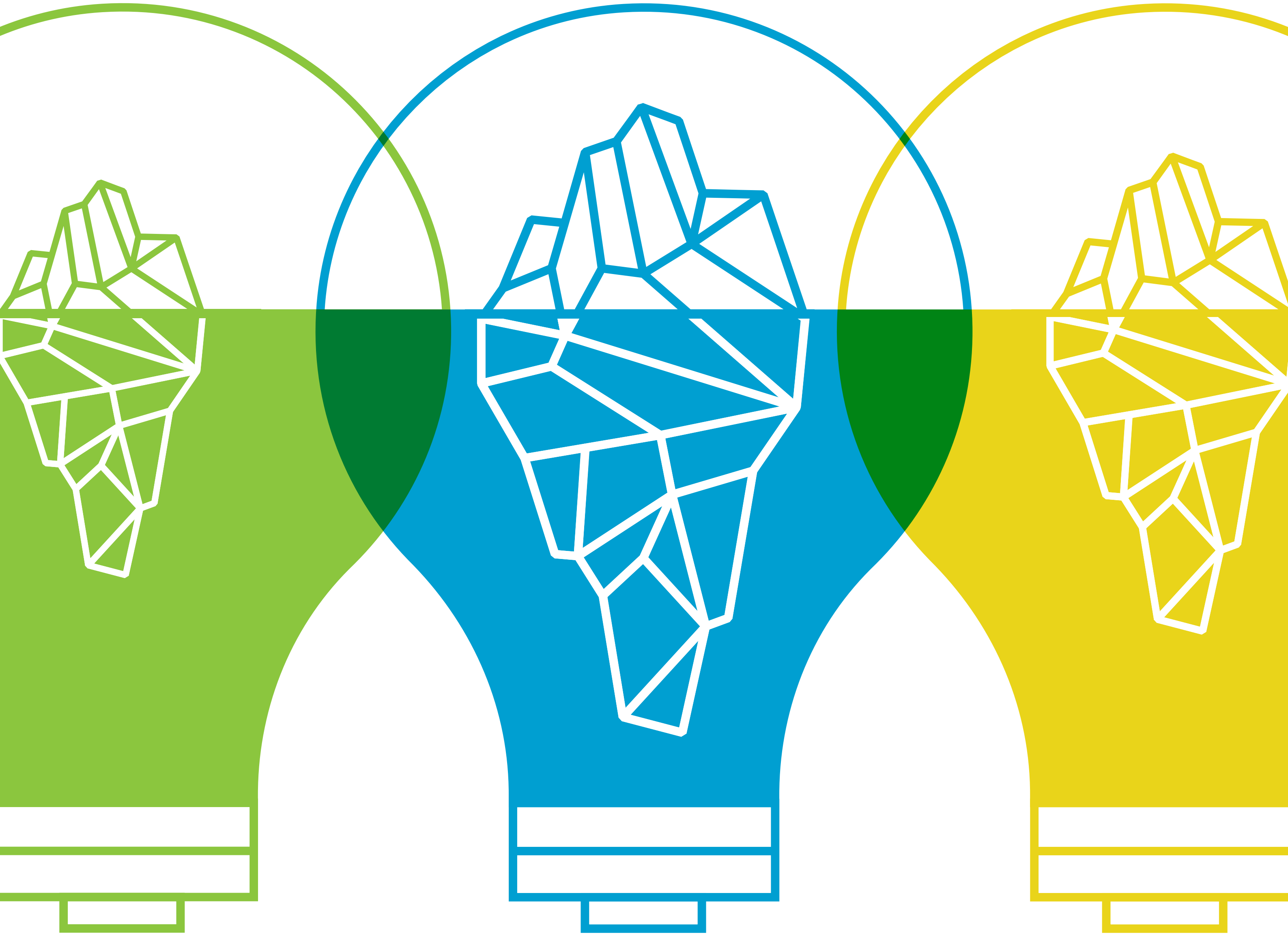

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# EXTREME EVENTS IN THE DEVELOPING WORLD

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# Editorial: Extreme Events in the Developing World

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**Editorial on the Research Topic**

**Extreme Events in the Developing World**

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## INTRODUCTION

The frequency and/or magnitude of extreme events is changing in the context of climate change, and this is clearly projected to continue (IPCC, 2021). Extreme weather has been the top global risk in terms of likelihood in each of the last 5 years, according to the World Economic Forum's Global Risks Report (World Economic Forum, 2021). On the grounds that risk is a function of hazard, exposure and vulnerability, developing countries are disproportionately at risk. Whilst changing the nature of hazards in the short-term may be challenging, it is possible to change exposure and vulnerability, and thus reduce risk.

This Research Topic "*Extreme Events in the Developing World*" showcases a selection of articles that develop our knowledge of extreme events in the developing world. Papers range from those presenting recent evidence for and future likelihood of changes in the occurrence and exposure to extreme events, together with examples of the impacts of extreme events in a variety of sectors. Papers also consider the range of climate services responses to this challenge, highlighting the need for new types of weather and climate information, new methods of producing and communicating that information in order to reduce risk, as well as providing some key examples of success stories, with a particular focus on Africa. Our intention here is to balance some of the bad news with what might work, and how we might learn from such examples.

## CHANGING NATURE OF EXTREME EVENTS

Three papers in the Research Topic focus on the changing nature of hazards, covering South America, Africa and Oceania. Looking at the changing trends in rainfall extremes in the metropolitan area of São Paulo, Marengo et al. show that there has been a change in rainfall distribution. Observed trends show an increase in extreme rainfall events over the last 60 years, particularly during summer, as well as an increase in the number of consecutive dry days. They attribute this to intensification and movement in location of the South Atlantic Subtropical Anticyclone, with implications for the transport of humidity and therefore precipitation.

Luhunga et al. analyse extreme rainfall and temperature trends based on observational records, and project this into the future. In the Kagera and Geita regions of Lake Victoria in Tanzania, there has been a statistically significant increasing trend in temperature and numbers of warm days and warm nights, whilst the numbers of cold days and cold nights have decreased significantly.

Based on modeling under two different Representative Concentration Pathways, temperature increase is projected to continue, as is an increase in rainfall.

Sabunas et al. consider how climate change is projected to affect storm surge and sea level rise around Vitu Levu, Fiji. They find differential levels of exposure to flooding and inundation considering the topography of Fiji, where exposure is highest in areas affected by the western wind direction, and in flat areas.

## IMPACTS OF EXTREME EVENTS

The changing nature of extreme events has implications for developing countries, affecting their vulnerability and adaptive capacity. Msemo et al. analyse the socio-economic costs of weather impacts in Tanzania. Between 2000 and 2019 severe weather accounted for just over two thirds of disasters in Tanzania, destroying over 35,700 houses and 1,000 examples of critical infrastructure (roads, bridges, schools, and hospitals), affecting 572,600 people and requiring the government to spend over $20.5 million in response.

Henriksson et al. take a longitudinal approach to explore the adaptive capacity of sugarcane contract farming schemes in Malawi. As well as noting differences in the composition of adaptive capacity between two schemes, they also highlight how adaptive capacity is eroded after exposure to a hazard. This increases risk of negative impacts from future events, particularly in the context of increasing frequency of exposure, which has already been highlighted as a key risk (Funk, 2020).

## IMPROVING CLIMATE SERVICES AND EARLY WARNING SYSTEMS FOR DISASTER RISK REDUCTION

In this context of increasing hazard and exposure, improving climate services and early warning systems is essential to enable disaster risk reduction. Papers in this Research Topic highlight opportunities for plugging data gaps and ensuring interoperability, generating new climate services and ensuring improved communication for uptake by decision makers.

Plugging or addressing data gaps is an important need for many developing countries, where incomplete observational records impede modeling and forecasting capacity. Landman et al. show how the extended records of rainfall data recorded by farmers at their properties in South Africa and Namibia enable development of farm-specific forecasts. In this way, additional data enables more localized tailoring of forecast information.

Oftentimes data is available, but is not necessarily accessible. This is particularly the case for extreme events and disasters, when such data is curated by different actors who may not formerly have collaborated. To overcome the issues of interoperability and lack of standardization, Davis-Reddy and Hilgart propose an open-access system for national hazard events in South Africa. Their database is based on a standardized, scalable design method that can be used to improve data collection and enable reporting that fulfills the mandate of South Africa's National Disaster Management Framework.

As well as more data, translating available data into more decision-relevant products increases its useability in risk reduction. Conventional weather forecasts focus on meteorological thresholds for extreme events, when it is the likelihood and potential severity of weather impacts that is more useful for decision makers. New and emerging information types are outlined in papers covering west and southern Africa. Impact-based forecasts that focus on storms, droughts and heatwaves have been developed in Ghana, Nigeria, and Senegal, as outlined by Nkiaka et al.

Two papers focus on examples from Malawi where there is potential to improve decision-relevant early warning. The findings of Calvel et al. show that early warning systems for slow-onset extreme events such as drought can be effective in triggering early warning and enabling better disaster preparedness. With the intention of improving the useability of seasonal forecast information for maize farming, Mittal et al. identified specific agro-climatic indices where temperature and rainfall thresholds were associated with different phenological stages of maize growth. As yet, the forecast skill of the UK Met Office's coupled initialized global seasonal forecasting system (GloSea5) over Malawi remains too low to provide confident predictions of total wet season rainfall and the agro-climatic indices correlated with it—but this represents a focus area for further development of models to enhance forecast skill.

In addition to generating more decision-relevant climate services, it is important to ensure effective communication to ensure it is available and accessible to relevant decision makers (Findlater et al., 2021). In their paper that undertakes a systematic review of literature in Kenya, Muita et al. find that there are differences in accessibility to, and use of, seasonal to sub-seasonal forecasts among crop farmers, pastoralists and agro-pastoralists on the basis of gender, availability of resources and mode of communication.

Ensuring effective communication of climate services is essential to ensure effective use in risk reduction, as addressed by many of the papers. Effective communication requires understanding the decision contexts and needs of users so as to be able to meet them. In Tanzania, Msemo et al. highlight a need to better understand the value of weather warning information at short timescales (1–5 days) and how this information can be better used in the individual decision-making processes of those receiving advisories and warnings. In West Africa, Nkiaka et al. highlight that increasing uptake of climate services will require the national meteorological and hydrological services to improve communication channels with user communities, as well as developing impact-based forecasts. In Malawi, Calvel et al. highlighted the need for drought early warning to be people-centered and timely and tailored to agricultural decision making, as well as provided through several channels.

Effective communication of climate services and early warning information often requires novel partnerships and greater collaboration between producers and users. In Kenya, Muita et al. recommend engagements with producers in the development and evaluation of forecast products and communication pathways to improve uptake and use of forecasts in decision-making. In Malawi, Mkwambisi et al. highlight that conservation agriculture can be an effective adaptation strategy for dry conditions, but that in the 2015/16 El Niño drought farmers were reluctant to use seasonal weather forecasts, even though they had access to them. They recommend that extension agents should be encouraged to advise on what techniques, or farm system actions, can be used to respond effectively to seasonal to sub-seasonal forecasts. Recognizing that an enabling policy framework might support more effective generation, communication and use of climate services and early warning information, both Nkiaka et al. and Msemo et al. recommend a review of policies, and the establishment of a National Framework for Climate Services (e.g., Hewitt et al., 2020).

## CONCLUSION

Whilst extreme events are likely to continue to change in character in the context of a changing climate, the papers in this Research Topic elaborate that the extent of negative impacts can be minimized through the locally-appropriate use of new knowledge and warning systems. There have been significant improvements in scientific capacity to predict extreme events, and to project the changes in climate in which such extreme events occur. At the same time, there has been growth in the field of climate services, which is concerned with generation and effective communication of decision-relevant information that enables people and society to reduce the risk of extreme events. The empirical findings from across the range of case study insights in this Research Topic demonstrate that improving information availability and communication systems has the potential to reduce the risk of extreme events translating into negative impacts for developing countries.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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**Conflict of Interest:** KV was employed by Kulima Integrated Development Solutions Pty Ltd, Pietermaritzburg, South Africa.

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# Changing Trends in Rainfall Extremes in the Metropolitan Area of São Paulo: Causes and Impacts

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This study analyses observed trends in extreme rainfall events in the Metropolitan Area of São Paulo (MASP). Rainfall data sets with more than 60 years of record in MASP are used. In MASP, extreme rainfall events represent hydro meteorological hazards that trigger flash floods and landslides. Changes in rainfall extremes can be partly due to natural climate variability. In addition, it can also be related to global warming and/or urbanization. Total annual precipitation and the number of days with precipitation of 20 mm exhibit the largest significant increase during 1930–2019. This is better noticed during summer. This tendency is also noticed in the number of days with precipitation of 100 mm or more. Therefore, the positive trend in annual precipitation is mainly due to an increase in the frequency of extreme precipitation events. On the other hand, our analysis shows that the number of consecutive dry days increased. Though these results appear to be contradictory, they indicate an important climate change in recent times. Intense precipitation is concentrated in few days, separated by longer dry spells. The focus is on how atmospheric circulation variations are contributing to these changes. During 1960–2019 the South Atlantic Subtropical Anticyclone has intensified and slightly moved southwestward of its normal position. This change influences the transport of humidity and therefore impact precipitation. This can explain the increase in the precipitation extremes in the MASP. However, other atmospheric systems may also be important.

**Keywords: climate extremes, natural disasters, climate change, South Atlantic Subtropical Anticyclone, São Paulo**

## INTRODUCTION

Episodes of heavy rainfall and wet and dry spells impact urban and rural areas worldwide. These extremes trigger natural disasters such as floods, flash floods, or droughts. These produce significant damage to the population, particularly in developing countries (IPCC, 2012, 2013, 2014). Significant modifications in weather systems have led to changes in extremes (Giorgi et al., 2014; Diffenbaugh et al., 2017). Extremes of weather and climate affect mainly risk areas where vulnerable people live (Bouwer, 2019), like urban areas, where most of the population is concentrated. Globally, more people live in urban areas (54%) than in rural ones, and by 2030, it is projected to the world to have 41 mega-cities with 10 million inhabitants or more (UN-Habitat, 2015). This is not going to improve with urbanization and occupation of risk areas under climate change. Megacities in Latin America would be among the most affected (Vergara, 2008; Magrin et al., 2014).

Several studies have focused on changes in mean and extreme precipitation trends worldwide. These show that for the last 50–60 years, warming trends are accompanied by more heavy rainfall episodes. These trends are particularly noticed during the summer and fall seasons (e.g., Seneviratne et al., 2012; Donat et al., 2013; Ren et al., 2013; Sillmann et al., 2013; Sun et al., 2018 and references quoted in).

Southeastern Brazil is the region that host the states that most contributes to the Brazilian economy. It shows an increase in total annual rainfall and in the frequency of intense rain events above a given threshold or percentile level (Alexander et al., 2006; Haylock et al., 2006; Teixeira and Satyamurty, 2011; Donat et al., 2013; Skanski et al., 2013). Since 2015 the states in southeastern Brazil (São Paulo, Minas Gerais, Espirito Santo, and Rio de Janeiro) have experienced 1,373 events of extreme rainfall. Extreme rainfall events were defined as those with precipitation above 50 mm/h. From those, 730 were detected in the state of São Paulo (EM-DAT 2019). According to the Center for Weather Forecasts and Climate Studies of Brazil (CPTEC-INPE; G1, 2020) among the municipalities with a population above 100,000 people, more than half of rainfall peaks during the last 5 years have occurred in the state of São Paulo. A combination of heavy rainfall and high population density is a lethal recipe for floods, flash floods, and landslides, resulting in fatalities and displaced people (Ávila et al., 2016).

A number of studies have focused on rainfall extremes in the MASP (Xavier et al., 1994; Carvalho et al., 2002, 2004; Dufek and Ambrizzi, 2008; Vasconcellos and Cavalcanti, 2010; Nobre et al., 2011; Sugahara et al., 2012; Marengo et al., 2013, 2020; Silva Dias et al., 2013; Magrin et al., 2014; Obregon et al., 2014; Ramires and Mello-Thery, 2018). These studies show an increase in the seasonal and annual precipitation. They also show increase in frequency and intensity of extreme rainfall events. This has contributed to more natural hydrometeorological disasters. In addition, it has been detected a reduction in the frequency of light rain events.

Changes in rainfall extremes have been identified in many sectors of the MASP. Decadal analysis of rain extremes from the IAG USP station (see **Figure 1** for its location). In the last 20 years the number of days with rainfall above 30 mm has varied between 10 and 15 days. In comparison, this number varies from 5 to 12 days in 1940–1960 (Nobre et al., 2011; Ramires and Mello-Thery, 2018). The data of the IAG USP station shows that in the city of São Paulo the number of days with rainfall >50 mm during the 1950's was almost non-existent. By 2000–2010 these events occurred between 2 and 5 times per year (Nobre et al., 2011). As for rainfall of 100 mm or above, data from the IAG USP and Mirante de Santana stations shows that they occurred three times during 1960–1980 and eight times in 2000–2018 (Marengo et al., 2020).

In MASP, rainfall trends are influenced by variations and changes in major systems affecting precipitation. Among them we have changes in the intensity and position of the South Atlantic Convergence Zone (SACZ). Furthermore, we have the intensity and position of the Subtropical South Atlantic High. Another factor in MASP is the Urban Heat Island effect UHI (Vemado and Pereira Filho, 2016; Zilli et al., 2016), due to its proximity of large urban centers and topographic features. The urbanization process in the MASP has been affecting the local climate Ruv et al. (under review). The intensification of the UHI effect resulted in a local climate with a 2–3°C warming difference between urban and rural areas (Nobre et al., 2011; Barros and Lombardo, 2016; Vemado and Pereira Filho, 2016, Ruv et al. under review). According to INMET, the Mirante de Santana and IAG-USP data show warming from 1 to 1.5°C in 1998–2018 when compared to 1961–1990. Abreu et al. (2019) estimate that the observed warming trend of 1.1°C between 1955 and 2004 is largely due to increasing greenhouse gases.

The water crisis in the MASP during 2014/15 is a good example of water insecurity and vulnerability of a megacity to seasonal droughts (Marengo et al., 2015; Otto et al., 2015; Nobre et al., 2016). Previous major droughts occurred in the region in 1953/54, 1962/63, 1970/71, and 2001 (Cavalcanti and Kousky, 2002; Drumond and Ambrizzi, 2005). In all those years the summer wet season was deficient in rainfall, mainly due to a weakening of the SACZ. This is the main mechanism responsible for the region's rainfall (Nobre et al., 2016). In the drought of 1953/54, rainfall deficit prompted construction of the largest water supply system (Cantareira) used for São Paulo city (Porto et al., 2014). The 2001 drought was associated an energy crisis and risk of blackouts (Cavalcanti and Kousky, 2002). During the 2014 summer, as in the other drought events, a complete absence of SACZ episodes was observed. This was due to a weak moisture transport that usually occurs from the tropical north Atlantic, crossing the Amazon Basin, to southeastern Brazil. This, together with a record maximum temperature worsened the water crisis (Nobre et al., 2016).

CMIP5 and regional climate change projections show an expected warming between 2 and 3°C in the MASP for the RCP4.5 and 8.5. It is projected a doubling of the number of days with heavy precipitation by 2,100 (Chou et al., 2014; Rosenzweig et al., 2018). Most of the natural disasters in Brazil are related to intense rainfall. According to CEPED UFSC (2013), the highest mortality rate in MASP is due either floods or landslides. In the last decade, more than half a million people became homeless because of these events.

In this study we provide updated information on trends in total and extreme rainfall events over the MASP until 2019. This is done through the analysis of different extreme rainfall indices. Observational data from two stations is available with more than 60 years of information. From the analysis of trends in rainfall extremes there were identify periods when rainfall regime changed. To investigate possible causes of trends, we investigate variations in the large-scale circulation in the South Atlantic sector. Details on consequences of rainfall extremes on natural disasters and impacts in vulnerable people living in risk areas are discussed in other studies (Nobre et al., 2011; IPCC, 2012; CEPED UFSC, 2013; Marengo et al., 2020).

## METHODOLOGY AND DATA

### The Megacity of São Paulo

MASP is located in south-eastern Brazil. It is the third-largest urban conglomerate in the world, with 39 municipalities totalling an area of 7,944 km$^2$. São Paulo city is the largest in terms

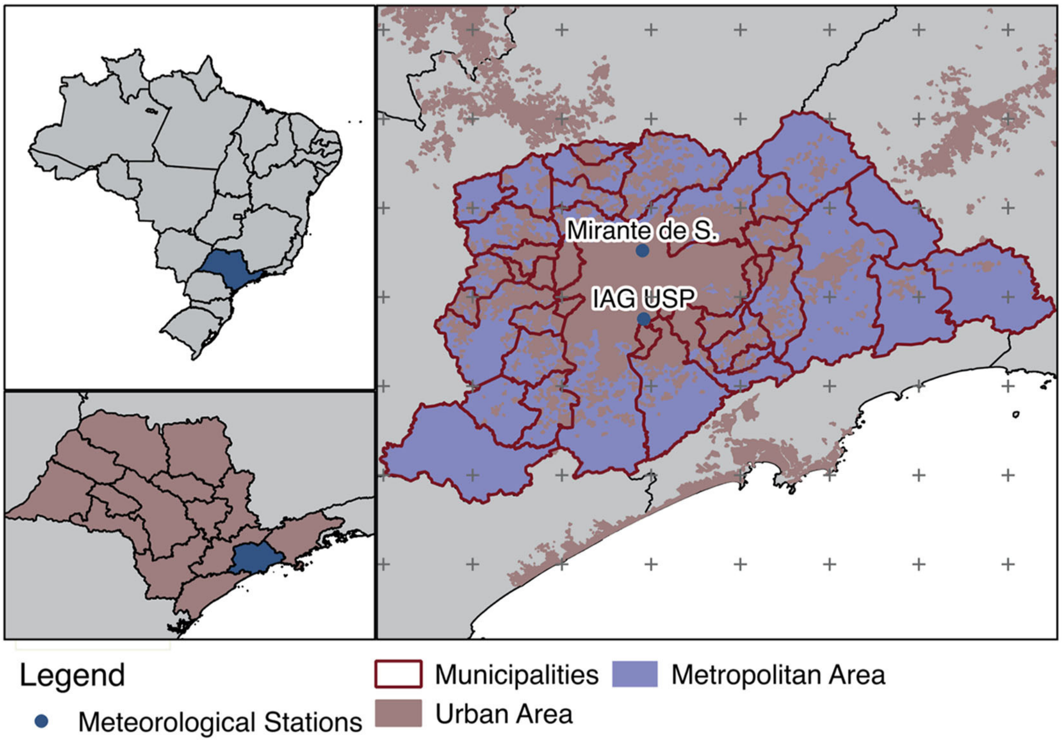


**FIGURE 1 |** Location of the Metropolitan Area of São Paulo (in red) in the state of São Paulo. Location of the two meteorological stations used of this study in the MASP region are shown by blue dots.

of population and economic development (UN-Habitat, 2016). In 1872, it had just over 31 thousand inhabitants; in 1920, its population was already 580,000. Population of around 20 million inhabitants (Instituto Brasileiro de Geografía e Estatística, 2011). More than 11 million people living in the city of São Paulo in an area of 1,530 km$^2$ (**Figure 1**). São Paulo is the leading state on climate adaptation strategies in Brazil (Simões et al., 2017). As pointed out by Di Giulio et al. (2018), São Paulo struggles with land-use planning and curbing $CO_2$ emissions as well as preventing and responding to climate-related impacts.

## Data

The data set used in here is the daily rainfall data from the Água Funda meteorological station of the Institute of Astronomy, Geophysics, and Atmospheric Sciences (IAG) from the University of São Paulo-USP (23.65°S, 46.61°W, 800 m above sea level, **Figure 1**). The second station is Mirante de Santana station from the National Institute for Meteorology (INMET; 23°29′ S 46°37′ W, 792 m above sea level, **Figure 1**). The Agua Funda station is located in the middle of an urban park separated from built urban areas. Mirante de Santana station in the urban area being representative of local climate of São Paulo city.

Concerning Água Funda meteorological station (hereafter IAG-USP), data is available since 1931. This data has been used in several studies (Nobre et al., 2011; Marengo et al., 2013, 2020; Silva Dias et al., 2013). About the homogeneity of the IAG-USP data, Sugahara et al. (2012) indicated that the data may have been contaminated by instrument replacement in 1958. However, there was no need for correction after the middle 1950's. Obregon et al. (2014) show that there is no evidence of "jumps" in rainfall from the middle 1950's, observing instead oscillations that can be associated to the Pacific Decadal Oscillation PDO in the 1970–1980 period, and other variations during 1955–1965 and 1980–1995 that they discuss in meteorological terms. The period of data for IAG-USP is from 1931 to 2019 and from Mirante de Santana is from 1960 to 2019.

## Climate Indices

The indices used to define long extreme rainfall events in this study are defined by Frich et al. (2002):

- Annual total precipitation (PRCPTOT): total annual accumulated precipitation (in mm),
- Consecutive dry days (CDD): the annual maximum number of consecutive days when daily precipitation was <1 mm (in days),
- Maximum 5 days precipitation (Rx5D): the annual maximum consecutive 5 days precipitation total that could lead to flooding (in mm),
- Extreme rainfall (R95P): the annual total PRCPTOT, when precipitation is >95th percentile of the 1961–1990 daily precipitation distribution (in mm),
- Wet days (R10, R20, R25, R30, R50, R80, R100): the number of days in a year with precipitation >10, 20, 25, 30, 50, 80, and 100 mm, respectively.

In addition, we defined other indices:

- Light rain (R1): the number of days with precipitation between 0.1 and 1 mm.
- Light rain (R5): the number of days with precipitation between 1 and 5 mm.

Our focus is from light rain (R1, R5) to heavy rainfall events (R50, R100, R95P, Rx5D) in the MASP. CDD is an indicator of dry spells that eventually could generate drought. Rx5D represents accumulated rainfall for 5 days that could potentially trigger landslides and flash floods.

We used non-parametric statistical tests to assess the significance of some metrics at the 90% level. The linear trend was assessed using the Mann–Kendall (MK) test (Kendall, 1975; Mann, 2008). This is done to compare the sample means using the Wilcoxon's Rank Sum test was used. The Kruskal-Wallis test was used to compare the sample variances. Non-parametric tests were used because such tests do not require a normality assumption.

## Regional Atmospheric Circulation Characteristics

The UHI is an important factor for heavy rain during the rainy season (Vemado and Pereira Filho, 2016). In addition, changes in the atmospheric circulation can also contribute to variations moisture transport and rainfall in southeastern Brazil. Then, one hypothesis is that the South Atlantic Subtropical Anticyclone (SASA) can experience anomalies in its climatological position and intensity. This in turn can intensify the moisture transport to MASP. To investigate this hypothesis, we applied the methodology from Reboita et al. (2019) to identify the SASA central position in each month of the year. Monthly mean sea level pressure data comes from the ERA-20C (Poli et al., 2016) and ERA5 reanalyses from the European Center for Medium-Range Weather Forecast (ECMWF). The spatial resolution of 1° lat-lon. The analyzed period was from 1900 to 2009 for ERA-20C and from 1979 to 2019 for ERA5. The position of the core pressure SASA was identified using the nearest neighbor technique. This method compares a grid point with those around it to find the highest-pressure value than the neighbors. This methodology was applied to the monthly data in the area of 40° S−20° S e 42° W−12° E. The final result is the latitude, longitude, and pressure of the grid point with the highest-pressure value. The detailed explanation of the methodology is presented in Reboita et al. (2019). We compared time series of extreme rainfall indices and the SASA position and intensity. This is done to find a possible correlation among them.

# RESULTS: OBSERVED RAINFALL EXTREMES IN MASP

Observed trends of rainfall extreme indices at the IAG-USP and the Mirante de Santana stations are shown in **Figure 2**. This analysis has been updated until 2019. Total precipitation in both stations has been increasing steadily, with a pronounced interannual variability. The rate is +53 mm/10 year at Mirante de Santana and at IAG-USP the change is about +55 mm/10 year, and those trends reach statistical significance as shown by the Mann-Kendall test. CDD shows almost no significant change since the beginning of the records in both stations. However, in the last 20 years CDD featured positive trends (**Figures 2A,B**), i.e., the number of consecutive dry days is increasing, from 30 in 200 to 50 between 2019. R95p and Rx5D (**Figures 2C,D**) show a steady increase, being statistically significant for R95p. Changes in CDD and Rx5D are not significant in both stations. We found that the most significant linear trends were for increases in R95P until 2019. One conclusion from **Figure 2** is that there are signals of change in the rainfall pattern. The increase in total precipitation is accompanied by more intense rainfall episodes. These heavy precipitation events occur with long dry spells in between tendencies in rainfall extremes at Mirante de Santana and IAG-USP stations are shown in **Figures 3A–F**. The number of days with precipitation from 10 to 50 mm (R10 to R50) has been increasing. The largest values are shown after 2000 in both Mirante de Santana and IAG-USP. The number of days with R10 at Mirante de Santana and IAG-USP varied from 40 to 60 during the last 20 years. It shows a positive significant trend. R20 and R25 also show positive trends (statistically non-significant) and with a strong interannual variability. The figure shows a positive non-significant trend in R30, and during the last 20 years, it has varied between 10 and 20 days, as compared to 5 to 10 days in 1940–1960. There is a positive and significant trend in R50 (**Figures 3B,E**) but perhaps the most important feature is the relatively large number of days with R80 and R100 from 2000 to 2019 as compared to the 1960's (**Figures 3C,F**). It can be concluded that all climate indices had increasing trend across the whole period of study. The results also have shown non-significant trends for most of the climate indices at recent period (2000–2019), despite rising trends observed in RX5day for IAG-USP and R80 for Mirante de Santana. Overall these trend results reveal the increasing tendency in heavy precipitation.

At the decadal level, there is a tendency for a reduction in number of days with light rain (R1, R5) in the last 20 years. **Figures 4A–F** shows decadal accumulations of CDD, Rx5day and R95p, as well as the number of days with rainfall exceeding 10, 20, 25, 30, 50, 80, and 100 mm in both stations in São Paulo. The mean number of days with CDD and Rx5d has not changed along the last six decades, but there is a strong year-to-year variability. An analysis performed by INMET with the Mirante de Santana station showed that in the 1960's there were periods with 15 days with no rain, and by 2012 this number reached 51 days. During the water crisis in the summer of 2014, there was a period of 47 days with no rain in the MASP during January-February 2014, with a heatwave with 26 consecutive days with temperatures above 30°C in February 2014 (Nobre et al., 2016). R95P has increased most particularly since the 1980's. The number of days with 50 mm or more has gradually increased. It varies from 52 days in 1960–1980 to 88 in 2000–2019 at the IAG USP and from 71 days in 1960–1980 to 94 in 2000–2019 at Mirante de Santana. Daily rainfall above 100 mm/day has the potential to trigger natural disasters.

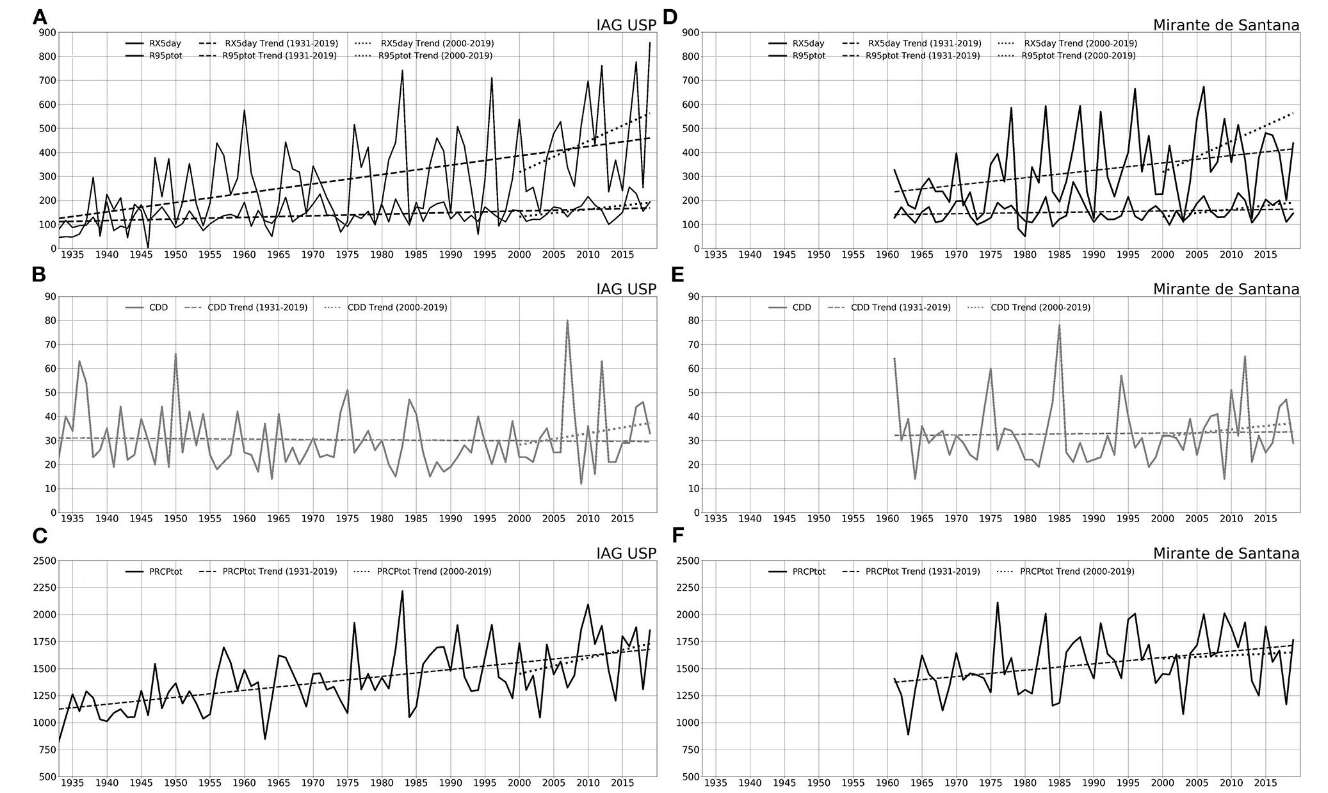


**FIGURE 2 |** Time series of heavy precipitation (R95P); 5 days accumulated precipitation (R5xD); consecutive dry days (CDD) and total annual precipitation (PRECTOT) during 1931–2019 for IAG-USP **(A–C)** and Mirante de Santana during 1961–2019 **(D–F)**. Linear trends are shown with full (since 1961) and broken (2000–2019) lines.

As shown in **Figures 5A,E** there is a reduction on the number of days with light rain (5 mm) during the last 20 years. This is better observed during DJF. At IAG-USP, the number of days with precipitation above 5 mm has decreased in, from 310 in the 1990's to 260 after 2010. In Mirante de Santana the reduction is more pronounced, with 310 in the 1990 to 250 after 2010. According to INMET, relative humidity in Mirante de Santana has been reduced by about 6% from 1960 to 2010. This is because the vegetation coverage is lower than in IAG-USP, suggesting impacts of urbanization. In addition, changes in the frequency of light rain have been linked to warming MASP (Conti, 1979; Tarifa and Armani, 2001; Pereira Filho et al., 2007).

At seasonal level (**Figures 5B–D,F–H**), the increase in the number of days with rainfall above 50, 80, and 100 mm is more intense in summer DJF. For rainfall above 50 mm in IAG-USP, in DJF there were identified 26 events in 1960–1980 and 11 events in 2001–2019. In Mirante de Santana, these numbers varied between 9 in 1980–2000, and 53 after 2000. Changes in the number of days with rain above 50 and 100 mm have been identified in the two transition seasons MAM and SON, after the 1980's.

There is an observed increase in number of days with precipitation above 80 and 100 mm in the last two decades. These changes are statistically significant at 95% level. Marengo et al. (2020) show that for both stations the number of days with rainfall above 80 and 100 mm has increased by a factor of four during the last 20 years as compared to 1940–1960. Between 1960 and 1980 the number of days with precipitation above 80/100 mm was 9/3 at IAG USP and 8/1 for Mirante de Santana. For the period 2001–2019, these numbers were 25/11 and 20/6. Two events with rainfall above 100 mm were detected in January and February 2020 at the IAG USP station.

The results from Vemado and Pereira Filho (2016) show that the warmer urban environment in MASP produces a UHI effect that interacts with the sea breeze. This intensifies thunderstorms that lead to flash floods and landslides. Therefore, the increase in rainfall extremes can be explained by the UHI and by changes in atmospheric circulation (see section Large Scale Circulation and Regional Influences).

In sum, we can affirm that:

- Total precipitation and frequency of days with extreme rainfall values are increasing
- There is a small negative trend of the number of days with light precipitation from the beginning of the 2000's.
- The number of days 80 and 100 mm has almost doubled in 2011–2019 as compared to 1971–1980, mainly in DJF.
- It is also worth mentioning that the precipitation above 80/100 mm started to be observed after the 2000's during austral winter (JJA).

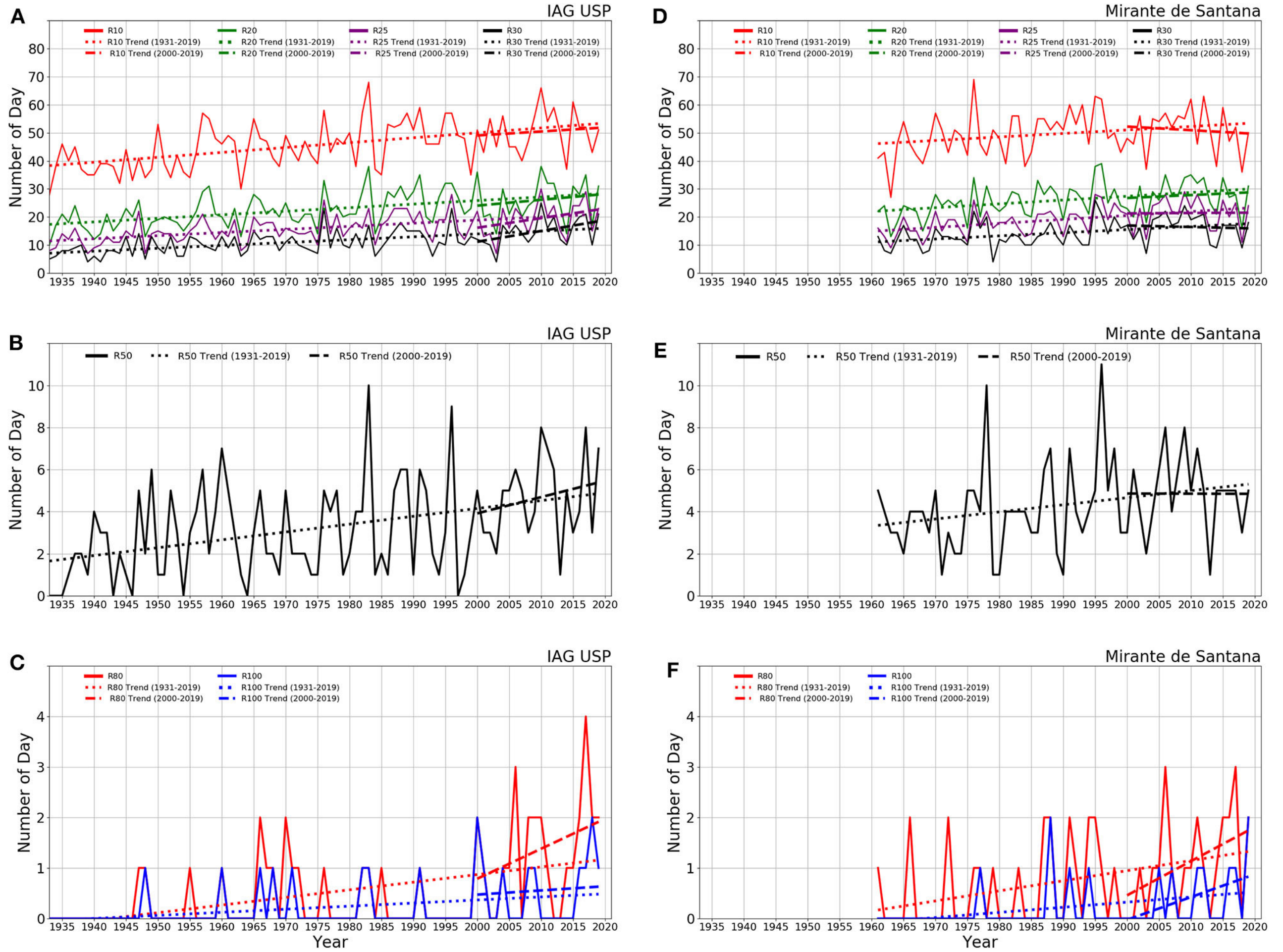


**FIGURE 3 |** Time series of numbers of days with precipitation above 10 mm (R10), 20 mm (R20), 25 mm (R25), 30 mm (R30), 50 mm (R50), 80 mm (R80), and 100 mm (R100) for IAG-USP during 1931–2019 **(A–C)** and Mirante de Santana during 1961–2018 **(D–F)**. Linear trends are shown with full (since 1961) and broken (2000–2019) lines. Linear trends are shown with full (since 1961) and broken (2000–2019) lines.

## LARGE SCALE CIRCULATION AND REGIONAL INFLUENCES

Zilli et al. (2019) and Jorgetti et al. (2014) identify underlying mechanisms associated with changes in precipitation intensity and position of the SACZ since 1979. They show evidence of increasing average daily precipitation along the poleward side of the SACZ. This likely related to a poleward shift of the convergence zone. These changes in circulation and moisture could be related to the poleward expansion of the SASA. The variability of the SACZ caused great natural disasters in Southeast Brazil at various time scales. In the past, SACZ's related intense rainfall triggered landslides that killed people in Serra do Mar (Seluchi and Chou, 2009) and in Rio de Janeiro state in 2011, causing 947 fatalities (Nielsen et al., 2016).

In terms of synoptic scale, the SASA action over Brazil differs between the wet and dry seasons. During the dry season (JJA), SASA is more zonally expanded reaching southeastern Brazil. This is responsible for inhibiting convection and the passage of frontal systems (Reboita et al., 2019). During the wet season (DJF) the SASA shrinks eastward. This favors moisture transport into southeastern Brazil. This moisture is important for the SACZ maintenance, for example. Reboita et al. (2019) observed during 1979–2005 a slightly southward displacement of the SASA core pressure center. This is in agreement with studies that indicate a poleward expansion of the Hadley cell in the present climate (Hu et al., 2018) and of the oceanic gyres (Yang et al., 2020).

**Figure 6** shows the variability of the SASA position (**Figures 6A–C**) and the intensity and total and extreme rainfall events (**Figures 6D–F**). There is a negative trend in latitude (indicating southern displacement) and longitude (indicating westward displacement) of the SASA core. Additionally, there is a positive trend in the intensity of pressure at the core of SASA (significant at the 90% level). This is accompanied by positive trends in total precipitation at Mirante de Santana and IAG USP (significant level of 95%). The trends in the SASA features are not statistically robust. These suggest that the observed trends in total and extreme rainfall in the long term may be partially

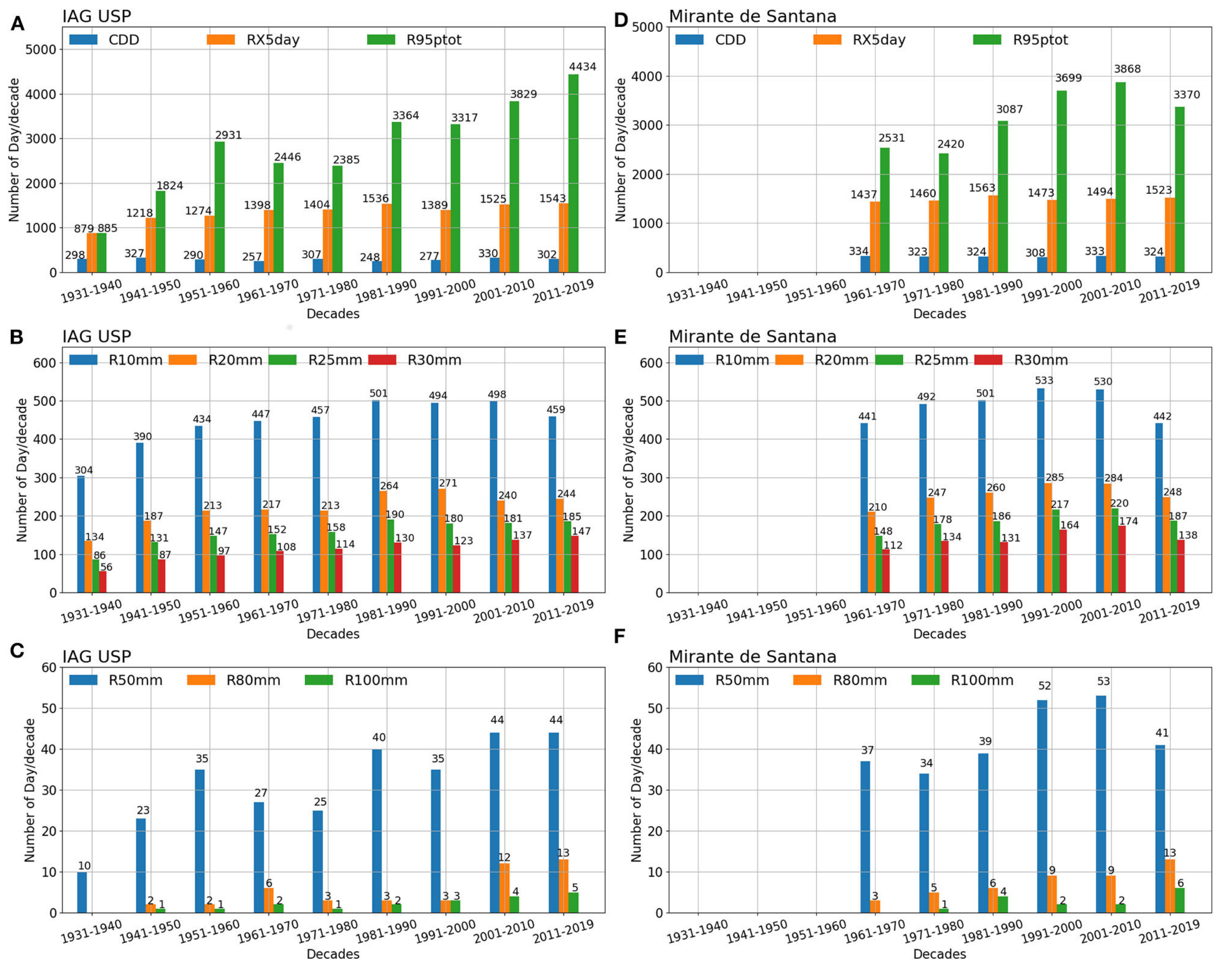


**FIGURE 4 |** Decadal accumulation of CDD (consecutive dry days), heavy precipitation (R95P), and 5 days accumulated precipitation (R5xD) for **(A)** IAG-USP and **(D)** Mirante de Santana; for numbers of days with precipitation above 10 mm (R10), 20 mm (R20), 25 mm (R25), and 30 mm (R30) for **(B)** IAG-USP and **(E)** Mirante de Santana; and for number of days with precipitation above 50 mm (R50), 80 mm (R80), and 100 mm (R100) for **(C)** IAG-USP, and **(F)** Mirante de Santana, with number showing the corresponding decadal numerical values.

related to variations in the circulation in the adjacent South Atlantic Ocean, which is reflected by changes in position and intensity of SASA.

Negative correlation is found between latitude at the core of SASA and precipitation in DJF in MASP. This suggests a southward position of SASA with more rain in MASP and eastern São Paulo state (**Figure 7A**). Positive correlation is found between longitude of SASA and precipitation, which indicates a westward SASA position during episodes with less precipitation over São Paulo (**Figure 7B**). **Figure 7C** shows that combining information, i.e., when SASA is concomitantly displaced southward and westward, it is observed that the intensity of the precipitation (mm/day) is higher than the seasonal mean over MASP and north sector of Southern Brazil. This can be a consequence of increased moisture transport from the northwestern sector of SASA as shown by the northeast winds (**Figure 7C**). This circulation pattern is consistent with results from a seasonal analysis performed by Silva et al. (2019) considering the five cases in which the ASAS was north (south) of its average position and the five cases in the west (east).

SASA position should be influenced by the Southern Annular Mode (SAM). Consequently, it also impacts precipitation over southeastern Brazil. In the SAM positive phase, there is higher frequency of cyclones near Antarctica and southeastern coast of Brazil and lower frequency near 45°S (Reboita et al., 2019). These cyclones near the southeastern coast of Brazil can influence the intensity and/or the displacement of the SASA, i.e., it can weak SASA or displaced southward. To evaluate this hypothesis, we calculated the correlation between the SAM index and SASA latitude (similar analysis was done for longitude). There is a negative and significant ($\alpha = 0.05$) correlation ($-0.25$) between these two variables, which means that in the SAM positive phase

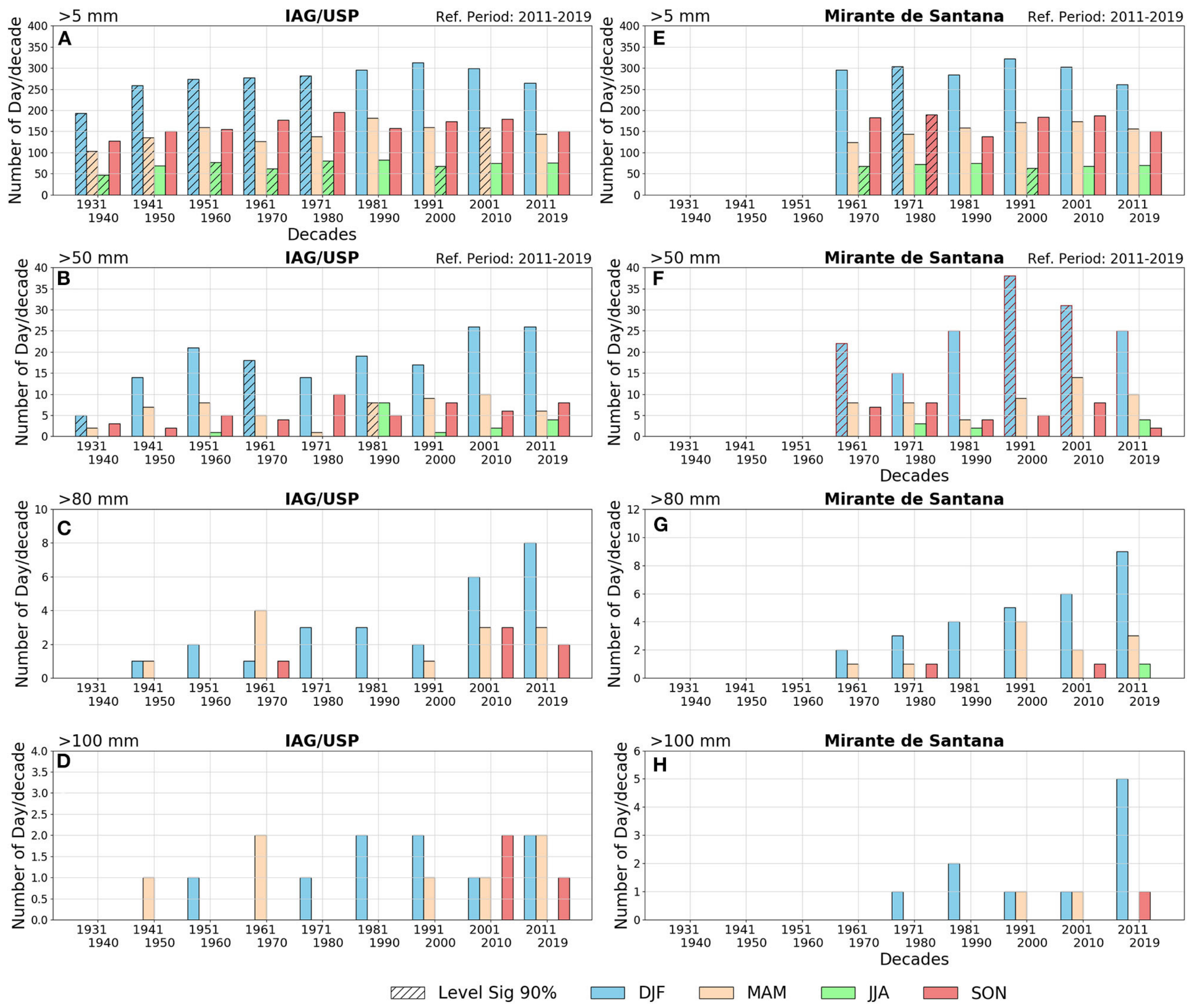


**FIGURE 5 |** Decadal accumulation of above 5 mm for fore the four seasons of the year in **(A)** IAG-USP and **(E)** Mirante de Santana; for numbers of days with precipitation above 50 mm for **(B)** IAG-USP and **(F)** Mirante de Santana; for number of days with precipitation above 80 mm **(C)** IAG-USP and **(G)** Mirante de Santana, and number of days with precipitation above 80 mm **(D)** IAG-USP and **(H)** Mirante.

the SASA is displaced southward. This correlation can explain, at least in part, the extreme events of precipitation over São Paulo state and the north sector of the southern Brazilian region. The precipitation signal shown here is in agreement with Reboita et al. (2009), Vasconcellos and Cavalcanti (2010), and Gozzo et al. (2019) who observed that anomalous positive precipitation occurs in the South Atlantic Convergence Zone region during the SAM positive phase, and at the same time there is anomalous negative rainfall over the south of Brazil. Opposite pattern occurs during SAM negative phase.

## FINAL DISCUSSION AND RECOMMENDATIONS

This study presents an updates analysis of trend of annual precipitation and rainfall extreme indices for two meteorological stations in the MASP region. The MASP is prone to severe weather. Heavy precipitation can trigger natural disasters with major impacts on society. In general, annual total and heavy precipitation shows a positive significant trend during 1930–2019, mainly during summer. The increase in total precipitation is related to the increase in frequency of extreme precipitation. On the other hand, the number of consecutive dry days (CDD) increased besides the increase in the number of days with very heavy precipitation (from R20 to R100 mm). Although these results appear to be contradictory, they indicate an important climate change in recent times. Intense precipitation is becoming concentrated in a few days across the period separated by longer dry spells, that vary from 30 to 50 dry days since 2000.

Changes in extremes can be partly due to natural climate variability. In other words, changes in the position and intensity

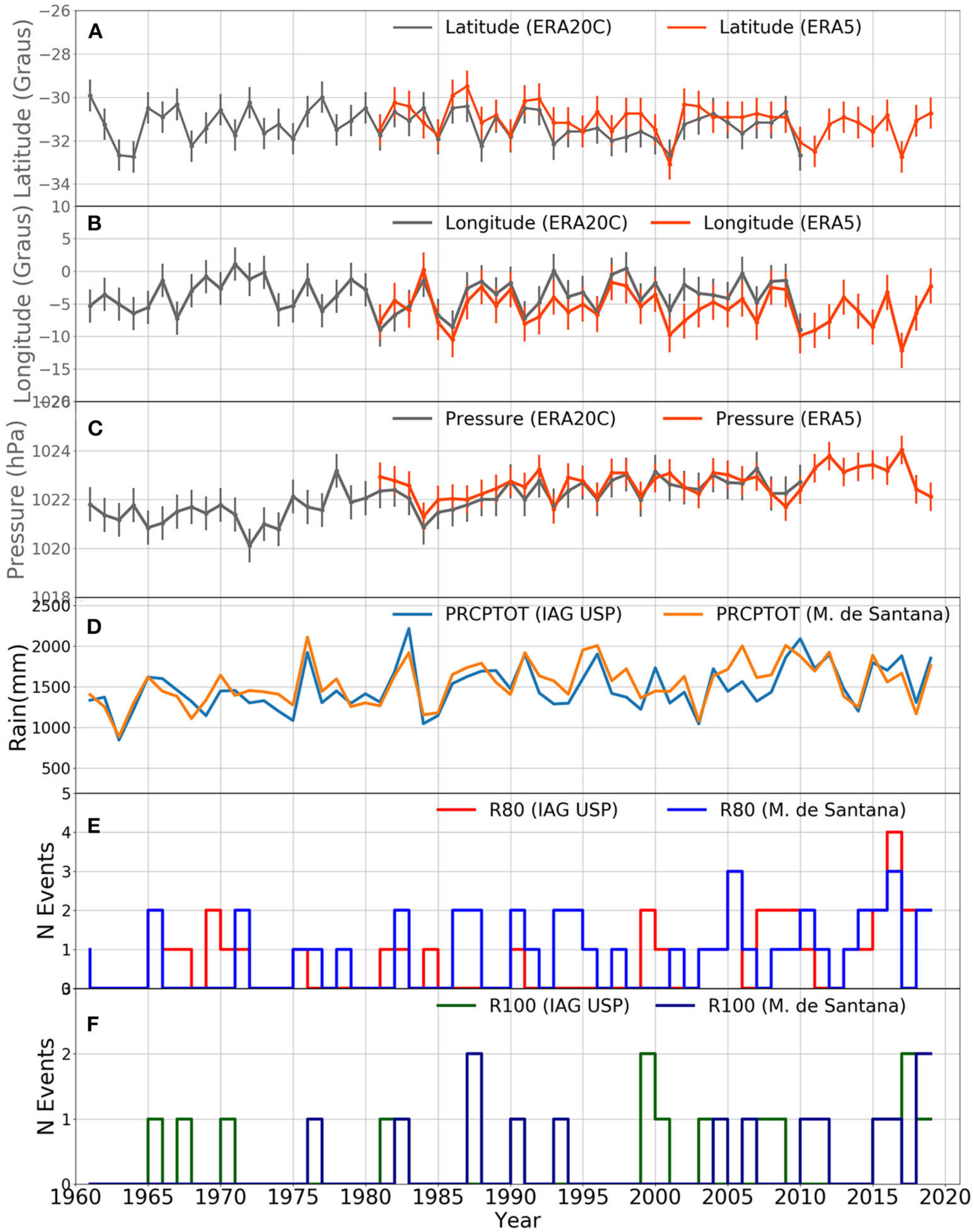


**FIGURE 6 |** SASA indicators: **(A)** Latitude, **(B)** Longitude, **(C)** Sea level pressure; **(D)** Annual precipitation PRPCTOT, **(E)** R80, and **(F)** R100. Vertical dashes represent the total standard deviation of the SASA series **(A–C)**.

of the South Atlantic Subtropical Anticyclone (SASA) are responsible for changes in the atmospheric circulation.

These changes affect rainfall extremes. It is clear from the analysis of its position and intensify considering the period of 1960 to 2019 that the SASA has slightly moved to the west and southward. This new climatological position can influence the transport of humidity and therefore impact the precipitation and extremes. This is a possible physical explanation for the increase in the precipitation extremes in the MASP besides the consecutive dry variability periods observed. A thorough study of this atmospheric dynamical aspect are currently been done and it will be presented elsewhere. However, the correlations between SASA features and total and extreme rainfall may be low even though significant.

The South Atlantic regional circulation changes work together with regional scale changes in the MASP region. However, changes can also be related to global warming and/or urbanization. Urban heat islands created by the concrete and lack of vegetation in big cities increase temperatures.

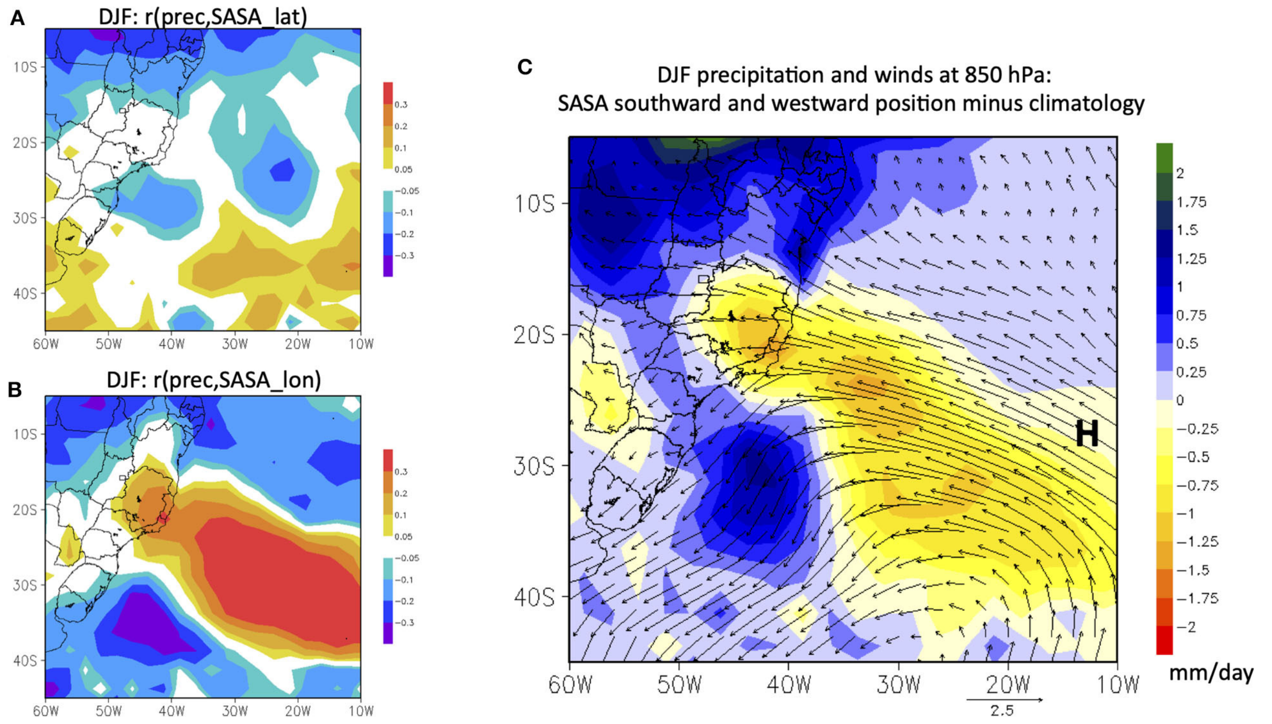


**FIGURE 7 | (A)** Linear correlation between monthly precipitation and SASA latitude in austral summer months (DJF) from 1979 to 2019; **(B)** the same as **(A)** but for SASA longitude and **(C)** anomaly of the monthly precipitation (mm/day) and wind direction at 850 hPa considering, concomitantly, the most southward and westward position of the SASA in relation to the DJF climatology (shaded).

When it is hotter, it rains more, and this gets worse if you have urban areas of concrete and asphalt. The lack of permeable ground means more flooding. This is in addition to a background signal of regional scale circulation. Such changes are probably related to regional warming. The UHI and land use change also affect the regional circulation in the form of sea breeze. As shown in previous studies urbanization intensifies thunderstorms in MASP (Lombardo, 1985; Pereira Filho et al., 2007; Barros and Lombardo, 2016). These produce intense rainfall that trigger landslides, flash floods, and floods. Attribution studies to identify if the causes of changes in extremes are due to natural or anthropogenic influences in MASP are being developed.

While positive trends in rainfall extremes represent hazards, they do not constitute a disaster itself. However, if these hazards impact population living in vulnerable areas, they constitute a disaster. An increase in extreme rain events is accompanied by an inappropriate occupation of vulnerable areas, such as slopes and banks of watercourses. This increases the risk of inundation, flooding, and landslides.

Changes have been identified in the frequency and intensity of light and heavy precipitation and dry spells in **Figures 2–6**. This pattern, as well as the observed changes in maximum and minimum temperature reported in previous studies, suggest that the MASP is experiencing more pronounced changes during the last 20 years. Since 2000, climate extreme weather and climate events that were rare 50–60 years ago they are now becoming the more frequent. More heavy rainfall episodes could increase the risk of frequent and flash floods and landslides in exposed areas, where vulnerable population and infrastructure may be allocated.

On February 10, 2020, intense rainfall affected the city of São Paulo, and floods, flashfloods, and landslides were recorded. According to the Civil Defense of São Paulo, four people died and 63 were left homeless due to landslides. Roads and highways were affected, and people were ordered to remain at home. Firefighters registered 796 floods, 140 landslides, and 120 trees fell in different neighborhoods of the MASP. In some places, it rained over 3 h the expected average for the whole month of February. The volume of rainfall reached 100 mm in a few hours–more than 50% of the average for the entire month. The Mirante de Santana station recorded 114 mm of rain between February 9th afternoon and Monday 10th. This is the largest amount of rain in 24 h for the month of February recorded in 37 years. Furthermore, February of 2020 was the wettest February since 1943 (INMET).

According to the Commerce Federation of the State of São Paulo (Agencia Brasil, 2020), the intense rainfall of February 10, 2020 produced economical losses of the order of $US 40 million mainly in the MASP.

The MASP urban area is expected to double in size by 2030. Under that scenario, up to 12% of the total area would become highly vulnerable to landslides if rainfall extremes increase by then (Nobre et al., 2011). The planning of large urban centers such as MASP requires a network of global articulation. This involves financial and economic interests. As recommendations, contingency plans are needed and must consider extreme rainfall with extended dry spells among some climate extremes. Rainfall climatology in several meteorological stations must be updated across the entire MASP and the state of São Paulo region, allowing for better studies to see if we have already entered into a "new normal" regime in MASP concerning heavy precipitation trends. There is a need for procedures to be adopted by governments and agencies working with disaster risk management consequence of weather and climate extremes. The main objective is to cope with the impacts of natural disasters in a warming climate with more rainfall extremes and people more vulnerable.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

NB and MS provided important analyses of the atmospheric and oceanic fields as well as processing of data from rainfall for calculations of the indices of rainfall extremes and their statistical analyses of rainfall data. AR provided, organized, and processed all data used in this study. JM, TA, LA, NB, and MS wrote the paper. All authors contributed to the article and approved the submitted version.

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# Citizen Science for the Prediction of Climate Extremes in South Africa and Namibia

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Seasonal-to-interannual variations of rainfall over southern Africa, key to predicting extreme climatic events, are predictable over certain regions and during specific periods of the year. This predictability had been established by testing seasonal forecasts from models of varying complexity against official station rainfall records typically managed by weather services, as well as against gridded data sets compiled through a range of efforts. Members of the general public, including farmers, additionally have extended records of rainfall data, often as daily values spanning several decades, which are recorded and updated regularly at their farms and properties. In this paper, we show how seasonal forecast modelers may use site recorded farm rainfall records for the development of skillful forecast systems specific to the farm. Although the uptake of seasonal forecasts in areas with modest predictability such as southern Africa may be challenging, we will show that there is potential for financial gain and improved disaster risk farm management by co-developing with farmers forecast systems based on a combination of state-of-the-art climate models and farm rainfall data. This study investigates the predictability of seasonal rainfall extremes at five commercial farms in southern Africa, four of which are in the austral summer rainfall areas, while one is located in the winter rainfall area of the southwestern Cape. We furthermore calculate a measure of cumulative profits at each farm, assuming a "fair odds" return on investments made according to forecast probabilities. The farmers are presented with hindcasts (re-forecasts) at their farms, and potential financial implications if the hindcasts were used in decision-making. They subsequently described how they would use forecasts for their farm, based on their own data.

**Keywords: Southern Africa, seasonal climate forecasts, co-production, profits, farm management**

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## INTRODUCTION

Seasonal forecast model development has a long history in South Africa (Landman, 2014). During this time, the seasonal forecast community in South Africa has developed complex climate models for operational seasonal forecasting (Beraki et al., 2014). The coupling of atmospheric climate models to models for the ocean, the land surface and sea ice, has led to improved seasonal forecasts, also for South Africa (Landman et al., 2012). Notwithstanding the proven accuracies of seasonal climate forecast models, statistical correction methods are recommended even for today's coupled climate model forecasts (Barnston and Tippett, 2017). Such statistical correction has had a long track record in terms of testing predictability over southern African countries including South Africa and Namibia (e.g., Bartman et al., 2003; Landman and Goddard, 2005), where local climatic mechanisms effecting seasonal-to-interannual variations over these countries have been studied comprehensively (e.g., Tadross et al., 2005; Hansingo and Reason, 2009; Reason and Smart, 2015). Statistical correction still forms part of the seasonal forecast systems developed at certain institutions for operational forecasting in South Africa, including the South African Weather Service and the University of Pretoria (UP). In addition to statistical corrections of global models forecast output, hindcasts (or re-forecasts) over multiple decades have also been used in the development of application models for agriculture in southern Africa (Malherbe et al., 2014), hydrology (Muchuru et al., 2016) and health (Landman et al., 2020), among others. In this study, we seek to use rainfall data provided by farmers to create and test seasonal forecast models specific to their farms, and to learn from them how such forecasts, including those relevant to climatic extremes, might impact on their farming decisions. Such a process of co-learning between forecast modelers and forecast users may help improve on seasonal forecasts tailored for commercial farm management, and, thus, potentially improve forecast uptake—a challenging aspect in southern Africa, where seasonal forecasting skill ranks modestly with other regions globally (Landman et al., 2019).

Farmers were invited to engage with the seasonal forecast bulletins of UP, during forecast presentations at farmers meetings, and during radio interviews, to make their rainfall records available for this kind of forecast system development and testing. There has, thus far, been a positive response, with more than 20 farmers providing their data, including dry-land end-of-season yield data at a small number of farms. In this paper, we have selected a small number of farmers who also indicated that they would be willing to respond to questions regarding use of forecasts in their farming decision-making. In addition to their willingness to participate, a further factor was that seasonal rainfall at the farm had, to some extent, to be predictable. Such use of citizen observations has already been proven useful in operational weather prediction (Nipen et al., 2020).

# DATA AND METHODOLOGY

## Data

Global climate model prediction output, in particular 3-month total rainfall fields, of the North American Multi-Model Ensemble (NMME; Kirtman et al., 2014) experiment are used as predictors for the forecast models developed for each farm. Here we use only the hindcasts from the GFDL-CM2p5-FLOR-B01 (referred to here as "GFDL") since this model has been shown to outperform other NMME models over southern Africa (Landman et al., 2019). This model data set is available from March 1980 to present, for 12 ensemble members and for 11 lead-time months. We only use hindcasts made at a 1-month lead-time. Further, only restricted areas of the GFDL output are used and include 35°-15° South, 15°-35° East (for the three South African farms in the summer rainfall region); 40°-15° South, 0°-50° East (for the Namibia farm), and 45°-20° South, 0°-40° East (for the farm in the winter rainfall region).

The rainfall data included in the study was made available from five farmers—respectively located in the southwestern Cape (winter rainfall), three farmers in the central and northwestern interiors of South Africa (mid-summer rainfall), and northern Namibia (late summer rainfall). Although the rainfall records of the farms do not all start on the same year, they are all up to date for the rainfall totals recorded up to the end of the 2019/20 summer rainfall season.

## Hindcast Method

The GFDL rainfall fields as specified over the domains above are considered for the development of statistically-based rainfall models for each farm. These rainfall models are produced by statistically downscaling the climate model's seasonal rainfall fields to concurrent seasonal rainfall totals at the farms. The canonical correlation analysis option of the Climate Predictability Tool (CPT; Mason and Tippett, 2016) is used in the development of the statistical models. Only 1-month lead-times are considered, and so typical configurations of the rainfall models is designed as follows: Predicting JFM rainfall totals, the GFDL was initialized in December for a JFM rainfall hindcast set downscaled to JFM rainfall totals at the farm.

The hindcast skill levels of the five rainfall models are tested using a cross-validation setup, with a 5-year-out window. It is important to note that the farms' rainfall data were first transformed into an approximate normal distribution before downscaling. The hindcast and observed data at each farm are subsequently normalized in order to produce rainfall indices as opposed to rainfall totals. **Figures 1–5** show the respective hindcasts vs. observed time series for each farm. We only show Pearson correlation values between cross-validated hindcasts and observed time series on these figures in order to represent the deterministic skill levels of the rainfall models. Each statistical rainfall model is then used to retro-actively produce forecast for the most recent years of the available farm data, ranging from 9 to 20 years. The retro-active forecast process is able to create probabilistic rainfall forecasts (Landman et al., 2012) for each farm for three categories with thresholds defined by respectively the 25th (low rainfall indices) and 75th (high rainfall indices) percentile values of the climatological record. These thresholds define extremely above- and extremely below-normal rainfall categories, in terms of extreme events.

The potential economic value of the five retro-active rainfall forecasts are subsequently assessed (Hagedorn and Smith, 2009). For this purpose, we make use of the cumulative profit (CP) values generated by the CPT software (see Mason (2018) for a comprehensive explanation on the calculation of the CP values). Because farming, naturally, has cost implications, it may, potentially, be of value to a farmer to consider the potential economic value of seasonal rainfall forecasts made for the farm. Cumulative profit values evaluate probabilistic forecasts (for

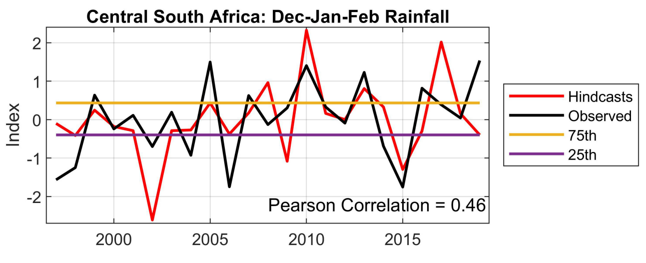


**FIGURE 1 |** Cross-validated hindcasts (red) vs. observations (black) for the Dec-Jan-Feb rainfall season of the farm located in the central interior of South Africa. The two horizontal lines respectively represent the 25th percentile value (purple) and the 75th percentile value (orange) of the climatological record. The Pearson correlation value between hindcast and observed is significant at the 98.6% level of confidence.

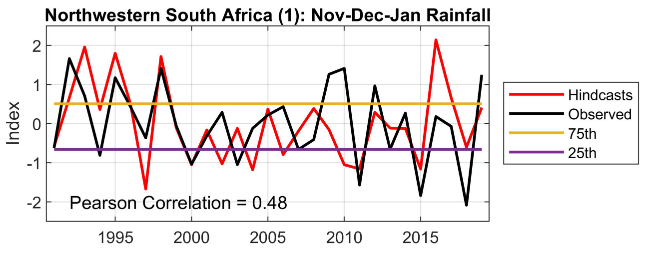


**FIGURE 2 |** As for **Figure 1**, but for the Nov-Dec-Jan rainfall of the first farm located in the northwestern interior of South Africa. The correlation value's level of confidence is at the 99.8% level.

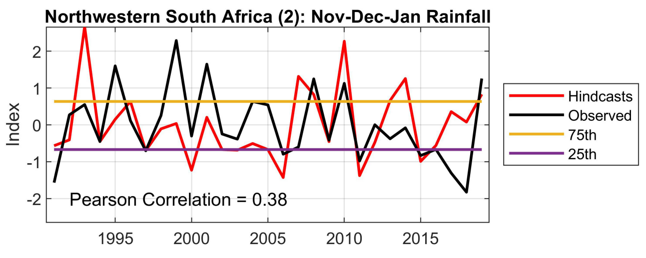


**FIGURE 3 |** As for **Figure 1**, but for the Nov-Dec-Jan rainfall of the second farm located in the northwestern interior of South Africa. The correlation value's level of confidence is at the 99.7% level.

example, 60% chance of above-, 30% of near- and 10% chance of below-normal rainfall) by means of quantifying the skill of the forecast based on its effective return. Here, we calculate the cumulative profit values over a number of probabilistic forecasts based on an arbitrary ZAR100 investment in the first year. The return on investment is calculated based on "fair odds" and assuming that the ZAR100 is spread across the forecast categories in proportion to the forecast probabilities. This means that for the observed category (above, below or normal), the farmer realizes effectively triple the investment in that category each year. The results shown on the cumulative profit figures (**Figures 6–10**) can be interpreted as follows: for example, the cumulative profit value of, say, 10 found for a specific year later on means that the

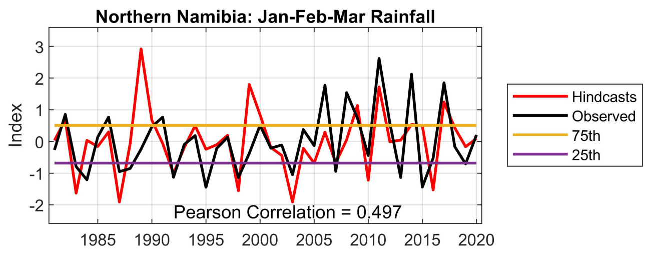


**FIGURE 4 |** As for **Figure 1**, but for the Jan-Feb-Mar rainfall of the farm located in the northern interior of Namibia. The correlation value's level of confidence is at the 99.99% level.

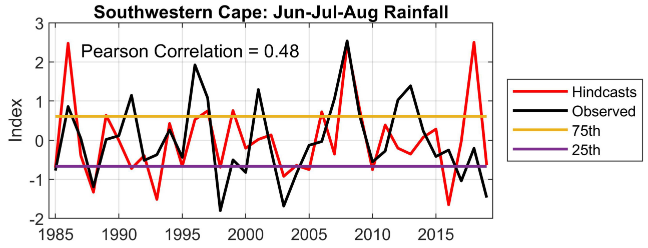


**FIGURE 5 |** As for **Figure 1**, but for Jun-Jul-Aug rainfall at the farm located in the southwestern Cape of South Africa. The correlation value's level of confidence is at the 99.4% level.

initial investment of ZAR100 in the first year would be worth ZAR(100 × 10 =) ZAR 1,000 in that specific year. One would (in this case study) subsequently invest, theoretically, all ZAR1000 based on the next year's forecast, and so forth. Skilful forecasts are associated with an increase in profits, while poorer performing forecasts are associated with a decrease in profits. This high skill—high profits relationship was clearly demonstrated in a study on the seasonal rainfall and inflows predictability for the Lake Kariba catchment which is located over central southern Africa (Muchuru et al., 2014, 2016).

## Questions to Farmers

Formulating precise questions without a proper understanding of the farms (and how they are managed) is, it should be noted, not the objective of this study. In fact, we have set out here to show that in using rainfall data provided by the farmer, skillful forecast models, albeit only at a 1-month lead-time (although we argue that this may still have utility), can be developed for the farm. We propose further that this development may be able to inspire and support interest by the farmer to engage in a co-learning process with climate modelers, in order to eventually improve forecast development, usability, uptake and constructive use. To this end, the following questions, along with the specific farm's hindcasts (**Figures 1–5**) and cumulative profits graphs (**Figures 6–10**), were given to the farmer:

1. What decision might you make based on the forecasts presented to you?

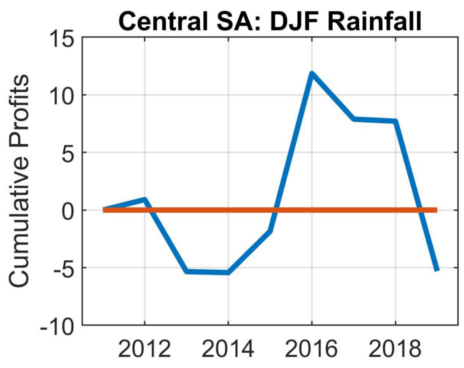


**FIGURE 6 |** Cumulative profits graph based on 9-years of probabilistic Dec-Jan-Feb rainfall forecasts for the farm located in the central interior of South Africa, to communicate the monetary value of probabilistic forecasts. The higher the amount of capital placed on a forecast that is correct, the higher the profit or return will be.

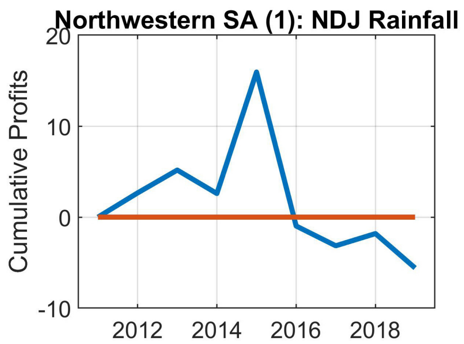


**FIGURE 7 |** As for **Figure 6**, but for Nov-Dec-Jan rainfall forecasts for the first farm located in the northwestern interior of South Africa.

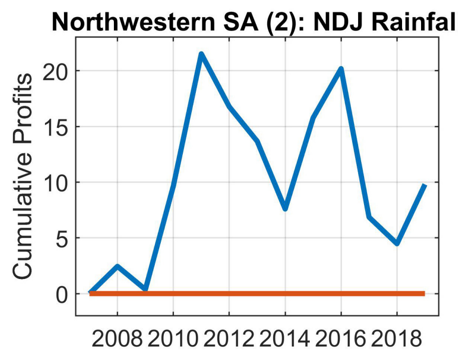


**FIGURE 8 |** As for **Figure 6**, but for 13-years and for Nov-Dec-Jan rainfall forecasts for the second farm located in the northwestern interior of South Africa.

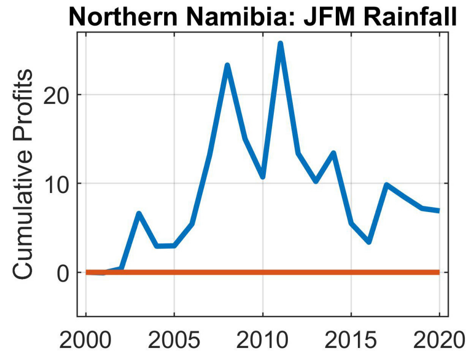


**FIGURE 9 |** As for **Figure 6**, but for 20-years and for Jan-Feb-Mar rainfall forecasts for the farm located in the northern interior of Namibia.

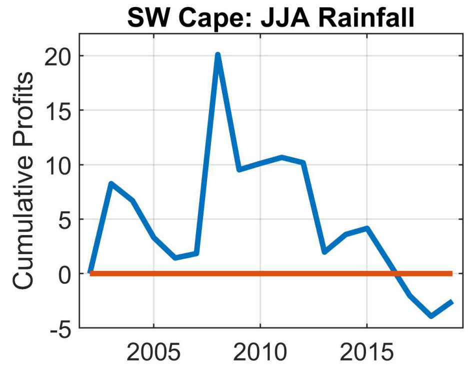


**FIGURE 10 |** As for **Figure 6**, but for 18-years and for Jun-Jul-Aug rainfall forecasts for the farm located in the southwestern Cape of South Africa.

2. Do the forecasts and what turned out to be the case have to be close together for a farming decision based on the forecast to be effective?
3. What percentage of farm expenditure or profit will be enhanced if the decision based on the forecast was correct?
4. Do you tend to trust the forecasts more or less so because data from your farm was used to produce the forecasts?
5. Do you want any improvements in the forecasts provided?
6. What is the ideal lead-time (in months) the forecasts should be provided before the onset of the rainy season to help you to better prepare and make farming decisions?

# RESULTS

## Deterministic Hindcasts

The selection of the five farms from the more than 20 farmers who responded to the call to make their rainfall data available is of course, fairly limited. However, we wanted to use rainfall data that are not only restricted to the summer rainfall regions of South Africa, where predictability studies have been conducted for a number of decades already (see references in Landman, 2014). We are therefore grateful that a farmer from the southwestern Cape has made data available for this study in a region that has only recently been shown to have some level of forecast skill (Archer et al., 2019). Further, the Grootfontein area of Namibia has a small number of farmers that have over recent years been actively engaging with seasonal forecast modelers in South Africa.

As a result, including that area was considered likely to prove useful. Moreover, as stated earlier, we are only presenting the forecasts for farms where we have found predictability to be present. Finally, farm data has been collected, but has neither been analyzed nor used in the development of forecast models yet for some farms, owing to the fact that we only recently received the data.

We begin our presentation of the seasonal rainfall predictions by considering hindcasts for the three farms in the summer rainfall region of South Africa, located respectively in the central and north-western interior (two) regions of South Africa. **Figure 1** shows the results for the central interior, and **Figures 2**, **3** for the north-western interior. Similar skill levels are found for the three farms, but the seasonal-to-interannual variation of both the observed and hindcast data differ. Notwithstanding, rainfall hindcasts during the strong El Niño events of 1997/98 and 2015/16 tend to show negative anomalies, although the outcome was not as severe for the 1997/98 season. The ENSO-neutral year of 2019/20 is associated with high rainfall totals for these three farms, even though the hindcast for that year does not always pick up on the high rainfall outcomes. The 2019/20 example may yet be another reminder of the major challenges faced in developing good forecasts for South Africa, when we are in an ENSO-neutral season (Landman and Beraki, 2012), notwithstanding the possible presence of climate factors in addition to ENSO that also have been found to be associated with southern African rainfall. These include sea-surface temperature of the Indian and Atlantic Ocean (Mason, 1995), dipole modes in the Indian Ocean (Reason, 2001; Washington and Preston, 2006; Hoell et al., 2017) and the Madden-Julian Oscillation (Pohl et al., 2009). The important effect of specific boundary forcing (e.g., ENSO) on the seasonal prediction skill for a given year remains an important consideration in seasonal forecasting (Hoell and Eischeid, 2019).

**Figure 4** shows the hindcast results for the farm site in northern Namibia. This area is associated with good forecast skill during ENSO years (Landman and Beraki, 2012), and it is thus likely that the phase of ENSO is largely responsible for the relatively good level of skill found for the farm there. A variety of farming activities are found in that part of Namibia, including cattle and maize (as well as wildlife management in different forms, in certain areas).

The southwestern Cape farm is also associated with significant predictability (**Figure 5**), but the rainfall model did not perform skilfully during the more recent years of the test period, especially for the 2018 season when the hindcast shows a large positive anomaly during a period when the southwestern Cape was facing significant water use challenges owing to prolonged droughts (Otto et al., 2018).

### Potential Economic Value of the Hindcasts

**Figures 6–10** show the cumulative profit values for the five farms over varying test periods. We arbitrarily selected the lengths of these periods on condition that the most recent years are included in the analysis. These figures show the economic value of skillful forecasts—but also what may happen with accumulated profits, when there is a sequence of poorly performing forecasts. Except for one of the South African farms and the Namibian farm, the accumulated profits become negative at the end of the forecast period.

The results of this economic value analysis shows that much more work has to be done in the investigation of the financial viability of introducing seasonal forecasts in decision-making in agriculture in southern Africa. This is not surprising as we have used an idealized calculation here to illustrate the method, whereas in the real world cumulative profits would depend on input costs and the price the crop is sold for, all of which vary from year to year. In a real sense, we are very early in the process of truly working with the agricultural sector in southern Africa in a way that truly captures iterative and longstanding processes of co-learning.

## RESPONSE FROM FARMERS

Our discussion on the farmer's responses start with the farm in northern Namibia, as forecast skill and economic profit are found to be highest for this farm of the five farms considered, and the response from the farmer has been comprehensive and positive. It is important to note that forecasts in real-time produced by UP for this particular farm have been provided to the farmer since 2018. Owing to this already existing relationship between the farmer and the forecast producer, it may be expected to find a more positive response from the farmer. In fact, the farmer states that the UP seasonal forecasts do influence farming decisions, and that the forecast service provided to the farmer is such that in future the farmer will consider to only use UP forecasts for farming decision-making—including, for example, decisions as how many hectares to stock or destock with cattle. Notwithstanding the recent good forecasts provided to the farmer, the farmer will continue to require that forecasts for future seasons capture the amplitude of the anomalous dry or wet season, due to high risks and profitability, and the unavailability of maize insurance in Namibia. When asked about percentage farm expenditure or profitmaking, the farmer stated that cattle profit or loss is about 40% of the farming, maize is also about 40%—while the rest is barbeque wood or charcoal produced from invader bush. Because cattle and maize both rely on seasonal climate, the farmer claims that seasonal forecasts play a significant role in profit or loss planning for the farm. In addition, the farmer states that profits can increase by at least a further 10% in a favorable rainy season which is predicted in advance, whereas in dry seasons, the farmer has to focus primarily on wood and charcoal. In reply to the question if forecasts that use data from the farm increase trust in forecasts, the farmer claims that the forecasts produced this way, especially for the 2020 summer season of high spatial variability, provided unprecedented guidance on expected rainfall outcomes. The farmer was happy to have used the UP forecasts for the past season regarding the planting of maize on the farm. However, the farmer would like to also see forecasts from neighboring farms (within a 20–50 km radius)—hopefully, thus, more farmers from the region will join the UP initiative. In addition to having more forecasts for the region, the farmer also require forecasts at multiple month lead-times—for instance, as maize farmer planning has to start as early as August for the first half of summer (Oct-Nov-Dec) as well as for the main rainfall season of Jan-Feb-Mar. As a cattle farmer, forecasts at such lead-times should also be able to advise on whether or not to sell cattle early in the season, or, if the farmer can delay the sale of existing cattle until February (the price per head picks up again in November after an initial drop).

The responses from the three farmers in the summer rainfall region are less comprehensive, but still valuable. The first farmer in the northwestern interior (see **Figures 2**, **7**) states that seasonal forecasts may influence his decisions on which crops to consider planting for a coming season, and also decisions relating to planting dates of the crops. Furthermore, seasonal forecasts should be able to help provide a holistic view on expenditure; for example the purchasing of farming equipment and fertilizer. However, forecasts need to be skillful and such forecasts may contribute to as much as 30% of the profit, according to the farmer. The farmer is also convinced that the inclusion of his own data in the development of a seasonal rainfall forecast model for his farm has made forecast more trustworthy as compared to forecasts available from other sources. The farmer would also, however, like to see his data being used to make forecasts for individual calendar months to supplement the seasonal forecasts, and that lead-times are extended to make forecasts for the coming summer rainfall season as early as July or August.

The second farmer in the northwestern interior (**Figures 3**, **8**) seems to be most interested in the forecasts when the forecasts favor an anomalously wet season. During such seasons the farmer will apply more fertilizer than would be the case for even "normal" years, and as a result boost production. As was stated by the first northwest farmer, forecasts need to be skillful before their potential can be fully realized. In fact, the second farmer would like to see more years of the test period as skillfully predicted as the years from 2005 to 2012 (**Figure 3**) since skillful forecasts can increase profits by as much as 25%. The farmer does not, however, have a lot of confidence in the current forecast model for his farm, notwithstanding the incorporation of his rainfall data in the model (in which he is confident they have been accurately recorded). Effectively, before the farmer would invest in such forecasts for his farm, he requires a significant improvement in forecast performance. On a positive note, he requires forecast lead-times of only a month or two, so an improved forecast system does not additionally have to cater for long lead-times.

The farmer in the central interior of South Africa stopped farming actively on his farm about 2 years ago, after selling more than 70% of his land. Although he still resides on the remaining land, he has since become a commodity trader. In spite of this development, his view on the utility of seasonal forecasts may still be of some use. In fact, he claims that as a speculator, he does consider seasonal forecasts to a limited extent, and that skillful forecasts may be able to make his business about 10% more profitable. However, he is of the opinion that the inclusion of his own data in the development of a forecast model for his farm has not necessarily made the forecasts for his farm more trustworthy. If the forecasts can improve, however, he would like to receive forecasts for the whole year and not just for the main 3-month rainfall season, and that these forecasts are issued at lead-times ranging from 4 to 6 months.

The farmer from the southwestern Cape believes that a number of farming decisions will be positively influenced by good and reliable seasonal forecasts. Even decisions as (in his view) mundane as how much effort must be spent to prepare the dirt roads for the winter months will benefit from skillful forecasts. Perhaps more importantly, decisions on those areas in which to plant crops in that year can benefit the most. However, from the hindcast graph provided to the farmer, the forecasts made for those years from 2010 are not very useful. These poor forecasts over the most recent years reduced the confidence the farmer may have in forecasts for coming seasons. Poor forecasts are especially problematic if the forecast is for a wet season and it turns out to be dry. Moreover, when the forecast indicated a wet season (in the above-normal category) then the outcome should at least be above the climatological average. Although there seems to be a lack of confidence in seasonal forecasts for that region, the farmer does state that there is a tendency to have increased faith in forecast models that include rainfall data from the farm.

When asked what percentage of farm expenditure or profit might be enhanced if the decision based on the forecast were correct, it was clear that the Cape farmer has not really considered this aspect thus far in farming operations. This may be the result of the general lack of available seasonal forecasts for South Africa's winter rainfall region. The farmer's previous experience with forecasts available online is that they generally do not give a clear direction in which the coming rainfall season was headed. Notwithstanding, the farmer states that more accurate seasonal forecasts will definitely have a positive effect on profit, but such an effort is currently difficult to quantify. Accurate forecasts would be especially beneficial if they can give guidance on particular months, not only on 3-month seasons. For example, if the forecast shows an enhanced likelihood of a dry winter, guidance on which single month has the biggest chance of receiving some rain will enable farmers to plant just before or after most of the rainfall has been received. Skillful forecasts, as was the case for the farmers in the summer rainfall areas, need to be made at several months lead-time in order to be most beneficial for decision-making. The farmer states that a 6-month lead-time would be preferred even if the forecast only provides a general direction—for example, if the consensus is for a wet or for a dry winter season. A more detailed forecast will be helpful 3 months before the winter season, including which single month is most likely to be wet. This information will allow for significantly improved planning for planting, especially if the forecasts also include the expected dominating wind direction.

## SUMMARY AND CONCLUSIONS

Statistical post-processing is required to improve on seasonal forecasts from global models (Barnston and Tippett, 2017). In addition to corrections of model biases and adjusting the variances of model output fields, statistical models can also be developed to relate global climate model output to commodities such as dry-land crop yields. Recently, such a procedure was used to develop statistical seasonal forecast models for malaria occurrence over the Limpopo province of South Africa (Landman et al., 2020). The malaria modeling was proven successful, not only as a consequence of the skilful models developed, but also as a result of the engagement between modelers and health practitioners in the region during the development stage of the models and the subsequent high uptake of the malaria forecasts. This successful collaboration required the provision of malaria data to modelers who in turn used the malaria data to develop forecast models in real-time. We wanted to show here that a similar co-production process can potentially lead to improved forecast value and uptake by a number of commercial farmers in southern Africa.

Rainfall data from five farms within southern Africa are considered. The statistical rainfall models for all five farms show statistically significant correlations ($p > 0.05$) between rainfall hindcasts and observed values, even though some of the years over the hindcast period are predicted poorly (**Figures 1–5**). Notwithstanding poor forecasts, there are a good number of consecutive seasons during which farmers can potentially experience enhanced profits based on forecasts (**Figures 6–10**). However, since there will always be seasons when even probabilistic seasonal forecasts will turn out to be less useful, farmers may benefit from knowing in advance when such seasons may occur and/or which seasons are more likely to be associated with reliable forecasts (Hoell and Eischeid, 2019).

This notion of "predicting" how reliable the probabilistic forecast for the next season is, is of course, difficult to do. However, verification work on hindcast data has provided the following general guideline that can also be followed by farmers in the larger part of southern Africa, namely, "no ENSO, no forecast" (e.g., Landman and Beraki, 2012). This guideline suggests that during ENSO-neutral seasons, farmers may improve their position by ignoring seasonal forecasts for planning purposes during such seasons. In addition to this guideline, probabilistic verification over the retro-active periods used for the profit calculations (**Figures 6–10**) shows that the relative operating characteristic scores (an indication of forecast discrimination; Wilks, 2011) for two of the South African farms in the summer rainfall region is about 0.8 for the extreme below-normal category and <0.5 for the extreme above-normal category. This result shows that these two farmers can be more confident when the forecast direction for a coming season shows drought (although we are not making claims here about the reliability of the forecast probabilities). Therefore, if an El Niño event is present (not ENSO-neutral), and the forecast for these two farms suggests a drought, this may be the point when these farmers should act on the forecast, by investing in protective action (Richardson, 2000).

In general, the farmers claim that using seasonal forecast can improve their profits. The prospects of using seasonal forecasts by the South African farmers seems to be viewed as less than that expressed by the Namibian farmer, who seems more optimistic about the forecasts. Two reasons for this conclusion are proposed here. The first is that there has been a track record, albeit short, and consequently greater trust between forecast user and forecast produced in the case of the Namibian farm. The second is that seasonal rainfall for the Namibian farm has higher forecast skill, and, thus, forecasts are subsequently associated with greater economic value.

When asked how forecasts can be improved and what their required forecast lead-time should be, most of the farmers wanted lead-times longer than the 1-month lead time hindcasts presented to them. This requirement should be achievable since skilful seasonal forecasts for parts of southern Africa have been shown to be possible at lead-times up to 3 or even 4 months (Landman et al., 2012). Further improvements could be achieved by making forecasts for individual months within a 3- month season. Higher temporal resolution forecasting has received some attention in the region (Phakula et al., 2018), but needs to be developed further. Further improvements may be possible through the use of dynamical variables from the GCMs as predictors for the statistical downscaling, instead of rainfall which is sometimes less well simulated. This could help build confidence in those farmers who observed the current forecasts are not sufficiently skilful.

This study is limited in the sense that only a small sample of only commercial farmers are considered in the analysis, and that even for the five farmers included here, the interaction between forecast user and producer has been brief. There remains a lot of co-learning to explore. For example, although cumulative profit results (**Figures 6–10**) were also presented to the farmers, and there was a question posed to them on their expected profits when using the forecasts, none of the farmers referred to the cumulative profit graphs on their responses—even though they were presented with an explanation on the interpretation of the graphs. This interaction may be improved in the future by engaging in the co-production of cumulative profit calculations, utilizing specific input costs and crop prices which are realized at each individual farm and therefore making the calculations more realistic for each farming enterprise.

Notwithstanding the caveats presented above, we feel we have moved further toward co-learning and co-development in agriculture in the region, including learning from this process. However, we need to iteratively improve on our engagement with the farmers, in order to develop a track record of trust, reach out to more farmers to make their data available for forecast model development for their respective farms, provide honest assessments on forecast performance and capability, and expand on the notion that using forecasts can be profitable, while being clear on the conditions under which that may occur.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

WL: Farm data analysis and modeling, led writing the manuscript. EA: Contributed toward writing the manuscript, and editing. MT: Set the questions posed to farmers, expanded on the cumulative profit calculations, and editing. All authors contributed to the article and approved the submitted version.

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# Exploring the Need for Developing Impact-Based Forecasting in West Africa

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While conventional weather forecasts focus on meteorological thresholds for extreme events, Impact-Based Forecasts (IBF) integrate information about the potential severity of weather impacts with their likelihood of occurrence. As IBF provides an indication of local risk, there is an increasing uptake of this approach globally. Despite the vulnerability of West Africa to severe weather, and the potential benefits of such a risk-based approach for informing disaster risk reduction, IBF remains rarely used in this region. To meet this need, three national workshops were held in Ghana, Nigeria and Senegal with forecasters, project researchers and users of Climate Information Services (CIS) from key sectors (e.g., agriculture, water resources, disaster, risk reduction). In addition, a more localized district level workshop was held in Northern Ghana to explore needs at a subnational scale in Tamale District. The objectives of these workshops were to evaluate the current use of forecast products provided by National Meteorological and Hydrological Services (NMHSs) and to explore the potential for applying IBF. Findings indicate a recognition that the quality of forecast products provided by NMHSs in West Africa has substantially improved in recent years. However, challenges remain related to user understanding, clarity about forecast uncertainty, insufficient spatial and temporal resolution of forecasts leading to limited trust in forecasts. The workshops identified high demand for weather information related to storms, droughts and heatwaves in all the three countries. Dust storms were identified as having strong potential for IBF application in both Nigeria and Senegal. To increase the uptake of CIS by users in West Africa, NMHSs will need to develop and implement user-tailored IBF in their normal weather forecast approaches and improve communication channels with user communities. There is an urgent need for governments in West Africa to enhance the capacity of NMHSs to incorporate IBF as a routine forecast activity by first establishing a National Framework for Climate Services with user engagement as a key first pillar.

**Keywords: disaster risk reduction, forecast evalution, stakeholder engagement, climate services, sub-Saharan Africa (SSA)**

## INTRODUCTION

Climate information services (CIS) aim to provide climate information in a way that assists decision-making by individuals and organizations (Allis et al., 2019). Effective integration of weather and climate information into societal decision making processes can build resilience to climate shocks across Africa (Jones et al., 2015; Nkiaka et al., 2019). The development of fit-for-purpose CIS is crucial for managing risk in climate–sensitive sectors such as agriculture, water resources, disaster risk reduction (DRR), and health (WMO, 2017; Machingura et al., 2018). Although developing countries have been slow to develop and implement strategies to mitigate natural disasters such as droughts, floods, storms and extreme temperatures, they are already more affected by weather and climate-related disasters as a result of their vulnerability and lack of adaptive capacity (Padli et al., 2018). This is particularly the case in sub-Saharan Africa (SSA) (Azzarri and Signorelli, 2020). Evaluating the quality of CIS provided to users in SSA is therefore of critical importance, as is identifying those weather events that pose the greatest threat to lives, well-being and socioeconomic development. It is argued that the use of CIS in DRR is an integral part of broader development planning (Street et al., 2019), with the provision of CIS to support the management of floods and droughts being an integral part of water resources management.

Within the published CIS literature there are comparatively few studies evaluating the quality of climate and weather information provision in SSA from a user perspective (Daly et al., 2016; McKune et al., 2018). A lack of user evaluation of the quality of climate services in SSA like in other regions may be attributed to the traditionally science-driven approach common in CIS production instead of a demand-driven approach (Brasseur and Gallardo, 2016). Notwithstanding, improving the quality of CIS to match users' needs has been highlighted as a key challenge for the successful implementation of the Global Framework for Climate Services (Hewitt et al., 2012). Results from previous studies in SSA show that evaluating the quality of CIS can offer numerous advantages. For example, evaluating the quality of CIS provided to users in Tanzania has led to the adoption of a national steering mechanism for climate services, highlighted a need to raise awareness among members of the public on the concept of climate services as well as efforts to enhance the delivery of climate information and also highlighted that perception of the credibility of CIS is critical for increasing users' satisfaction (Daly et al., 2016). Another study evaluating how CIS provided to farmers in Senegal and Kenya are used revealed that the timely availability of good quality CIS may lead to the adoption of better agricultural practices (McKune et al., 2018). However, most of the studies evaluating the quality of CIS provided to users in SSA have targeted the agriculture and food security sector (e.g., Coulibaly et al., 2015; McKune et al., 2018; Vaughan et al., 2019), while other sectors such as water resources management and hydropower, disaster risk management and the health sectors have received less attention. Our current study was undertaken with the aim of enriching the CIS evaluation literature in SSA by examining the alignment between CIS provision with the needs of the users in different sectors in three West African countries. Our study also fills an important knowledge gap by evaluating the quality of CIS provided to users in other sectors which have received less attention in the past.

Effective climate risk management strategies have the potential to lessen the impacts of disaster risks and contribute to boosting resilience globally (Mysiak et al., 2018). This can be achieved through the use of CIS across all phases of a DRR cycle which include disaster mitigation, preparedness, response, and recovery (Lamond et al., 2019). Communication plays a critical role in the dissemination of warnings and the coordination of relief operations for disaster risk management (ITU, 2013). Recognizing this, the UN emphasizes the role of early warning systems for climate and weather hazards in the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015). Other studies have equally highlighted a need for weather warnings that can enhance public perception of personal risk and promote a rapid and effective public response (e.g., Drost et al., 2016). This has led to the development of Impact-Based Forecasting (WMO, 2015) which is intended to improve risk communication by using a targeted communication strategy concerning the hazard, source, and impact of the forecast event with clearly identified potential threats (Drost et al., 2016). We posit that Impact-Based Forecasting could represent a significant opportunity for the enhanced provision of CIS in the disaster risk management sector, with warnings being linked to the potential harm that specific severe weather events may cause.

This paper reports on the findings of four workshops held across three different West African countries [Ghana (including both national and sub-national workshop), Nigeria and Senegal]. These workshops were undertaken to conduct a multi-stakeholder user evaluation of the quality of current weather forecast products available for users in different sectors and to explore the potential for Impact-Based Forecasting (IBF) to be developed and applied for climate sensitive sectors such as disaster risk management, agriculture, and food security, water resources management, energy, and health. It should be noted that in identifying and inviting sector-specific users to participate in the workshop, we purposefully targeted those with policy making or decision making responsibilities at a national or sub-national level, along with representatives of farming and fishing organizations. While this was critical for supporting interaction between National Meteorological and Hydrological Services and sector leaders and evaluating forecast provision and use at these levels, it is important to note that the decision making contexts of workshop participants differs from those whose lives and livelihoods are most precariously affected by severe weather (e.g., subsistence farmers). Hence, while participants provide valuable insight into sector-specific use of climate information, this limitation must be acknowledged. Another important aspect of the workshops was that it allowed National Meteorological Agencies to highlight their needs for resources to policy makers, as well as giving sector specific users a platform to state their forecast needs. In analyzing the findings of these workshops, we aim to address the following questions:

1) How do users of weather information in climate sensitive sectors perceive the quality of forecast products currently

provided by National Meteorological and Hydrological Services (NMHSs)?

2) Is there a demand for impact-based approaches to weather forecasting amongst decision makers in climate sensitive sectors?
3) Which severe weather events have the greatest impact on the various sectors of activities in the different West African countries and what are the nature of these impacts?

This study is in line with recent calls advocating for a need to align climate information services to the needs of users in different sectors to enhance uptake among different user groups (Ouédraogo et al., 2018; Nkiaka et al., 2019; Carr et al., 2020). This study is particularly timely considering that the climate services community has spent much more time thinking about the quality of the information, and much less time thinking about the impact of that information on the presumed users (McNie, 2012; Vaughan et al., 2019).

## BACKGROUND AND CONTEXT

Within the last decade, meteorological services have been moving away from providing phenomena-based warnings, based on specific meteorological thresholds (e.g., 10-min mean wind speed above 10 m/s or h rainfall above 30 mm), toward risk-based warnings that integrate information about the likelihood and severity of impacts arising from weather (WMO, 2015; Silvestro et al., 2019). WMO has termed this method for providing forecast information based on the potential impact of the event as "Impact-Based Forecasting." By providing a risk-based forecast, Impact-Based Forecasting (IBF) aims to enable individuals and communities to prepare appropriately while providing emergency responders crucial information to respond to threats posed by severe events (WMO, 2015).

Recent studies in developed countries indicate that, in comparison to traditional phenomena-based warnings, IBF is more consistent with how public audiences interpret the link between weather warnings and weather impacts (Taylor et al., 2019), can lead to improved understanding of forecasts (Potter et al., 2018) and may increase peoples' intention to take protective measures against severe weather (Casteel, 2016; Weyrich et al., 2018). However, the development of IBF has inherent challenges. Bringing users and producers of climate information together to link weather forecasting capability with sector-specific impacts and actions to respond to them, can require a significant resource in terms of time, money, and personnel that may not be available. At a technical level IBF also requires the processing of large datasets through data assimilation. However, recent advances in computer technology, information dissemination, use of real-time data capable of providing forecasts with greater accuracy, geographic precision and lead time offer new opportunities for enhancing IBF (Silvestro et al., 2019).

Successful implementation of IBF requires, collaboration between forecasters, and different stakeholders with expertise in geographic information systems; hydrological, crop or epidemiological modeling; social sciences and representatives of the communities at risk (WMO, 2015; Silvestro et al., 2019). Although WMO advocates the use of IBF in DRR, the development of IBF in West Africa is still nascent.

West Africa was selected for this study because the region has experienced a number of severe weather events with devastating socio-economic impacts (Schaer and Hanonou, 2017; Salack et al., 2018; Gbode et al., 2019). In addition, climate change induced extreme weather conditions are expected to significantly affect crop production in the region (Sultan and Gaetani, 2016; Ibn Musah et al., 2018). Changing climate is also expected to cause a substantial drop in hydropower production in West Africa (Yang et al., 2018; Falchetta et al., 2019) and increase the risk of infectious disease outbreaks (Bell et al., 2018; Thomson et al., 2018).

## RESEARCH DESIGN AND METHODS

Data was collected through a series of multi-stakeholder workshops organized in three West African countries (Ghana, Nigeria, and Senegal) between November 2018 and August 2019. In total, 198 participants attended four workshops bringing together forecast users from a range of climate sensitive sectors with operational weather forecasters and researchers (**Table 1**). In the first workshop in Ghana, only participants from institutions with offices in Accra and its environs were invited while in Senegal and Nigeria, participants from other regions outside the capital cities were invited. In Ghana, a second regional workshop was organized in Tamale in the north of the country to complement feedback from Accra. Workshops took place over 2 days in Accra, Dakar, and Abuja, and 1-day in Tamale. Workshop sessions in Ghana and Nigeria were conducted in English while French was used in Senegal. On the eve of each workshop, there was a planning meeting between the forecasters and researchers to prepare the agenda of the workshop, discuss the activities to be carried out and assign facilitators to coordinate and assist group discussion and activities. We equally visited the workshop venue to check on electronic equipment (projector and sound system), how tables will be arranged and rearranged during group activities and also check on catering.

At the beginning of each workshop, there was a brief presentation from the director of each NMHS explaining to participants the importance of climate information in socio-economic development and climate change adaptation. This highlighted the importance of bringing different user communities together to exchange ideas on ways that users think the quality of the forecast products provided by NMHSs may be enhanced. A facilitator then explained to participants the objectives of the workshops, the expected outcomes and how the workshop will be structured. This was followed by presentations from professional forecasters from NMHSs showcasing their various forecast products and services with explanations to some technical terminologies. The need to organize stakeholders' workshops bringing together forecast producers, researchers, and users of climate information to co-produce and contextualize weather forecast has been highlighted by many scientists (e.g., Buizer et al., 2016). During the workshop participant's ideas were recorded on flip charts by researchers according to the theme

**TABLE 1** | Summary of workshops participants per sector and country.

| Workshop participants | Country | | | |
|---|---|---|---|---|
| **Sector** | **Ghana (Accra)** | **Ghana (Tamale)** | **Nigeria (Abuja)** | **Senegal (Dakar)** |
| Agriculture (crop and pastoral farming) | 12 | 11 | 24 | 19 |
| Fishery | 2 | 1 | – | 8 |
| Farmers | – | 5 | – | – |
| Water Resources | 11 | 5 | 7 | 1 |
| Disaster management | 6 | 8 | 10 | – |
| Health | 2 | – | 3 | – |
| Construction | – | – | 5 | – |
| Media | 5 | 1 | 5 | |
| Professional Forecasters | 6 | 2 | 8 | 6 |
| Researchers | 6 | 4 | 9 | 4 |
| Total number of participants | 50 | 37 | 73 | 38 |

*The agricultural sector is divided into two: (1) officials from the Ministry of Agriculture and related Services and (2) farmers who practice crop farming as their main livelihood activity.*

under discussion. Photographs of all artifacts (flip charts) were taken as backup. The information on the flip charts was later analyzed and salient points raised during the workshop extracted.

The objectives of the workshops were to: (1) facilitate a user-evaluation of the current forecast products provided by NMHSs in the target countries, (2) explore how communication of forecast products and tools of communication can be improved, and (3) explore the potential for developing IBF through identifying which weather events have the greatest impact for each climate sensitive sector. This paper focuses principally on the users' evaluation of current forecast products and exploring the potential for developing impact-based forecasting for extreme events management. It also reports on country-specific workshop activities, such as a session dedicated to identifying key actors involved in forecast communication in Senegal where more significant investments have been made in climate communication systems (e.g., Ouédraogo et al., 2020). Another workshop session in Tamale-Ghana was dedicated to a game designed by the Red Cross Red Crescent Climate Centre called "Before the Storm[1]" to understand what motivates users of climate information to take certain decisions when forecasts indicate a high likelihood of a severe storm event.

## Forecast Evaluation

To evaluate the quality of forecasts provided by National Meteorological and Hydrological Services (NMHSs), and explore how forecast communication could be improved, participants in each of the workshops were divided into sector specific groups to discuss the same questions on: (1) how forecasts are accessed and used, (2) how they are understood and trusted, (3) clarity about forecast uncertainty, and (4) how current forecast provision can be improved. This was facilitated by both a researcher and a professional forecaster from the NMHS. These small-group discussions were followed by a plenary session during which the same questions were deliberated upon again by all participants. Salient points that emerged from the plenary session were recorded on flip charts by researchers.

## Mapping Actors Involved in Forecast Dissemination in Senegal

In Senegal an additional exercise was dedicated to stakeholder mapping to identify key actors involved in forecast communication in the agricultural, livestock, and fishery sectors. This exercise was aimed at identifying the key actors and institutions involved in forecast communication, particularly in rural areas. Most of the workshop participants were extension officers involved in the provision of advised to farmers, pastoralists and fishermen, including forecast information. There was a general discussion between the participants and forecasters on the administrative bottleneck reducing the quick flow of information and how this can be reduced. Participants enumerated the different institutions through which information goes through before getting to them. This was mostly seasonal forecast and advisory notes given that daily forecasts are disseminated through radio and SMS in local dialects. Participants were then asked to make proposals on how to improve on existing communication channels, and areas that they thought new communication links could be established to improve the flow of forecast information from producers to users. This information was used to produce visual map as shown on the flip charts in section Actors Involved in Forecast Dissemination (Senegal) below.

## Before the Storm Game (Tamale)

Contextual factors particularly the availability of additional expertise in the project team also led the workshop facilitators to run an additional activity in the final workshop in Tamale to understand what motivates users to take certain decisions before a storm event. "Before the storm" is a participatory game designed to (a) broker a constructive dialogue without hierarchies, (b) reveal key insights about obstacles to forecast communication, and (c) elicit concrete ideas for forecast use. The objective of the game is to win the most rounds by playing

[1]https://www.climatecentre.org/downloads/modules/games/Before%20the%20Storm.pdf

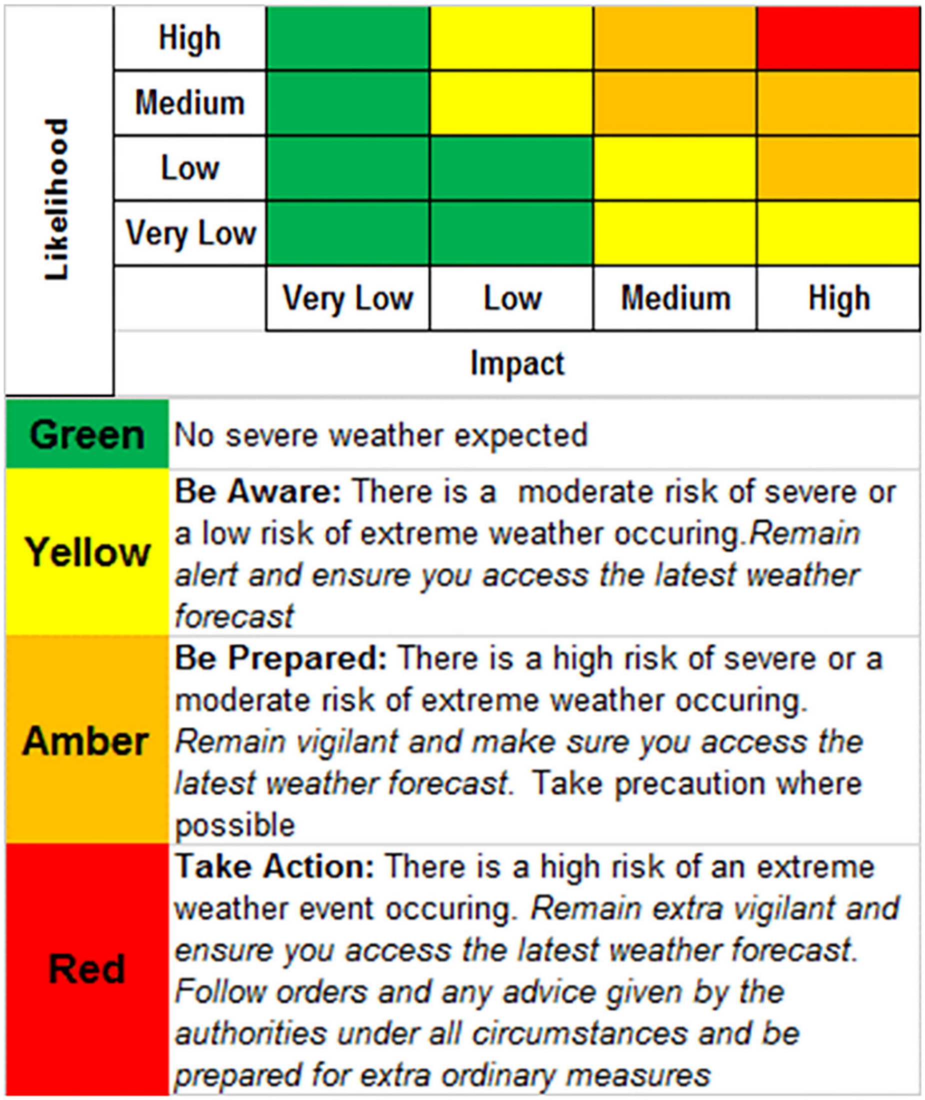


**FIGURE 1 |** Colour coded weather warning matrix (source: WMO, 2015).

an action card from one's hand to best "match" that round's forecast card as chosen by the game's facilitator. Through this game, workshop participants learned about weather forecasts, making appropriate and timely decisions for different lead times before disasters. After each round of the game, there was a general discussion to see if the decision taken by those taking part in the game matched the expectation of other workshop participants.

## Exploring Sector-Specific Weather Impacts and the Potential for IBF

Impact-based forecasting was introduced to workshop participants based on WMO guidelines (WMO, 2015) using tools developed by the UK Met Office. Key concepts were explained to participants using examples from previous cases where IBF has been developed. A weather warning risk matrix that uses color codes to combine information about impact severity and likelihood of event happening was used to further illustrate these basic principles (**Figure 1**). This was used to encourage participants to think about what the impact of a severe weather event could be in terms of damages or risk to life and what kind of action can be taken in order to reduce the risk and danger to life and property. Participants were also encouraged to use their collective memory how they have dealt with previous high impact weather events in their various sectors.

Examples were used such as the impact of forecasted rainfall accumulations over 20 mm for the following day between 1400 UTC and midnight, on possible road closures due to flooding across the city. Using this example, participants were asked to indicate how they would react to such a forecast using the weather warning matrix in **Figure 1**. We highlighted that this was an exploratory exercise and participants should not expect their NMHSs to immediately start providing this kind of forecast.

After each example, participants who were in favor or note were asked to raise their hands. The number of participants who agreed or disagreed were recorded.

In each group exercise, participants were asked to give an example of a specific weather event with significant socio-economic impact that has recently affected their area. Using the hazard table shown in **Appendix A**, the event was classified according to the source of the event, the different kinds of hazard(s) caused by the event, impact severity (cost, loss of lives, and reputation) and impact probability (likelihood of event happening). Hazards were classified into primary, secondary and tertiary hazards while impacts and likelihoods are categorized as very low, low, medium and high. Facilitators, addressed specific questions from the participants. For example, the primary hazard from a tropical storm could be intense rainfall, lightning, and strong winds; secondary hazard could be flooding, disruption of telecommunication signals and the tertiary hazards could be displacement of people and loss of lives and properties. Participants first identified specific high impact weather events affecting their sector, before using their knowledge of past events, to identify what the impacts of these events could be. Each potential impact was then rated by its level of severity and its likelihood of occurrence.

# RESULTS AND DISCUSSION

## Forecast Evaluation

During the plenary discussions following the forecast evaluation activity in each country, more than 90% of workshop participants across the three countries expressed the opinion that the quality of forecast products provided by their NMHSs has substantially improved in recent years. This finding is consistent with prior work in Ghana in which workers in the public sector reported a perceived improvement in the quality of forecast delivered by the Ghana Meteorological Agency (Anaman et al., 2017). Another CIS evaluation exercise in Senegal has also revealed that more than two million farmers now receive seasonal forecast information as a result of enhanced quality of forecast products characterized by region-specific and timely dissemination of seasonal rainfall forecasts that suit the needs of farmers[2] This indicates that the provision of CIS is improving with different user communities becoming increasingly aware of the NMHSs' responsibilities and the forecast products they provide. A summary of the outcome of forecast evaluation is given in **Table 2**.

### Forecast Accessibility

Participants from capital cities (i.e., Accra, Dakar, and Abuja) primarily accessed weather forecasts through television and print media. Participants from other regions, such as Tamale in Ghana, Saint Louis in Senegal, and Kano in Nigeria indicated that, they mostly access forecasts through community radio and short message service (SMS). This is consistent with earlier studies suggesting that radio is the preferred means of receiving weather forecasts amongst rural farming communities (Nkiaka et al., 2019). In Senegal, access to weather forecast by means of SMS, WhatsApp group messages and voice call (in local language) is very common particularly among the farming and fishing communities as revealed by participants during the workshop and in other studies (e.g., Ouédraogo, 2018; Diouf et al., 2019; Ouédraogo et al., 2020). In Ghana and Nigeria, agriculture sector participants reported that SMS messages are being received by a selected few members of farming organizations involved in CIS projects. For example, one farmer remarked during the workshop in Tamale that: "*only few members of their community involve in CIS projects do receive forecast through SMS and once the project ends, they cannot longer access the forecasts through this means. For this reason, members of our community do not rely on weather forecasts to make farming decisions because we are not sure when the next CIS project will come and if the same farming group will be selected to take part in the project.*" This prevents continuous uptake and use of climate information by members of such communities. Our workshop findings highlight that intermittent services linked to short-lived projects are detrimental to the uptake and adoption of climate services among farming communities (see also Singh et al., 2016). This underscores the importance of mainstreaming project sustainability at the early stages of project design to ensure that CIS are provided to users without interruption at the end of the pilot project.

In both Ghana and Nigeria, participants from the agriculture and food security sector expressed dissatisfaction with their inability to access seasonal forecasts and updates from NMHSs. Other studies in the region have also identified the lack of access to seasonal forecasts (and sub-seasonal updates) to be a major constraint to climate change adaptation for farming communities (Otitoju and Enete, 2016; Ifeanyi-Obi et al., 2017; Guodaar and Asante, 2018; Naab et al., 2019). However, this was not the case in Senegal, where evidence from workshop participants suggested that "Agence Nationale de l'Aviation Civile et de la Météorologie" (ANACIM) has developed a successful approach for disseminating forecasts to different user communities. The success of ANACIM in developing a better strategy to disseminate climate information may be attributed to experience in managing climate related risks following the Sahel droughts and significant investment from the international community to build the country's resilience to climate risks (Carr et al., 2016; Diouf et al., 2019; Ouédraogo et al., 2020).

Participants from the DRR, water management and hydropower sectors in Ghana and Nigeria indicated that their access to CIS is by formal institutional requests to NMHS. However, they also highlighted that when forecasts for high impact weather events such as storms and strong winds are issued, Ghana Meteorological Agency (GMet) and Nigeria Meteorological Agency (NiMet) send forecasts and advisories to their institutions using formal administrative channels, with follow-up calls to ensure that the forecasts have been received. Participants from the water management sector mentioned that when forecasts for high impact events are issued, dam managers and DRR organizations work together to inform communities living downstream of storage dams about safety measures to take

[2]https://ccafs.cgiar.org/bigfacts/#theme=evidence-of-success&subtheme=services&casestudy=servicesCs3

**TABLE 2 |** Summary of forecast evaluation.

| Forecast theme evaluated | Participants views | | | |
|---|---|---|---|---|
| | **Ghana- Accra** | **Ghana-Tamale** | **Nigeria** | **Senegal** |
| General forecast quality | Significant improvements | Significant improvements | Significant improvements | Significant improvements |
| Mode of accessibility | TV, print, radio, and institutional requests (sector specific) | TV, Radio, SMS (farmers preference but not available) | TV, print, radio and institution requests (sector specific) | TV, Radio, SMS, WhatsApp, voice call (in local language) |
| Uses | Uses vary by sector | Uses vary by sector | Uses vary by sector | Uses vary by sector |
| Trust | Lack of trust due to forecast being issued late, lack of updates, and repeated incidences of false alarms/misses | Lack of trust due to forecast being issued late, lack of updates, and repeated incidences of false alarms/misses | Lack of trust due to forecast being issued late, lack of updates, and repeated incidences of false alarms/misses | Lack of trust due to forecast being issued late, lack of updates, and repeated incidences of false alarms/misses |
| Uncertainty /Understanding /Clarity | Multiple challenges such as coarse spatial resolution, format and content, lack of advisory notes | Multiple challenges such as coarse spatial resolution, format and content, lack of advisory notes | Multiple challenges such as coarse spatial resolution, format and content, lack of advisory notes | Multiple challenges such as coarse spatial resolution, format and content, lack of advisory notes |

depending on the duration and volume of water to be released from the dams. This demonstrates the existence of close working relationships between NMHSs and users in key sectors, which could support the implementation of IBF by NMHSs.

### Forecast Use

The ways the forecasts are used varies from sector-to-sector reflecting the different types of decisions made in each and this was consistent across the four workshops. Participants in the agricultural sector reported that they use seasonal forecasts to plan for their farming activities and make decisions about crop variety and planting dates. Those in the water management and hydropower sector use forecasts to plan for dam management operations. Participants from the DRR sector highlighted that seasonal forecasts are mostly used for planning for relief operations while weather forecasts are used for operation decisions such as training of volunteers and pre-positioning of relief materials. Other participants from semi-arid regions of Senegal and northern Nigeria indicated that they use daily forecasts to make decisions regarding suitable clothing.

### Trust in Forecast

In spite perceiving improvement in the quality of forecast products provided by the NMHSs, the majority of workshop participants in each country noted that there was still a lack of trust in the forecast provided. This was attributed by many participants to the view that forecasts, particularly those for high impact events, are often issued too late for any meaningful actions to be taken. The fact that forecasts are not always regularly updated (e.g., notifications not being issued to signal that warnings are no longer in place), was also highlighted as a barrier to trust. False alarm/misses were also highlighted as a critical factor contributing to a lack of trust in forecast. This finding is in line with research in developed countries suggesting false alarm or misses erode public trust in weather warnings and when uncertainties are not adequately communicated (LeClerc and Joslyn, 2015).

### Uncertainty and Understanding

Clarity about forecast uncertainty was mostly attributed to the fact that forecasts most often do not cover areas of interest due to a lack of adequate spatial resolution. Poor understanding of forecasts was partly attributed to the fact that the content and format are too technical and not clearly explained. This issue has been identified to be a key barrier to the uptake and adoption of CIS in SSA (Ochieng et al., 2017). Participants highlighted that the time slots allocated to forecast presentation on TV and radio are usually very short and does not always provide detailed spatial coverage and advice on what to do by members of the public.

### How Can Current Provision Be Improved?

Various ways of improving forecast uptake were suggested by participants. For example, participants suggested that forecasts (daily and seasonal) should carry advisory notes both for members of the public and for specific sectors especially the farming and pastoral sub-sectors where most users cannot interpret forecasts. For this to be successful, participants recognized that providers of CIS will need to work in collaboration with users from different sectors to contextualize and co-produce forecast products with advisory notes suitable to the needs of specific users. A similar approach is currently used in Kenya to facilitate bottom-up community-led disaster risk management and food security coordination (Nurye, 2016). Other studies have also reported that a strong collaboration between producers and users of climate and weather information is critical to enhance the uptake and adoption of CIS in SSA (Amegnaglo et al., 2017; Hansen et al., 2019). Of course, while a strong collaboration between users and producers of CIS is encouraged, enabling these collaborations to take place is a challenge in CIS development, owing to constraints in time, personnel availability and financial resources. Successful collaboration also requires that careful consideration be given to procedures to effectively assess users and their needs, identify and overcome barriers to the use of CIS, scale-up CIS, and address the challenge of dealing with the rapidly evolving knowledge (Carr et al., 2020). Participants stressed the need for NMHSs to provide adequate training on CIS to agriculture extension officers given their close working relationship with the farming and pastoralist communities. According to the participants, this training will enhance their skills on how to interpret forecast products. Adopting more suitable communication channels were equally suggested as ways to improve forecast delivery and uptake. This is in addition to points mentioned earlier about improving spatial and temporal resolution and regularly updating forecasts. Approaches identified for enhancing forecast accessibility include: allocating sufficient time on TV for forecast presentation, translating seasonal forecast products into local languages and making it accessible directly to users by using social media platforms such as WhatsApp groups. Across all the sectors evaluated, participants emphasized that the use of simple, easy to understand language, as opposed to unexplained technical language will facilitate successful uptake and implementation of IBF in West Africa.

## Actors Involved in Forecast Dissemination (Senegal)

In Senegal, a stakeholder mapping analysis was undertaken to identify key actors involved in forecast communication. This allowed identification of existing and missing links in information flow within sectors (**Figure 2**). In **Figure 2**, the left panel shows that the seasonal forecast bulletins prepared by "Agence Nationale de l'Aviation Civile et de la Météorologie" (ANACIM) are not directly communicated to the farmers and also a lack of communication between ANACIM and local administrative authorities (absence of a communication link). The right panel shows that there is a lack of communication between ANACIM, the pastoralist community and other decentralized services (absence of communication link). The two figures were produced by stakeholders from crop farming and pastoral sub-sectors. The exercise highlighted the need for ANACIM to establish direct links with Local Councils, administrative authorities, and local multidisciplinary working groups, given their proximity to farming communities. There was also some expectation for ANACIM to establish stronger links with farmers, pastoralists, and fishing communities so that forecasts and advisories can be provided directly to them, with intermediaries explaining those aspects of the forecast that are unclear.

## Outcome of Before the "Storm Game" (Tamale)

Workshop participants found this game to be very engaging and speed up the learning process among participants. Participants across different sectors gave examples of decisions they would take in real life given predicted weather conditions. Most of these decisions resonated strongly between selected game players and the whole workshop participants working within similar sectors. However, the participants regretted that the time allocated for the exercise was not enough to raise other specific issues that may hinder their decision-making processes.

A remarkable outcome of the district-level workshop organized in Tamale is that it was possible to get the voices of the farmers which was not possible for workshops organized in urban centers such as Accra, Abuja, and Dakar. As highlighted earlier, one of the farmers expressed the frustration that the use of climate information in decision making in their community is low because of intermittent forecast provision. Another significant outcome was that while the interest of urbanites in CIS was more focused toward disaster prevention particularly flooding, those from rural areas were more interested in the onset and cessation dates for rainfall which is more related to agricultural drought management. However, there was no significant difference in the type of weather events identified by urbanites and people living in rural areas.

## Exploring the Potential for Impact-Based Forecasting in West Africa

Amongst participants in all four workshops, there was high demand for the development of weather warnings that are linked to the consequences of severe weather events rather than the exceedance of meteorological thresholds alone, and for this to linked to recommended actions. A strong interest was expressed in receiving daily forecasts with color-coded warnings to aid in better understanding the risk posed by weather. Together, this indicates strong support for risk-based approaches to warnings and that the development and application of IBF could increase the usefulness and uptake of weather forecasts in West Africa. The new generation of high resolution forecast models such as the UKMO 4 km convection permitting simulation model with improved skill for capturing precipitation distribution at both daily and sub-daily time-scales over the West Africa can greatly enhance IBF implementation in the region (Berthou et al., 2019; Kendon et al., 2019).

**Table 3** provides a summary of high impact weather events identified during the workshops. Tropical storms were a challenge for virtually all sectors and countries, while other events had a more restricted sectoral or regional impact. Common weather events identified included tropical storms, drought, heat waves and dust storms/strong winds. These were identified as common high impact events significant socio-economic impact for most sectors. In most cases, the events identified were consistent with existing work indicating that they are increasing in frequency and intensity. Recent studies focussing on West Africa, for instance reported an increasing trend in heat waves (Moron et al., 2016; Ceccherini et al., 2017), child mortality attributed to dust storms (Foreman, 2018; Adhvaryu et al., 2019) and high intensity rainfall caused by storm events (Berthou et al., 2019). The results of this exercise suggested that amongst sectors represented in the workshops, tropical storms, droughts, and heat waves were rated as having a higher level of impact than dust storms or strong winds.

### Tropical Storms

Most of the impacts identified as resulting from tropical storms were caused by floods ranging from the displacement of

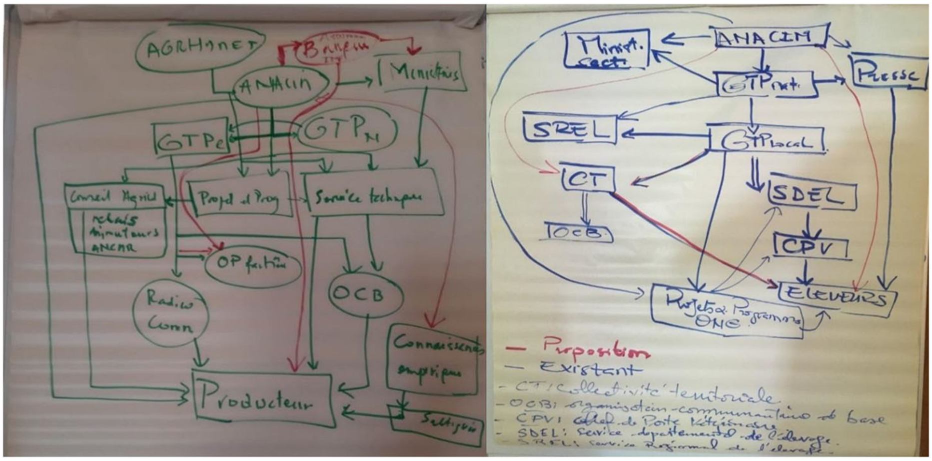


**FIGURE 2 |** Example of organization chart showing existing and missing links (red) for the agricultural sector (left) and livestock sector (right) produced by stakeholders in Senegal.

**TABLE 3 |** Summary of high impact weather events, impact severity, and likelihood.

| Weather event | Sectors impacted | Impact severity | Likelihood | Country |
|---|---|---|---|---|
| Tropical storms | agriculture (crop cultivation, livestock, and fishery), water resources and hydropower, disaster management, construction | High | High | Ghana, Nigeria, and Senegal |
| Drought | Agriculture, environment, health | High | High | Nigeria, Senegal |
| Dust storms | Health, livestock, construction | Medium | High | Nigeria, Senegal |
| Strong winds | Agriculture, fishery, construction, disaster management, | Medium | Low | Nigeria, Ghana, and Senegal |
| Heat waves | Health, livestock | High | High | Ghana, Nigeria, and Senegal |

**TABLE 4 |** Key recommendations from the workshops.

| |
|---|
| Ensure sustainability of CIS projects |
| Improvement of spatial and temporal resolution of forecasts |
| Provide forecasts with advisory notes |
| Develop and implement IBF for tropical storms, droughts, heatwaves, and dust storms |
| Enhance the capacity of NMHSs to incorporate IBF in their work |
| Regularly updating forecasts on television |
| Allocating sufficient time for forecast broadcast on TV |

people, loss of lives, livelihoods, the submersion of hydropower stations, the disruption to power production and slow down of economic activities across most sectors. Flooding could also cause disruption to urban water drainage and treatment, triggering water-borne diseases such as cholera and leading to the loss of life. Flooding caused by a tropical storm can also destroy crops directly or through the increased incidence of pests and cause death of livestock which are all threats to food security. It can also reduce dam storage capacity through sedimentation and dam failure leading to loss of lives and disruption of services. Landslides resulting from a tropical storm usually lead to the disruption of transport activities with negative impact on economic activities. Many studies have reported about the impact of floods in West Africa (Schaer and Hanonou, 2017; Salack et al., 2018; Gbode et al., 2019; Ansah et al., 2020). Participants also highlighted that tropical storms via increased wave conditions have significant negative impact in the fishing sector including the destruction of small-size fishing boats and loss of lives, destruction of fishing infrastructure in coastal areas and disruption of fishing activities.

## Drought

Drought was equally identified as an event with many impacts including the destruction of crops, increased incidence of crop pests, loss of pasture for livestock and dry-up of water points for livestock which usually cause starvation, dehydration and death of livestock resulting in food insecurity and loss of livelihood for the farming and pastoralist communities. Drought is also a major cause of land degradation and loss of soil fertility and biodiversity which are triggers of famine and food insecurity in West Africa (Zakari et al., 2014). It is also a major cause of farmer—pastoralist conflicts as reported in other studies in West Africa (e.g., Okpara et al., 2015). Additional impacts from drought include low water levels in hydropower and urban water supply dams as a result of reduced river flows and increased evaporation. This could lead to power rationing (load shedding) which has a significant negative impact on the economic productivity in West Africa (Diboma and Tatietse, 2013).

Although climate change is expected to increase the frequency and intensity of drought events around the world (Field et al., 2012), drought remains a relatively understudied topic (Padma, 2019). The new generation NOAA operational satellite JPSS-1 capable of early detection of drought, accurately monitor it at high spatial resolution, provide drought intensity, duration, and predict agricultural losses 2 months ahead of crop harvest offer new opportunities for monitoring the impact of drought in West Africa (Kogan et al., 2019). Such advances in earth observation represent a significant step in the implementation of IBF in the region.

### Heat Waves

Heat waves were identified as a major high impact weather event with significant impact on human health particularly in Nigeria and Senegal. Participants stated that heat waves frequently lead to outbreak of deadly diseases such as meningitis which is in line with what has been reported in other studies in the region (Agier et al., 2013; Koutangni et al., 2019). Heat waves have been reported to have significant impact on mortality and morbidity in Africa with the urban heat island effect increasing the health risk for people living in cities (Zaitchik, 2017). The impact of heat waves on the livestock sector include (1) the massive death of livestock leading to economic losses and (2) increase transhumance activity which usually triggers farmer—pastoralist conflicts. Heat waves were also identified as a major trigger of wildfire which may lead to substantial loss of vegetation and destruction of terrestrial ecosystems in the region (Pereira et al., 2020).

### Dust Storms

It was highlighted during the workshops in Nigeria and Senegal that dust storms frequently cause traffic accidents as a result of reduced visibility. Participants also highlighted their significant health impact including the outbreak of diseases such as meningitis which is in line with results of previous studies in the region (Diokhane et al., 2016). It also causes disruption of economic activities particularly in the construction sector leading to a drop in economic productivity as highlighted by participants in Nigeria. Hence, providing adequate forecast for dust storms may be regarded as an integral package of IBF products in West Africa.

### Strong Winds

Strong winds were equally identified as another weather event with significant economic and human impact especially for the construction sector in Nigeria and the fishing sector in Senegal. Participants from the construction sector in Nigeria stated that strong winds are the primary cause of accidents on construction sites as strong winds destroy power cranes, thus disrupting construction activities. This is also in line with results published in other studies that have equally reported an increase in wind hazards in Nigeria with substantial direct and indirect impacts on socio-economic activities (Adelekan, 2012). This shows that there is a recognized need to develop IBF for strong winds in both Nigeria and Senegal. A summary of key recommendations from the workshops is provided in **Table 4**.

## CONCLUSION AND POLICY RECOMMENDATIONS

Our findings show that forecast accessibility, forecast use, trust in forecast, forecast uncertainty and understanding were key concerns raised by participants across the target countries and sectors in West Africa. Access to weather forecast by means of SMS messages was more developed among the farming and fishing communities in Senegal than in Ghana and Nigeria where accessing forecast through SMS messages was only possible through short-lived projects. To enhance the uptake and adoption of CIS, there is a strong need to mainstream CIS sustainability as a key deliverable in CIS projects to ensure that the provision of weather information to users is not disrupted when the project ends. Participants recommended that further improvement of the spatial and temporal resolution of forecasts, co-producing forecast with different user groups, regularly updating forecasts, providing forecasts accompanied with advisory notes, and allocating sufficient time for forecast broadcast will improve the uptake of CIS.

Given the substantial socio-economic impact of tropical storms, droughts, heat waves, dust storms/strong winds, forecasters need to prioritize the development and implementation of impact-based forecasting for such events. This reinforces the need to implement IBF in West Africa. For this to be successful, there is an urgent need for governments in the region to enhance the capacity of NMHSs so that they can incorporate IBF as a routine forecast activity in their work plan. This could be achieved by first putting in place a National Framework for Climate Services (NFCS). The government could also organize workshops with different sectors to contextualize climate information and advisory notes for each sector, how to enhance forecast dissemination and also identify barriers to the uptake to climate information. Moreover, the National Meteorological and Hydrological Services need to work in partnership with other institutions across the target countries to identify the most vulnerable provinces/states/regions and villages which are usually most affected by such high impact events in order to develop additional plans to be put in place to reduce their vulnerability.

## DATA AVAILABILITY STATEMENT

The datasets generated for this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary Material**.

## AUTHOR CONTRIBUTIONS

EN analyzed all the data collected from the four workshops and wrote the first draft of the paper. ATa, AD, and PA-A commented on the methodology and study design. All authors participated and facilitated at least one workshop session in the capacity of either a project researcher or a professional forecaster and provided contributions to the final manuscript. From the fifth author, names appear in alphabetical order.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2020.565500/full#supplementary-material

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# Extreme Natural Events Mitigation: An Analysis of the National Disaster Funds in Latin America

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This paper reviews, compares, and analyzes the legal and institutional framework of Latin American government insurance systems for disaster risk. Data and information are obtained through an intense examination of disasters database, the scientific literature and legal framework of administrative and operational procedures, and mainly sources of financial funds related to disaster risk management. The results demonstrate that all countries, with the exception of Ecuador and Chile, legally establish some form of fund by their own legislation and regulation, as a total or partial form of financing the management of natural disasters, particularly those classified as post-disaster recuperation and reconstruction practices. North and Central American countries have more complex and well-structured funds, presumably based on their history of natural disasters and high social vulnerability. The funds are composed of initial values defined by law, annual contributions of general budgets, donations, and the financial gains of resources deposited into bank accounts. The paper concludes that the unavailability of required resources in an emergency situation has led Latin American countries to choose disaster funds as a primary disaster risk management financing strategy. However, the uncertainty of natural disaster occurrence is one of the main obstacles to the use of public financial resources in prevention and preparedness strategies and actions, increasing even more with the inclusion of climate change uncertainties.

**Keywords: risk disaster reduction, public insurance, adaptation, financial instruments, disaster mitigation**



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## INTRODUCTION

Climate changes affect natural processes, increasing the magnitude and frequency of extreme events, and consequently the characteristics of disasters of natural origin (Banholzer et al., 2014; Hallegatte, 2014). A natural disaster can be defined as a temporary event, triggered by a biophysical hazard that overwhelms local response capacity and seriously affects social and economic development (Xu et al., 2016).

Adaptation is one of the main strategies adopted by the population, various economic sectors, urban areas, and governments in the face of climate change (extreme events) risk scenarios and natural disasters (Solecki et al., 2011; Burke and Emerick, 2016). It involves a wide range of behavioral adjustments (involuntary or planned) that households and institutions make—including practices, processes, legislation, regulations, and incentives—to mandate or facilitate changes in socio-economic systems, with the aim of reducing vulnerability to extreme events and disasters (Smit et al., 1999; Füssel, 2007).

One of these, the protection and civil defense system, acts in different phases of disaster management (Lixin et al., 2012; Jones et al., 2015). In all cases, before or after the occurrence of a natural disaster, governments worldwide are forced to use many of their own public resources. Sometimes, this can be for pre-disaster actions such as prevention and preparedness activities (particularly in more unequal societies), and always for emergency relief, reconstruction of dwellings, and the restoration of vital structures (Cavallo and Noy, 2011; Neumayer et al., 2014). When local governments exceed their response capabilities, they request help from the central government (e.g., city/province, province/nation). In large-scale disaster cases, countries that lack sufficient resources are forced to request aid from other countries and international or non-governmental organizations (Becerra et al., 2014; Wei et al., 2019).

At a local level, some countries' capital cities and larger municipalities have enough financial resources to provide infrastructure and services following a disaster. However, the immense majority of small and poor regions and municipalities are largely dependent on national government resource transfers.

Government assistance can take different forms, considering the type of disaster, the magnitude of the impact, the logistical infrastructure, or the vulnerability characteristics of the affected population, among other things. It can be channeled through direct donations of materials (e.g., food and medicine), cash distribution, or financial loans with little or no interest rate and a wide term payment (Jayasuriya and McCawley, 2010), all in addition to sharing the costs of the impacts through insurance systems (Paudel, 2012; Kousky and Kunreuther, 2018).

Insurance coverage is one of the disaster management instruments (Smolka, 2006; Crichton, 2008). Each country tries to have a catastrophe insurance system according to its own circumstances and characteristics—development level, history of disasters, most common hazards, etc. Therefore, a wide variety of consolidated and disseminated private and public insurance coverage systems against natural disasters could be described and analyzed, particularly in socio-economically developed countries (Ibañez, 2000; Tsubokawa, 2004; Aakre et al., 2010; Schwarze et al., 2011; Jiang et al., 2019; Paleari, 2019). Less is known with regard to developing countries and regions (Cummins and Mahul, 2009; Surminski and Oramas-Dorta, 2014).

In the context of the Sendai Framework for Disaster Risk Reduction 2015–2030, UN members outline targets and priorities for action to prevent new and reduce existing disaster risks, such as (i) understanding disaster risk; (ii) strengthening disaster risk governance to manage disaster risk; (iii) investing in disaster reduction for resilience; and (iv) enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation, and reconstruction (UNISDR, 2015).

In Latin America, while an important part of these actions, programs, and measures to achieve goals and priorities are implemented with resources from regular national budgets, considerable sums are allocated to the National Disaster Funds, a name given to the financial reserves destined to be used in case of states of abnormality.

Thus, the objective of this paper is to review, compare, and analyze the legal and institutional framework of Latin American government insurance systems (generally called "funds") for disaster risk, in order to increase knowledge of financing strategies and instruments used to address the challenges associated with the disaster risk following extreme natural events, in scenarios of climate change.

## NATURAL DISASTERS AND IMPACTS IN LATIN AMERICA

The devastation caused by calamities In Latin America and the Caribbean due to natural hazards and conditions of socioeconomic vulnerability is very well-known (Maynard-ford et al., 2008, Stillwell, 1992).

Latin America and the Caribbean form one of the regions of the world most susceptible to natural disasters (Caruso, 2017). Intense seismic and volcanic activities are explained due to the region sitting atop the South American, Caribbean, Cocos, and Nazca tectonic plates. Landslides, mudslides, and lahars are moderately common due to the nature of soils and topography. There are several climate zones in the region, with different rainfall patterns and associated propensity to floods, hurricanes, and droughts. Mexico, Central America, and the Caribbean are in the pathways of both western Atlantic and eastern Pacific hurricanes and tropical storms. Floods are the most common natural hazard in the region and are a function of the climate (e.g., hurricanes, tropical storms, El Niño phenomenon), hydrology (e.g., flash floods in very steep areas, lower parts of largest drainage systems), and soil characteristics. Seasonal droughts occur in climates that have well-defined annual rainy and dry seasons, such as the climatic zones that are both arid and cold. In these areas, the risk of desertification is also high. Forest fires are associated with the dry season, drought conditions, and human intervention (Charvériat, 2000).

Several different projections suggest that extreme events due to climate change could exacerbate and/or modify the frequency and spatial distribution of many of the hazards in Latin America. The number of extremely hot days is likely to increase, while the quantity of very cold days is likely to decrease. Average precipitation and so too the intensity and frequency of extreme precipitation are projected to rise in the coming decades, increasing the risk of flooding and landslides. However, mid-continental areas such as the inner Amazon basin and northern Mexico are projected to become dryer during the summer months (Magrin et al., 2014; Leal Filho, 2018).

In Latin America, conditions of vulnerability of the population and their socio-economic activities are associated, among other things, with the historical processes of territorial occupation, cities with high population densities and disorderly growth, and poverty and social inequalities. Political corruption and low degrees of legal framework implementation should also be mentioned (Rebotier, 2012; Rubin and Rossing, 2012; Nagy et al., 2018).

According to the CEPALSTAT database (https://estadisticas.cepal.org/), referring to the impact of disasters in Latin America and the Caribbean in the period 1990–2019, 1,350 events of geophysical origin [earthquakes, volcanic eruptions, and mass

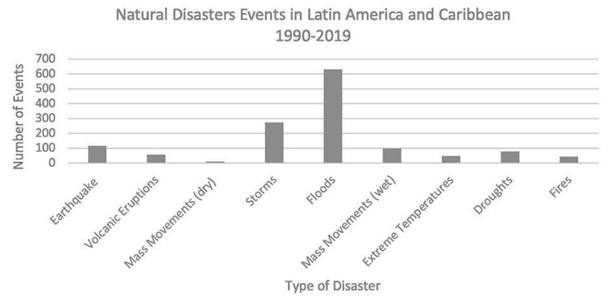


**FIGURE 1 |** Number of natural disaster events in Latin America and Caribbean (1990–2019) classified by type of the origin. Source of data: CEPALSTAT database (https://estadisticas.cepal.org).

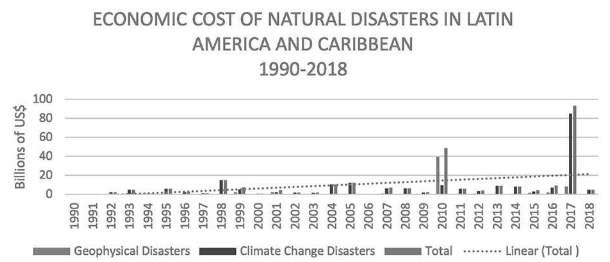


**FIGURE 2 |** Economic costs of natural disasters in Latin America and Caribbean (1990–2018) expressed in billions of US$. Source of data: CEPALSTAT database (https://estadisticas.cepal.org).

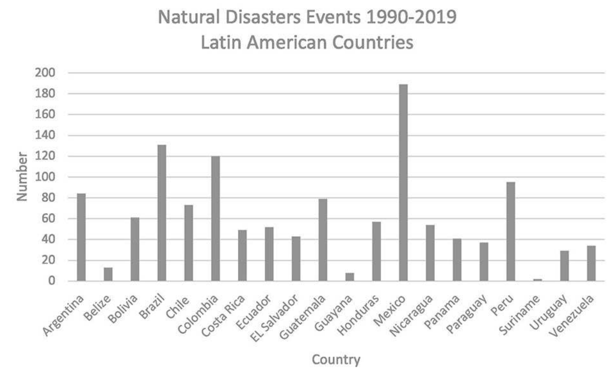


**FIGURE 3 |** Number of natural disaster events in Latin America (1990–2019) classified by country. Source of data: CEPALSTAT database (https://estadisticas.cepal.org).

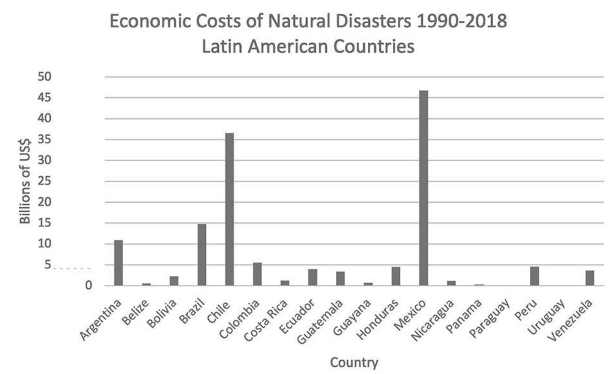


**FIGURE 4 |** Economic costs of natural disasters by countries of Latin America (1990–2018) expressed in billions of US$. Source of data: CEPALSTAT database (https://estadisticas.cepal.org).

movements (dry)] and climate change origin [storms, floods, mass movements (wet), extreme temperatures, droughts, and fires] have been quantified. The largest number of entries focus on flood and storm events (**Figure 1**). Recent natural or socio-natural events account for around 91,464 deaths and ∼188 million people directly affected (injured, homeless, and affected people requiring immediate basic assistance, including food, water, shelter, sanitation, and medical assistance in an emergency period caused by a natural disaster).

The economic cost of natural disasters (value of total economic damages and losses directly or indirectly related to extreme natural events and disasters) totaled around 273 billion U.S. dollars (79% associated with climate change). These costs are increasing over time, probably due to a variety of factors, including the growing concentration of population and assets exposed to risky areas and disasters. Particular attention should be paid to the highest values in 2010 (e.g., earthquakes in Chile in February and in Haiti in January, major floods in February and August in Mexico, heavy winter rains in Colombia and in December in Venezuela) and 2017 (e.g., earthquake in Mexico in September, hurricanes Maria in Puerto Rico and Irma in the Caribbean, heavy rains and flooding in Peru) (**Figure 2**).

Natural disasters and their effects are not evenly distributed among the countries of the region. Between 1990 and 2019, according to the CEPALSTAT database (https://estadisticas.cepal.org/), Latin American countries registered 1,220 events (90% of the total). Mexico, Brazil, and Colombia stand out, perhaps due to their locations, extensive territories, diversity of natural landscapes, large population contingents, and the concentration of the largest economies and goods in the region being in these countries (**Figure 3**).

The impacts of natural disasters are increasing and becoming more spatially distributed as the world becomes more populated, with lower equality, and as people continue to damage the environment (Shen and Hwang, 2019). Although, in absolute terms, the costliest disasters mainly occur in developed countries, or particularly in Latin America in the larger economies (Mexico, Chile, Brazil, and Argentina), the less developed economies suffer the most when loss of life, injuries, and effects on GDP are considered (Zorn, 2018) (**Figure 4**).

## FINANCING DISASTER RISK MANAGEMENT

Disaster risk management requires actions that work to minimize the creation of new risks and reduce any that already exist, as well as to prepare for and respond to disasters (IPCC, 2012). Among the actions that minimize and reduce risks are emergency preparedness (e.g., planning and exercises, communication systems, public awareness, and technical response capacity) and investments in both soft and hard infrastructure (e.g., strengthening and enforcing building codes, and constructing defenses). During and after the occurrence of a disaster, strategies and actions are directed to the emergency response (e.g., programs to cope with damages) and the reconstruction and rehabilitation of damaged goods and economical chains (e.g., housing, transport, and industrial reconstruction; economic and social recovery) (Miller and Keipi, 2005). Institutional structures, population engagement, and scientific and technical knowledge among others are important factors for the implementation of these actions. Financial instruments and aspects are particularly highlighted.

Even with different characteristics, most governments, particularly those less developed or in development countries, are generally clearly unaware of the financial risks they face in the event of natural disasters (Mu and Chen, 2016). However, or perhaps for that reason, they use a portfolio of sources, strategies, and instruments of economic support in the different stages of disaster risk management. The financing of disaster relief is associated with actions to be taken before, during, and after a disaster, trying to reduce or avoid any major disruption or impacts to the objectives of their development.

This finance may come from international donations or private or public domestic funding structures and instruments. International funding from general resources or specific contingents (countries, international or multilateral governments, or institutions) supports many different aspects of disaster management, including humanitarian aid, development processes, and reducing the impacts of climate change. Some aspects of the international contributions to disaster management in Latin American countries were studied by Fagen (2008). Private-sector finance is diverse and involves foreign direct investment, insurance markets on various scales, and civil society and philanthropic organization remittances (Kunreuther and Michel-Kerjan, 2014; Kapucu, 2016; Mbaye and Drabo, 2017; Benali and Feki, 2018).

In the region, assistance from donors, often generous, is highly dependent on the visibility of a given event and usually arrives long after the event. Disaster insurance coverage is limited, due to the non-insurability of many assets (e.g., irregular settlements without property title or valuation and dwellings built without solid materials), high insurance premiums, regulatory obstacles to the development of insurance, and disinterest in insurance fostered by the availability of national and international assistance in times of crises (Miller and Keipi, 2005).

Considering the existing domestic public financing structures in disaster risk reduction, each country allocates resources to (i) broader development policies (e.g., land use and water planning and management, infrastructure reforms, retrofitting schools and hospitals, and environmental and risk-driven social protection), (ii) specific risk management projects in the national budget (e.g., climate and risk monitoring, early warning systems), and (iii) special calamity funds (Kellett and Peters, 2014).

## THE CIVIL DEFENSE SYSTEMS AND SPECIAL CALAMITY FUNDS IN LATIN AMERICA

After understanding the importance of the impacts of natural disasters on the economy and security of the population, as well as their close relationship with socio-economic development conditions, Latin American countries established and improved various levels of civil defense systems. This included the organization of emergency and reconstruction aid and, subsequently, with a more integrated vision of risk management, preparation and prevention activities.

National institutions, policies, and plans are critical for effective disaster risk management. For this to happen, countries must find ways to ensure sufficient liquidity of resources before the disaster, but mainly during the periods of emergency as soon as the disaster strikes, shortly after, and during the recovery phase. Due to the unavailability of insurance, and considering the problems of economic resource scarcity, mandatory priorities in periods of "normality," and sometimes poor government management of resources with annual general budgets, the countries of Latin America have put their own calamity funds into place.

The present research methodology, adapted from Vatsa et al. (2003), consists of an intense examination and analysis of the scientific literature and legal framework of administrative and operational procedures, and mainly sources of financial funds related to disaster risk management in Latin American countries. All countries (14), with the exception of Ecuador and Chile, legally establish some form of fund as a total or partial form of financing.

### Mexico

The General Law on Civil Protection, 2012 (last reform in 2018), establishes the basis for coordination between the three government levels in the field of civil protection, through the National System of Civil Protection. The system is an articulated set of structures, functional relationships, methods, standards, instruments, policies, procedures, and services, which determine the co-responsibility between voluntary groups and organizations; the public sector; legislative, executive, and judicial powers; autonomous constitutional bodies; and municipalities. Its purpose is to carry out coordinated actions for civil protection in case of disaster risk in the short, medium, or long term, caused by anthropogenic or natural phenomena, through comprehensive risk management and the development of relief.

The Federal Executive, through the Secretary of Finance and Public Credit, in terms of the Federal Law on Budget and Responsibility, provides the financial resources for the timely attention of emergencies. When impacts of natural disasters are unpredictable and the local response capacity is exceeded, complementary support can be requested for the national government's Natural Disaster Fund (FONDEN). FONDEN was established in 1996. Each federal entity can create and manage its own civil protection fund.

In order to access the resources of FONDEN, a request must be submitted to the Secretary of the National Civil Protection System expressly stating that circumstances have exceeded the operational and financial capacity of a particular region to deal with the disaster on its own, stating the disruptive natural phenomenon, the specific period of occurrence, as well as the municipalities and the population concerned. Therefore, the Secretary issues the "Emergency Declaration" (recognition of the imminence, high probability, or presence of an abnormal situation generated by a disruptive natural agent that causes immediate assistance for the population at risk to be required) and the "Declaration of Natural Disaster" (identification of the presence of disaster damage that exceeds the local financial and operational aid capacity).

Once the declaration of emergency is issued, the federal entity may be supported by FONDEN, to which it must submit an application for the urgent needs of the affected or potentially affected population, such as (i) consumable and durable supplies sufficient to meet urgent needs, or according to the estimated population that will be vulnerable or susceptible to impact; (ii) medicines, healing materials, and others related to the care and health protection of the population [application made through the National Center for Preventive Programs and Disease Control of the Ministry of Health (CENAPRECE)]; and (iii) reagents and insecticides used to control vector-borne diseases that must meet the sensitivity and specificity characteristics required for epidemiological and health surveillance.

The appropriate requests are sent by FONDEN to the Directorate-General for Material Resources and General Services of the Federal Government (DGRMSG) that, within its competence, makes the respective purchases and delivery in the province or municipality affected.

Considering the possibility of processual delays or in the case where the local authority does not submit any request, FONDEN authorizes a minimum package of care inputs for the vulnerable population affected or susceptible to effects, comprising the following products: food, drinking water, and bedding. FONDEN may immediately authorize mobilization of the remnants of inputs from other national or international (prior to the opinion of the Secretariat for Foreign Affairs) emergencies.

## Republic of Guatemala

The National Security System law (Decree 18/2008—https://mingob.gob.gt/wp-content/uploads/2016/01/ley_marco_d018-2008.pdf) establishes the legal rules for the coordinated realization of activities by the State of Guatemala, so that in an integrated, systematized, efficient, and effective way, it is able to anticipate and give effective response in case of risks, and be prepared to prevent, confront, and counter them. The law is also the basis of the National Security System.

The purpose of the system, developed by the Internal and Foreign Security departments; State Intelligence, Risk Management, and Civil Defense areas, is to strengthen state institutions, prevent risks, control hazards, and reduce vulnerabilities that prevent the State from fulfilling its purposes. The system is composed of the Presidency of the Republic, ministers (foreign relations, government, and national defense), the Attorney General's Office, the National Disaster Reduction Coordinator (CONRED), the Secretariat of Strategic Intelligence of the State, and the Secretariat of Administrative and Security Affairs of the Presidency of the Republic.

When disasters occurred, budget reallocations of the different institutions were carried out. Since 2019, the State General Revenue and Egress Budget Act (Law 5610—https://www.congreso.gob.gt/detalle_pdf/iniciativas/5609) has been providing a budget forecast for an emergency fund as part of the financial resilience mechanisms in the face of a possible need to pay attention to the occurrence of natural disasters, in order to address any contingency more expeditiously, and does not directly impact public finances, affecting the development of the implementation of the various programs contained in the public budget. These resources are activated only at the time of decreeing a state of calamity by the President of the Republic and ratified by the Congress.

## Republic of El Salvador

The National System of Civil Protection, Prevention, and Mitigation of Disasters (Decree 777/2005—https://www.asamblea.gob.sv/decretos/details/476) is an interrelated and decentralized set of public and private bodies responsible for formulating and implementing the respective work plans for civil protection, disaster risk prevention, and mitigation of disaster impacts. The system consists of the national departmental and municipal commissions for civil protection, disaster prevention, and mitigation. A fund for civil protection, disaster prevention, and mitigation has been created for the sustainability of the system.

The Fund for Civil Protection, Prevention, and Disaster Mitigation (FOPROMID) (Decree 778/2005—https://www.asamblea.gob.sv/decretos/details/39) is an entity of public law, with legal personality and its own assets, also enjoying administrative and financial autonomy. The administration of FOPROMID is the responsibility of the Minister of Finance.

FOPROMID's balance is made up of an initial contribution from the General Budget of the State and donations from any national or foreign entity. It is subsequently added to funds allocated annually in the General Budget of the State and contributions from any other source. The financial resources with which FOPROMID is constituted, as well as others that will be perceived in the future, must be deposited into a special bank account.

FOPROMID resources may only be used for disaster prevention or in cases where timely and effective disaster emergency attention is required. In the event of a disaster of great proportion, FOPROMID may request an emergency budget from the Council of Ministers.

## Republic of Nicaragua

The National System for Disaster Prevention, Mitigation, and Response (SINAPRED) was created as part of Law 337/2000 (http://ocu.ucr.ac.cr/images/ArchivosOCU/Normativa/NormativaExterna/Ley_Contratacion_Administrativa.pdf).

It is responsible for performing actions aimed at reducing the risk of natural and man-made disasters, as well as protecting society, such as with the development and execution of disaster prevention, mitigation, and response plans, the promotion of scientific and technical research, the reduction of population vulnerability, and helping the affected population. The guarantee of public financing for these activities is established through the National Fund for Disaster that is regulated by Decree 88/2007 (http://legislacion.asamblea.gob.ni/Normaweb.nsf/fb812bd5a06244ba062568a30051ce81/2436a8e1d0fdd1b60625736e0061389e?OpenDocument).

The fund's resources are available to SINAPRED to act in the case of imminent risks or disaster situations and are deposited into a bank account, to which only the chairman of the board of directors of the fund has access to, to manage and withdraw. The fund is made up of financial resources—the General Budget of the Republic; financial contributions, donations, legacies, and inheritances or grants made by natural or legal persons, national or foreign; and any other returns from the resources mentioned above originating from interest accrued in the bank accounts—and non-financial resources. After the presentation of the expense report, the resources of the fund are subject to all control and audit procedures established by the laws of the Republic and are the responsibility of the Ministry of Finance and Public Credit.

## Republic of Costa Rica

The National Emergency and Risk Prevention Law (Law 8488/2005—https://www.ucr.ac.cr/medios/documentos/2015/LEY-8488.pdf) established the National Risk Management System, understood as the integral, organized, coordinated, and harmonious articulation of state institutions, seeking the participation of the private sector and organized civil society, with the purpose of planning and executing public policy guidelines that enable incorporation of the concept of risk management as a cross-cutting axis of planning and development practices. The National Risk Management System was designed for risk prevention and preparations to deal with emergencies through the National Commission for Risk Prevention and Emergency Assistance. The commission is a body of the Presidency of the Republic, with its own assets and budget. The commission has the following sources of funding for the performance of its functions: transfers from the national budget, the amount provided for in Article 46 of the law for the financing of the National Risk Management System, and the resources of the National Emergency Fund.

The National Emergency Fund is administered by a commission, which is authorized to invest in securities of public-sector institutions and companies. All resources must be used to address emergency, prevention, and mitigation situations. The fund consists of the following resources: the regular and extraordinary national budgets; contributions, donations, and transfers from natural or legal persons, national or international, state, or non-governmental bodies; the transfer of resources from all central government institutions, the decentralized public administration, public enterprises to the value of 3% of the profits and budget surpluses that each of them report; contributions from financial instruments; and interest generated by the transitional investment of resources. State institutions, local governments, state-owned enterprises, and any other persons, natural or legal, public or private, are authorized to donate sums for the formation of the National Emergency Fund.

The acquisition of goods and services with the resources of the fund to attend to the declared emergency events is governed by the principles set out in the law on administrative procurement (Law 7494/1995—http://ocu.ucr.ac.cr/images/ArchivosOCU/Normativa/NormativaExterna/Ley_Contratacion_Administrativa.pdf). The administration, use, and disposal of resources deposited to the fund are subject to audit by the Controller General of the Republic and the Internal Audit of the Commission. The costs required for the administration, management, control, and audit of the National Emergency Fund are covered by up to 3% of the amount that makes up the fund.

## Republic of Panama

The National System of Civil Protection (SINAPROC), established by Law 22/1982 (https://docs.panama.justia.com/federales/leyes/22-de-1982-nov-22-1982.pdf) and Organic Law 7/2007 (https://www.gacetaoficial.gob.pa/pdfTemp/25727/GacetaNo_25727_20070207.pdf), is responsible for helping to protect the population from damage caused by disasters of any origin. To this end, it coordinates measures to prevent and reduce the impact of disasters, mitigate or neutralize the damage that such cataclysms could cause to people and property, and carry out emergency response actions. The administration, direction, and operation of SINAPROC is managed by a director-general appointed by the President of the Republic, with the participation of the Minister of Government and ratified by the National Assembly.

Part of SINAPROC's activities are financed by the Panama Savings Fund (FAP). FAP was established by Law 38/2012 and amended by laws 87/2012 and 51/2018 (https://www.gacetaoficial.gob.pa/pdfTemp/27050_A/GacetaNo_27050a_20120606.pdf). FAP aims to establish a long-term savings and stabilization mechanism for cases of emergency status and economic slowdown, as well as to reduce the need for debt instruments to address the circumstances described above. Administration of FAP is carried out by the National Bank of Panama. FAP is constituted by all the assets of the Trust Fund for the Development of Panama and was authorized to accumulate assets of 50% of any contribution by the Panama Canal Authority to the National Treasury of more than 2.5% of nominal GDP for the 2018 and 2019 fiscal year, reduced to 2.25% from fiscal 2020; FAP yields from FY 2018, which were capitalized in FAP for the following fiscal term, until its assets were more than 5% of the previous year's nominal GDP; funds from the sale of shares of state-owned joint ventures; and the inheritances, legacies, and donations that are made to FAP. Withdrawals may only be associated with situations of state of emergency as declared by the Cabinet Council, provided that the related cost is equal to or >0.5% of GDP. The Ministry of Economy and Finance (Trustee) may take out catastrophe insurance (an insurance policy covering material or consequential losses suffered by the insured) as a tool for forecasting potential natural disasters.

## Bolivarian Republic of Venezuela

Act 1557/2001 aims to organize, integrate, coordinate, and operate the activities of the Civil Protection and Disaster Management Organization at the national, provincial, and municipal level (https://www.eird.org/wikiesp/images/Ley_Proteccion_Civil_y_administarcion_de_desastres_Venezuela.pdf). This organization is a member of the National System of Risk Management and the National Coordination of Citizenship Security. Its objectives are to plan and establish national disaster preparedness policies and measures, to develop training and education programs to promote the population participation in emergency and disaster responses, to strengthen care and emergency management agencies, and to ensure that the government provides the necessary resources and operational support for civil protection and disaster management.

The Disaster Prevention and Management Fund was created to develop these activities, linked to the Ministry of the Interior and Justice. The objective of the fund is to manage the extraordinary budget allocations and resources from the contributions made to any title by natural or legal persons, national or foreign, foreign governments, and international organizations, for financing disaster preparedness and aid activities, and rehabilitation and reconstruction.

## Republic of Colombia

The Colombian Civil Defense is an entity of the Ministry of Defense for preventing and controlling disasters, and driving the operational part of the National System for the Prevention and Care of Disasters. All governmental agencies must include special resources for prevention and disaster response in their budgets. However, at the national level, there is a special account, characterized by its patrimonial and administrative independence called the National Calamities Fund. The fund is established by Decree 1547/84 (https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=66925). According to Decree 919/89 (https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=13549), the fund's resources are designated to (a) financially supporting aid for disasters and calamities; and prioritizing the production, conservation, and distribution of food, medicines, and provisional accommodation; (b) controlling the impact of disasters and calamities; (c) maintaining environmental sanitation conditions during the rehabilitation and reconstruction phases; (d) financing installation and operation of information systems suitable for prevention, diagnosis, and aid for disasters (e.g., the national seismograph network); and (e) encouraging the use of private insurance coverage taken with legally established companies in the Colombian territory. Decree 919/89 is regulated by national decrees 976/1997, 2015/2001, and 4550/2009.

For disaster management purposes, central administration institutions' and agencies' resources rely on trusteeship, such as through the "*La Previsora*" trustees, an industrial and commercial state-owned company, linked to the Ministry of Economy. This fiduciary society has an advisory board with responsibilities to direct the general policies of management and investment of the fund's resources, as well as destination and priority for their usage. Requests from the states and municipalities in crisis reach this board after their own budgets for aid to the affected population are exceeded.

## Republic of Peru

The National Disaster Risk Management System of Peru (SINAGERD) (Law 29664/2011, regulated by Supreme Decree 48/2011) was created with the aim of identifying and reducing disaster risks or minimizing their effects, avoiding the generation of new risks, and contributing to the preparedness for and attention to disaster situations (http://www.leyes.congreso.gob.pe/Documentos/Leyes/29664.pdf). SINAGERD consists of the Presidency of the Council of Ministers; the National Disaster Risk Management Council; the National Center for Disaster Risk Estimation, Prevention, and Reduction (CENEPRED); regional and local governments; the National Center for Strategic Planning; as well as public entities, the armed forces, the Peruvian National Police, private entities, and civil society.

SINAGERD's instruments are the National Disaster Risk Management Plan, the National Disaster Risk Management Information System, the National Radio for Civil Defense and the Environment, and the Disaster Risk Financial Management Strategy. This strategy considers the budget programs linked to disaster risk management, organized by processes of estimation, prevention, and risk reduction, as well as preparedness, response, and rehabilitation. The resources of the strategy are those existing in the Contingency Reserve and the Fiscal Stabilization Fund, credits, donations, and other market instruments for disaster care that were contracted by the Ministry of Economy and Finance.

In this sense, Law 30458/2016 established the Fund for Interventions in the Event of Natural Disasters (FONDES), for the Ministry of Economy and Finance, with the aim of financing public investment projects for mitigation, rehabilitation, and reconstruction in the event of natural phenomena (http://www.leyes.congreso.gob.pe/Documentos/Leyes/30458.pdf).

The national, regional, or municipal governments can access FONDES to finance interventions for the following reasons: (i) mitigation and responsiveness to the occurrence of natural phenomena, aimed at reducing existing risk, and preparing for emergency and/or disaster response; (ii) imminent risk response and rehabilitation, aiming to reduce the likely damage that the impact of an imminent natural or anthropic phenomenon may cause; actions in the event of disasters; and the rehabilitation of damaged infrastructure and/or public services, once the disaster has occurred. Such interventions pre-require the Declaration of State of Emergency for Disaster or Imminent Risk; and (iii) reconstruction, carried out to establish sustainable development conditions in the affected areas.

## Plurinational State of Bolivia

Law 602/2014 (regulated by Supreme Decree 2342/2015) is the legal basis for the National System of Risk Reduction, Disaster Prevention, and Emergencies (SISRADE) (http://www.silep.gob.bo/norma/13365/ley_actualizada), establishing a framework for risk management, which includes risk reduction through prevention, mitigation, and recovery actions; disaster and/or emergency care by means of activities to prepare, respond to, and rehabilitate after disasters caused by natural, socio-natural, technological, and anthropic hazards; and the resolution of social, economic, physical, and environmental vulnerabilities.

SISRADE is made up of central and local (department and municipal) level government entities, social organizations, and people, who interact with each other in a coordinated and articulated manner. The system is formed by the National Council for Risk Reduction and Disaster and Emergency Aid (CONARADE) and the departmental and municipal committees for risk reduction and disaster aid. The system's funding is associated with the budgets of national entities, as well as local and autonomous territorial units, as set out in their development, emergency, and contingency plans. Another source of resources is the Fund for Risk Reduction and Care for Disasters and/or Emergencies (FORADE), established by the Ministry of Defense for a period of 10 years with the aim of capturing and administrating resources to finance risk management at the national, departmental, municipal, and autonomous indigenous levels.

FORADE's funding sources are the National General Budget (0.15%), monetary donations, credits, specific resources for multilateral or bilateral cooperation for risk management, and revenues generated by FORADE itself, among others. In order to ensure the sustainability of the trust, the resources may be invested under principles of security and liquidity and its administration is subject to an annual external audit as a minimum.

One of CONARADE's functions is to approve the distribution of FORADE resources, considering the efficiency criteria, the balance between risk management components, and existing priorities according to the different scenarios of risk and disaster. CONARADE authorizes the allocation of resources to entities at the central and/or autonomous territorial level of the State, providing they meet the following minimum conditions: the submission of a request for funding on a particular technical proposal or project (in case of preparation), the respective declaration of disaster with the assessment of the level of impact of disasters and estimation of rehabilitation costs (in case of emergency care and rehabilitation), and the request for funding on a given project previously technically and financially assessed (in case of projects focused on knowledge or risk reduction).

The Vice-Ministry of Civil Defense is able to access FORADE's resources through authorization from CONARADE, in exceptional cases, and exclusively to finance humanitarian aid activities requiring immediate assistance, in order to provide urgent support necessary to safeguard the life, health, and physical integrity of the affected population.

## Republic of Paraguay

The Secretariat of National Emergency (SEN), responsibility of the Presidency of the Republic, was established by Law 2.615/2005 (https://www.bacn.gov.py/archivos/2410/20151016083211.pdf) with the objective of preventing and counteracting the effects of emergencies and disasters caused by agents of nature or any other origin, as well as promoting, coordinating, and guiding the activities of public and private institutions with the aim of preventing, mitigating, and responding to emergencies or disasters, and the rehabilitation and reconstruction of communities affected by them. In this sense, SEN may collect information, identify risks, record statistics of disasters and their impacts, coordinate assistance to affected communities, encourage the creation and organization of emergency-risk reduction, develop and implement education programs in communities, seek international cooperation on risk reduction and mutual assistance in civil protection, and conduct outreach campaigns related to civil protection systems and methods.

The resources necessary for the operation of SEN are provided by the general budget of the nation, by the ministries that must carry out specific assistance in cases of emergency, and those existing in the National Emergency Fund.

The National Emergency Fund functions as a special account of the nation with economic, administrative, accounting, and statistical independence. Half of the resources are designated to finance disaster prevention and/or mitigation projects. The remaining 50% is earmarked for preparedness and response measures. If the budgeted resource is not used in a fiscal year, it will return to the Nation's General Income Account.

The origins of the resources of the National Emergency Fund are (i) 10% of the tax collections from sales of cigarettes and alcoholic beverages, (ii) the General Direction of the Treasury when an emergency or disaster is declared, (iii) the Social Assistance Institution (DIBEN) that provides specific resources to support emerging preparedness and response programs, and (iv) donations received from domestic or foreign persons or institutions. The administration of the National Emergency Fund is managed by SEN.

The resources of the National Emergency Fund can be applied to the financing of one-off actions aimed at the prevention and mitigation of events capable of causing disasters, and the preparation, response, and rehabilitation of communities affected by disaster situations when at least one of the following occur:

(a) There are plans and programs submitted to the SEN council. Where the plan or program corresponds to actions projected by states or municipalities, the allocation of finance resources from the National Emergency Fund is subject to the contribution of a counterparty of the state or municipality. The proportion of the counterparty will be determined in each case.

(b) There is an emergency situation or declaration of disaster.

(c) The institutions have replenished duly documented and authorized operating expenses that have been committed to the care of an emergency of significant magnitude.

## Federative Republic of Brazil

Law 12608/2012 provides for the National Policy for Protection and Civil Defense (PNPDEC) and the National System of Protection and Civil Defense (SINPDEC) (http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12608.htm). PNPDEC covers prevention, mitigation, preparation, response, and recovery actions focused on protection and civil defense, integrating the policies of territorial planning, urban development, health, environment, climate change, water resource management, geology, infrastructure, education, science and technology, and other sectoral policies, with a view to promoting sustainable development. SINPDEC is composed of the organs and entities of the Federal Public Administration, the states, the Federal District and the municipalities, and the public and private entities of significant performance in the area of protection and civil defense. SINPDEC aims to contribute to the process of planning, articulation, coordination, and execution of protection and civil defense programs, projects, and actions.

Transfers from the Union to the states, the Federal District, and municipalities are mandatory for the development of SINPDEC activities. In the case of recovery actions, the beneficiary must submit a work plan to the body responsible for the transfer of resources within 90 days of the occurrence of the disaster. In the case of response actions, exclusively providing help and assistance to victims, the Federal Government can provide prior support for federal recognition of the emergency situation or state of public calamity, and the beneficiary is responsible for the presentation of the necessary documents and information.

The transfer of financial resources can be done by (i) depositing money in a specific account maintained by the beneficiary entity in an official federal financial institution; or (ii) withdrawing from the National Fund for Public Calamities, Protection, and Civil Defense (FUNCAP) to funds constituted by states, the Federal District, and municipalities with specific purpose. The body responsible for transferring the resource must follow and monitor the application of the resources transferred.

FUNCAP, linked to the Ministry of National Integration and established in 1969 (Decree 950/1969—http://www.planalto.gov.br/ccivil_03/Decreto-Lei/1965-1988/Del0950.htm), has the purpose of funding, in whole or in part, prevention actions in disaster risk areas dispensing with the conclusion of an agreement or other legal instruments. It also funds actions to recover disaster-stricken areas in federal entities that have the emergency situation or state of public calamity recognized and approved. FUNCAP resources are appropriations included in the Annual Budget Law of the Union, and its additional credits, donations, and other sources of income are kept in the National Treasury Single Account and managed by a board of directors, who should establish the criteria for prioritization and approval of work plans, monitoring, supervision, and approval of accountability. Social control over the allocations of FUNCAP's resources is exercised by councils linked to the benefited entities, ensuring the participation of civil society.

## Oriental Republic of Uruguay

The National Emergency System (SINAE), created by Law 18621/2009 (https://legislativo.parlamento.gub.uy/temporales/leytemp8156395.htm), is a permanent public system, whose purpose is the protection of persons, goods, and the environment, in the eventual or actual occurrence of disaster situations, through the coordination of the National Government with the appropriate use of available public and private resources, in order to promote the conditions for sustainable national development.

The functioning of the system is embodied in the package of governmental actions aimed at the prevention of risks linked to natural or human disasters, foreseeable or unforeseeable, periodic or sporadic; mitigation and attention to disasters; and the immediate rehabilitation and recovery tasks that are necessary. SINAE is integrated by the Presidency, the National Emergency Directorate, the National Advisory Commission for Risk Reduction and Disaster Care, autonomous institutions and decentralized services, as well as local emergency committees.

SINAE is financed by budget and non-budget resources that integrate the National Fund for Disaster Prevention and Care. The fund consists of donations and legacies to the system or to the performance of its specific or coordinated activities, and transfers from other public entities. Any kind of donations, legacies, and transfers addressed to SINAE are exempt from any type of national taxes. SINAE has ownership and availability of the entire fund. Resources not affected or executed at the end of each financial year continue to integrate the fund and may be used in the following years.

## Argentine Republic

The National System for Integral Management of Risk and Civil Protection, established by Law 27287/2016 (http://servicios.infoleg.gob.ar/infolegInternet/anexos/265000-269999/266631/norma.htm), aims to integrate and articulate the actions and the functioning of the agencies of the national and provincial governments, the Autonomous City of Buenos Aires and its municipalities, non-governmental organizations, and civil society, to strengthen and optimize actions aimed at risk reduction, crisis management, and recovery. The system is composed of the National Council for Integral Risk Management and Civil Protection, and the Federal Council for Integral Risk Management and Civil Protection. The National Council is the highest body for decision, articulation, and coordination of the resources and is intended to design, propose, and implement public policies for comprehensive risk management.

The National Fund for Integral Risk Management was created to finance the prevention and response actions managed by the Executive Secretariat of the National Council for Integral Risk Management and Civil Protection. The fund is a trustee, and its economic resources come from the nation's, the provinces', and the Autonomous City of Buenos Aires' resources; donations and legacies; gains from financial investments; national and international loans, and others provided by the State when dealing with emergencies; taxes that are created with specifically for the fund; and any other resource assigned to it. The national fund resources come from the General Budget of the Nation of the corresponding year.

Contributions to the fund may be made in cash or bonds from the contributing jurisdiction so as not to affect the liquidity of the budgets during their constitution or their possible recapitalization after a large event has occurred. The resources of the National Emergency Fund originating from revenues of financial assets may be applied to prevention actions only with authorization from the National Council for Integral Risk Management and Civil Protection.

The National Emergency Fund is drawn from in an emergency or disaster, established by the National Council for Integral Risk Management and Civil Protection to provide liquidity by selling its assets or applying them as a warranty in term banking operations aimed at obtaining short-term liquidity.

## DISCUSSION

The analysis of the funds associated with financing disaster risk management in Latin America presents some commonalities.

Protection and civil defense systems are in some cases associated with more far-reaching security systems and almost always integrating broader concepts of sustainable development. These systems are composed of public-sector departments, with the participation of the private sector and the population, and can be replicated in subnational instances. With well-defined organization, they all present a broad portfolio of forms of financing, including emergency funds.

Most of the funds, established in civil protection and defense system laws or by their own legislation and regulation, mainly relate to the management of natural disasters, with very few references to other types, as well as not clearly differentiating events by the magnitude of the hazard or the impact generated.

Prevention and preparedness activities, such as monitoring and early warning or climate extreme events, are clearly central to the analysis and reduction of climate-associated disaster risks. As a result, they are also fundamental in reducing the expenditure allocated in mitigation and recovery stages. Therefore, some mechanisms that financially support prevention and preparedness activities to cope with the imminence of a public calamity are identified. However, the vast majority of these arrangements can be classified as post-disaster recuperation and reconstruction practices. In this sense, the official declaration of states of calamity and emergency, approved by the fund managers, are the fundamental instruments for initiating and legalizing the processes.

Among the 16 countries analyzed, only Ecuador and Chile do not present a fund as a financial strategy for management of natural disasters. North and Central American countries have more complex and well-structured funds, presumably based on their history of natural disasters and high social vulnerability; however, the Brazilian FUNCAP is the oldest, established in 1969.

Either the funds are the only sources of resources, or they complement other previously existing resources for disaster risk management such as money destined for different development-related programs in ministries or autonomous institutions' budgets. Regardless of the type of fund, they are composed of a varied range of possibilities, which are mainly concentrated in initial values defined by law, annual contributions of general budgets, donations (national and international, private and public), and the financial gains of resources deposited into bank accounts.

Resources are used by all levels of government management (national, provincial, municipal, those of autonomous territories) and can be distributed to areas affected by the central government as money or as necessary materials purchased after formal orders.

Considering the scarce resources, but mainly the historical problems with the proper use of public money, the resources are earmarked for a single-purpose account for the needs set out in the legislation related to the formation of the funds, often in an official bank and with only one person responsible for withdrawals. In the same sense, the processes of auditing expenditures are described in detail, as well as the destination of resources not used in the year, which remain in the next year's budget or are available for another affected area or disastrous event.

## CONCLUSIONS

All Latin American countries have established disaster risk management systems, which are being updated frequently, due to the need to adapt to new environmental realities, but mainly new political–administrative and fiscal scenarios. Frequent changes in legal frameworks are a common reality in the region. Experiences of calamities with large and diverse impacts, however, have shown that financial preparedness is much less developed in the region.

In this sense, a broad portfolio of possibilities for financial strategies and instruments have recently been established, although, in countries with few resources and low levels of development, there is still a high reliance on resources from international disaster-fighting assistance. The unavailability of required resources in an emergency situation has led Latin American countries to choose disaster funds as a primary disaster risk management financing strategy.

The present work compares the different existing funds; however, the fact that many of them were recently established and the absence of clear and available information for all countries do not allow an assessment of their effectiveness. Some articles evaluate in different ways the funds in Colombia (MÃ©ndez et al., 2013) and Mexico (Rodríguez Esteves, 2004).

Likewise, it is possible to mention as important elements for the wide adoption of disaster funds by almost all countries of the region the facts that the funds (i) are free of conditions imposed by the international donor or the private sector (this has important implications on the domestic policy of some countries); (ii) greatly reduce the impact of a disruption to planned fiscal and macroeconomic development; (iii) represent an opportunity to include resources in a larger and general plan for sustainable development and integrated disaster management (particularly pre-disasters actions) than in simple humanitarian aid actions; and (iv) reduce financial pressures following a disaster, as they have no obligation to be repaid.

While many resources used in the implementation of prevention and disaster preparation measures are distributed budgets of social policy or public infrastructure, the probability or uncertainty of natural disaster occurrence and strict control of public expenditure in the context of anticorruption measures are some of the main obstacles to the use of public financial resources (e.g., Funds) in prevention and preparedness strategies and actions. This obstacle is increased even more with the inclusion of climate change uncertainties.

In this sense, the resources of permanent and exclusive disaster management funds take importance. However, the funds do not explicitly mention climate change or variability, and/or extreme events issues in addition to their close relationship with natural disasters. In a context of climate change scenarios, it is possible to indicate the need to allocate greater resources to funds for speed and flexibility in resource distribution through less bureaucracy and the creation or distribution of greater autonomy, and the responsibility for funds at local levels, closest to the affected populations and regions.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: The data are available at the different and several websites of the governments of Latin America countries, and are included in the “reference” chapter of the document.

## AUTHOR CONTRIBUTIONS

CS was responsible for the conception of the work, research data and information, and the drafting of the document.

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# Impact Assessment of Climate Change on Storm Surge and Sea Level Rise Around Viti Levu, Fiji

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Projecting the sea level rise (SLR), storm surges, and related inundation in the Pacific Islands due to climate change is important for assessing the impact of climate change on coastal regions as well as the adaptation of the coastal regions. The compounding effects of storm surges and SLR are one of the major causes of flooding and extreme events; however, a quantitative impact assessment that considers the topographical features of the island has not been properly conducted.

Therefore, this study projects the impact of storm surge and SLR due to climate change on Viti Levu, which is the biggest and most populous island in Fiji. The impact of SLR on the inundation in coastal areas was simulated using a dynamic model based on the IPCC SROCC scenarios and the 1/100 years return period storm surge implemented based on the RCP8.5 equivalent scenario. The affected inundation area and population due to storm surges and SLRs are discussed based on the compound effects of SLR and storm surge.

Although the contribution of SLR to the inundation area was quite significant, the 1/100 year storm surge increased by 10 to 50% of the inundation area. In addition, a narrow and shallow bay with a flat land area had the largest impact of storm surge inundation. Furthermore, the western wind direction had the most severe storm surge inundation and related population exposure due to the topographic and bathymetric characteristics of Viti Levu Island.

**Keywords: inundation, Fiji, storm surge, sea level rise (SLR), climate change vulnerability, population displacement**

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## INTRODUCTION

Since Broecker first projected a rise in temperature due to global warming in 1975, the climate change impact on human activities has received increased interest in various fields (Broecker, 1975). For example, recently, the impact of anthropogenic climate change has received political and diplomatic interest. The United Nations has set "taking urgent action to combat climate change and its impacts" as one of its sustainable development goals (SDGs) for the year 2030 United Nations (2015), naming climate change as the biggest potential threat to the global economy during the World Economic Forum (2016). Additionally, environmental risks such as "failure of climate-change mitigation and adaptation" and "extreme events" are perceived as the biggest sources of concern, according to the newest Global Risks Perception Survey (GRPS), compiled by the Global Risks Report 2019 (World Economic Forum, 2019).

The effects of climate change on society are varied and not limited to the economy. For example, one of the repercussions of climate change-induced sea level rise (SLR) on the society is involuntary migration or displacement of the inhabitants. In addition, other climatic drivers may also serve as natural hazards. The areas most affected by natural hazards due to climate change-induced SLR include the low-lying coastal regions. Meanwhile, 10% of the world's population lives in low-lying coastal regions within a 10 m elevation of the present sea level (Carrasco et al., 2016). Muis et al. (2016) estimated that 1.3% of the world's population is at risk of coastal flooding. Particularly, in Oceania, where the SLR is estimated to have the greatest relative impact on the land area and GDP, as well as in urban areas, agricultural land, and wetlands, where the relative impact of SLR is the second highest under the least severe SLR scenario (Dasgupta et al., 2009).

The most recent data from the 5th Assessment Report (AR5) predicted an SLR of 43–84 cm with a 5% range confidence interval by the end of this century under the highest greenhouse gas concentration scenario, which will, in turn, pose a serious threat to coastlines and several islands (IPCC, 2014). The effect of SLR on small islands can be especially severe since coastal zones often harbor a significant proportion of the human population and infrastructure; in particular, the atoll islands are the most vulnerable because of a lack of resilience caused by limited relocation opportunities further inland (Woodroffe, 2008; Nurse et al., 2014). The situation is further aggravated in the tropical Western Pacific (∼12 mm/yr between 1993 and 2009 have been reported) where the SLR is not uniform and is four times above the average, and remains at least 1 mm higher throughout the South Pacific region (Fasullo and Nerem, 2018), which is known for its numerous inhabited islands (Meyssignac et al., 2012; Nurse et al., 2014). To accurately evaluate the SLR impact, several studies have reported the importance of applying a synergetic approach, wherein the coastal morphology, as well as the complex interactions with the ecological environments are considered (Passeri et al., 2015; Hagen et al., 2017).

In addition to the SLR, extreme events such as storm surges have a significant impact on extreme inundation, particularly its compounding effects with SLR (Little et al., 2015). According to a study on Florida's Big Bend Region, storm surge is enhanced by the shore elevation, as well as other physical characteristics such as coastline angle, wide continental shelf, and basin geology (Hagen and Bacopoulos, 2012). Storm surges are mainly induced by tropical cyclones (TCs) in the Pacific, North Atlantic, and Indian Ocean and cause catastrophic hazards in the coastal region (Mori et al., 2014). Storm surge occurs when water is pushed onshore by wind and can also be caused by the atmospheric pressure gradient (Kim, 2019). The amplitude of the storm surge depends on the orientation of the storm track in relation to the coastline, intensity, size, wind speed, and bathymetric features [National Oceanic Atmospheric Administration (NOAA), 2020]. The impact of climate change on TC is expected to increase in intensity, but to decrease in frequency (IPCC AR5). The increase in the intensity of TC causes an increase in the storm surge height, thus resulting in severe inundation. Bilskie et al. (2019) estimated the 500-year return period of extreme events near the northern Gulf of Mexico to be a 100-year return period by the year 2100. Studies evaluating the impact of climate change on storm surges typically use three methodologies: the global climate model (GCM) simulation (direct storm surge simulation based on wind fields and sea-level pressure of GCM output) (Yasuda et al., 2010, 2014; Yang et al., 2018; Mori et al., 2019); the pseudo-global warming technique (Takayabu et al., 2015; Ninomiya et al., 2016); and the statistical modeling, which is based on a synthetic tropical cyclone model (McInnes et al., 2014; Nakajo et al., 2014). Although the importance of the impact assessment of TC and storm surge has been discussed (e.g., Mori and Takemi, 2016), a regional impact assessment combining SLR and storm surge has not yet been achieved. Here, using Fiji as an example, we assessed the impact of SLR and storm surge on coastal inundation.

Fiji is the largest island nation in the Pacific Islands after Australia and New Zealand, however, it has its vulnerabilities such as relatively higher population density in urbanized areas, as well as in low-lying regions, some of which are inhabited or serve as economic hubs. Furthermore, the island can be severely impacted by cyclones and other weather-related events. For example, as many as 76,000 inhabitants were internally displaced during Tropical Cyclone Winston, which struck the country in February 2016. In addition, 40,000 houses were damaged or destroyed with over 350,000 people significantly affected, wherein a significant part of them were living in the northern part of Viti Levu [World Meteorological Organization (WMO), 2016]. The Internal Displacement Monitoring Center (DMC) estimates that 3,614 Fiji inhabitants are annually displaced due to storm surges and another 2,076 due to cyclonic winds (Internal Displacement Monitoring Center (IDMC), 2020). The most recent tropical cyclones: Cyclone Mona and Cyclone Sarai, which hit Fiji on January 2, 2019, and December 12, 2019, respectively, internally displaced a total of 4,800 people (Internal Displacement Monitoring Center, 2020). Several studies have discussed the impact of SLR and storm surges on Fiji. For example, McInnes et al. (2014) researched the impact of TC on the coastal areas of Viti Levu and Vanua Levu islands using the Monte Carlo method, based on historical cyclone occurrences. They found that storm tide risk is higher on the northwest coasts of both islands, while the southwestern coasts of Viti Levu may have been affected during the El Niño and La Niña years. Meanwhile, the study conducted by Gravelle and Mimura (2008) on the vulnerability of the coastal areas of Fiji to SLR identified Suva, Lautoka, and Nadi as being among the most vulnerable areas in Fiji, while the villages in the north, Tavua, and Nailaga are vulnerable due to the lack of adaptive measures. In addition, they found that in many cases, retreat from the affected areas is more realistic than building protection structures or applying other related methods. However, there are no studies on the compound effect of SLR and storm surges on coastal areas.

Therefore, the objective of this study is to estimate the total inundation and affected population due to SLR and storm surge on an island under different future climate change scenarios and extreme storm surge levels. Viti Levu, which is a major island in Fiji was selected as the case study. First, a numerical model was developed to estimate the inundation area due to SLR and storm surge using topography data, atmospheric forcing, and population dataset. Second, a series of numerical simulations was conducted by combining two SLR changes and extreme wind forcing for storm surges. Finally, the compound effects of SLR and storm surge on the inundation extent are discussed and the extent of population to be affected based on exposure in vulnerable areas was estimated.

## MATERIALS AND METHODS

The section describes the methods developed in this study for assessing the impact of storm surge and SLR on inundation. The numerical modeling of storm surges was performed using linear shallow water equations (SWE) with spherical coordinates. Both SLR and storm surge were simulated for the inundation area. The comprehensive dataset including the topography, bathymetry, and population density was set up by combining different sources coordinating grid size. Finally, the population dataset was integrated into the comprehensive dataset for the social impact assessment.

### Numerical Modeling of the Storm Surge and SLR Inundation

This study is aimed at estimating the inundation area due to storm surge, SLR, and their compound effects. Therefore, the dynamic modeling of inundation is necessary. However, since a wide area of computation is required, a model with a low computational load is necessary. Thus, inundation was simulated using in-house SWE with a spherical coordinate system in $\theta$ and $\varphi$, latitude, and longitude. The numerical model was validated using the analytical solution for ideal bathymetry. The governing equations for the free surface $\eta(\theta, \varphi)$ and momentum flux $P$ and $Q$ in the latitudinal and longitudinal directions are as follows:

$$\frac{\partial \eta}{\partial t} + \frac{1}{Rcos\theta}\left[\frac{\partial P}{\partial \phi} + \frac{\partial Qcos(\theta)}{\partial \theta}\right] = 0, \quad (1)$$

$$\frac{\partial P}{\partial t} + \frac{gh}{Rcos\theta}\frac{\partial \eta}{\partial \phi} = -fQ + \frac{\tau_s^{\phi} - \tau_b^{\phi}}{\rho_w} - \frac{h}{\rho_w Rcos\theta}\frac{\partial P}{\partial \phi}, \quad (2)$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial \eta}{\partial \theta} = fP + \frac{\tau_s^{\theta} - \tau_b^{\theta}}{\rho_w} - \frac{h}{\rho_w R}\frac{\partial P}{\partial \theta}, \quad (3)$$

where $t$ is the time, $h$ is the water depth, $D$ is the total depth ($D = \eta + h$), $P$ is the atmospheric pressure, $R$ is the Earth radius, $f$ is the Coriolis force, $\rho_w$ is the seawater density (1,025 kg/m$^3$), and $g$ is the gravitational acceleration (9.8 m/s$^2$). The terms $\tau_s$ and $\tau_b$ in Equation (2, 3) are the surface stress and bottom stress along the directions of the $\theta$ and $\varphi$ coordinates, respectively. The origin of the free surface $\eta$ is located at the mean water level and toward the upward level.

The surface wind stress, $\tau_s$, is calculated using the standard quadratic law of wind speed:

$$\tau_s^i = \rho_a C_D \left|U\right| U_i \quad (4)$$

where $C_D$ is the wind drag coefficient, $\rho_a$ is the air density (1.225 kg/m$^3$), and $U$ is the wind speed at 10 m elevation (subscript $i$ indicates latitudinal or longitudinal component). The surface drag coefficient $C_D$ given by Honda and Mitsuyasu (1980) is:

$$C_D = (1.29 - 0.024U_{10}) \times 10^{-3} \qquad U_{10} < 8\ \frac{\text{m}}{\text{s}} \quad (5a)$$

$$= (0.581 + 0.063U_{10}) \times 10^{-3} \qquad U_{10} \geq 8\ \frac{\text{m}}{\text{s}} \quad (5b)$$

The bottom stress, $\tau_b$, represents the bottom friction and is expressed by a quadratic law, as shown in Equation (6).

$$\tau_b^i \rho_w = k\left|U\right| U_i \quad (6)$$

where $k$ is the bottom friction coefficient and is typically $k = 0.025$ for the sea bottom (Flather and Tippett, 1984). The governing equations are discretized by the standard explicit first-order upwind scheme.

The open boundary condition offshore is given by the Flather type equation (Flather and Tippett, 1984)

$$q_{n+1} = q_n + \left(\frac{c}{h}\right)(\eta_{n+1} - \eta_n) \quad (7)$$

where $c = (gh)^{\frac{1}{2}}$, and is the long-wave velocity, $q_n$ is the discretized depth-averaged velocity at grid $n$. Assuming long wave propagation outward, Equation (7) gives a non-reflected boundary condition. The inundation due to storm surges was considered using the moving boundary scheme (e.g., Liu et al., 1995; Kotani et al., 1998). **Figure 1** illustrates a schematic view of the inundation scheme. The total depth $D_{n+1}$ at grid $n$+1 for calculating $P_{n+1}$ is given by:

$$D_{n+1} = \eta_n + h_{n+1} \quad (8)$$

where the surface elevation $\eta_{n+1}$ in the land includes the ground level at grid $n$, $\eta_n$ in the ocean is defined from the mean water level at grid $n$, and $h_{n+1}$ is bathymetry at grid $n + 1$ (inland area $h_{n+1} < 0$). There are two cases when the grid point $n$ is located in the inundated area. $P_{n+1}$ is calculated using (2) if $D_{n+1} > 0$ (grid $n + 1$ becomes newly inundated as shown in **Figure 1A**) and $P_{n+1}$ is zero if $D_{n+1} \leq 0$ (grid $n + 1$ is not inundated as in **Figure 1B**). The minimum total water depth $h_{\min}$ for the calculation of friction terms is 0.03 m in this model.

**Figure 2** shows the schematic illustration of the inundation modeling used in this study. To simulate changes in the inundation edge/area, we considered the SLR, storm surge, as well as their compound effects with storm surges. The inundation due to storm surges was considered by the numerical model due to dynamic momentum and mass transfer of sea surface to land. The inundation area can be estimated using the altitude without considering the houses and other small structures. The accuracy of the numerical model was verified using an ideal uniform slope condition with changing slopes and wind speeds. The error of maximum storm surge height ranged from 5.3 to 5.9% for most cases.

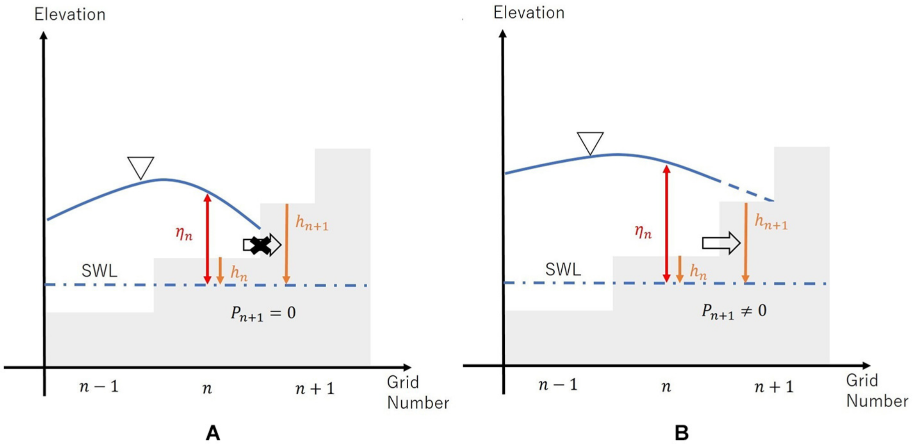


**FIGURE 1 |** Schematic view of the inundation scheme [**(A)** the case grid $n + 1$ is not inundated, **(B)** the case grid $n + 1$ becomes inundated].

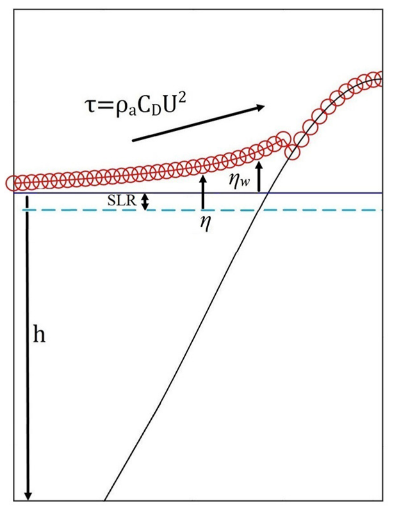


**FIGURE 2 |** Schematic cross-sectional view of the coastal inundation simulation considering SLR and storm surge, where $\eta_w$ is the inundation due to storm surge and $\eta$ is the cumulative inundation due to storm surge and SLR.

# Model Configuration and Dataset

## Computational Setup

The domain size of the numerical simulation ranged from 18°24′ S to −17°8′30″ S in the latitudinal direction and 176°56′ W to 178°48′ W in the longitudinal direction. The total modeled area was approximately 28,000 km$^2$. The computation domain includes the Viti Levu Island (10,388 km$^2$), which is a major island in Fiji, as well as numerous smaller islands, including Ovalau (106.4 km$^2$).

The spatial resolution of the computation was 3 arc-s (∼90 m) and the details of bathymetry, topography, and forcing data are explained in the following section. The temporal discretization was 1 s and integrates 1 h for each forcing condition. Herein, we assessed the impact of SLR and maximum storm surge height on the inundation extent in Fiji. The effects of SLR were implemented as changes in the mean water level in the numerical model, and the storm surge was considered based on the dynamic model described in Section Numerical modeling of the storm surge and SLR inundation. Since the inundation process requires a dynamic model, the compound effects of SLR and storm surge on inundation were considered by changing the combination of the two phenomena using the numerical model. The combined effect of SLR using two different representative concentration pathways (RCP) scenarios and storm surges were examined by changing the wind directions. The details of the wind forcing and SLR scenarios are discussed in the following section.

## Bathymetry and Topography Data

The topography and bathymetry data of the target region were compiled using the NASA's Shuttle Radar Topography Mission (SRTM) and General Bathymetric Chart of the Oceans (GEBCO) databases, respectively. The SRTM digital elevation model (DEM) provides high-resolution topography data (3 arc-s) used for land elevation data input (Jarvis et al., 2008). GEBCO, a global bathymetric grid with 30 arc-s spacing is used for ocean bathymetry data input (Becker et al., 2009). Since the two datasets have different grid coordinates and spatial resolutions, both bathymetric and topographic data were linearly interpolated and merged into the same grid with 3-arcs resolution for the computation. Subsequently, a global self-consistent hierarchical high-resolution geography (GSHHG) database was utilized for the shoreline validation.

**Figure 3A** shows the combined bathymetry and topography data for the Fiji area, while **Figure 3B** illustrates the topography data with a focus on the low-lying area of Fiji, lower than 20 m. Despite being mountainous (86.9% of the territory is located higher than 20 m above sea level), prominent low-lying areas are also present (3.3% of the island is lower than 5 m above sea level, **Figure 3B**). The areas in the south-eastern, southern, western, north-western, and northern parts all have a significant portion of areas below 5 m (**Figure 3B**). As discussed later in the text, these

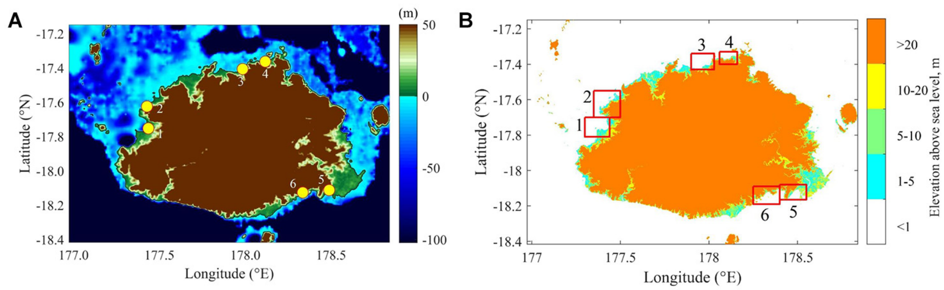


**FIGURE 3 |** Computational domain, bathymetry, and topography with the selected low-lying locations [contour indicates elevation (m), **(A)**] and the map indicating altitude changes in Viti Levu **(B)**.

areas are usually more densely populated. Coastal areas are also economically significant for the country, as some of them serve as tourist beaches or resort locations. Six target locations in the low-lying area were selected for detailed analysis, as shown in the boxes in **Figure 3A**.

## Forcing for the Numerical Model

For the impact assessment of inundation by storm surge and SLR, we considered both effects for the numerical modeling. Extreme wind input is necessary for the storm surge modeling of Fiji, however, there are only few available historical data on forcing. Atmospheric analysis such as Climate Forecast System Reanalysis (CFSR) or European Center for Medium-Range Weather Forecasts Re-Analysis (ERA) product can be used for estimating extreme TCs, however, the available reanalysis data is too short and less accurate for the TC events and related storm surges (e.g., Mori and Takemi, 2016). In contrast, synthetic TC models used to increase the number of TC events have been used for the estimation of extreme TCs and storm surges (e.g., McInnes et al., 2014; Nakajo et al., 2014). These statistical approaches are straightforward approaches used to estimate the intensity and probability of extreme storm surges. However, the computational cost is quite high due to the large number of computations (e.g., 10,000 years simulation). Moreover, the estimation of TCs on small islands can be regarded as random processes. Thus, to estimate the maximum storm surge heights for a given return period, we assumed that constant strong winds blow over the island. This approach can estimate the hot spot of the vulnerable areas of the island, however, it neglects the inhomogeneous distribution of the wind fields of TC. Additionally, we used extreme wind speeds based on climate projection as follows.

We used the extreme sea surface wind speed data of mega ensemble projection by atmospheric GCM with 60 km resolution to estimate the extreme storm surge along the coasts of Fiji. The mega ensemble climate projections, (so-called d4PDF) (Mizuta et al., 2017) is a set of long-term ensemble projections for historical and warmer future climate conditions for a period of over 5,000 years. The projections assume a +4K global mean atmospheric temperature compared to the pre-industrial climate. The +4K climate corresponds to the temperature change under the RCP8.5 scenario by the end of the 21st century. Mori et al. (2019) estimated the future changes in the wind speed and storm surge for a 100-year return period using the d4PDF. The projections for the historical climate and +4K future climate integrated 6,000 and 5,400 years, respectively, in the d4PDF. Therefore, extreme events (e.g., wind speed in a 100-year return value) can be used to easily estimate non-parametric analysis without standard extreme value analysis.

The estimated weakening of TCs, and a consequent decrease in the wind speed and storm surge heights in the future in the Southern hemisphere, including Fiji, was discussed by Mori et al. (2019). In this study, we used the same dataset around Fiji, as shown in **Figure 5**. The wind speed in a 100-year return value around Viti Levu was estimated at 38.7 and 45.6 m/s for the +4K future and historical climate condition, respectively. The decreasing wind speed in the future climate can be attributed to the weaker TC intensity in the Southern hemisphere (Mori et al., 2019). Despite the weakening trend of the wind speed, the storm speed around Fiji remains the mightiest in the region for extreme wind speeds in the Southern Pacific, with the most prominent ones located in the Coral Sea (latitudes 20° to 15° S, and longitudes 150° to 160° E), followed by New Caledonia and parts of Vanuatu (**Figure 4**). Since this study focuses on estimations of future climate, the corresponding value is used throughout the study.

To estimate the impact of the storm surge on the coastal areas of Fiji, the TC characteristics should be considered for the storm surge modeling. However, it is difficult to implement variability for an island due to the TC's track, translation speed, and other factors. Therefore, for simplicity, we assumed that spatially uniform wind was blowing from all four cardinal directions with the same probability.

In this study, we considered the SLR and storm surge. The SLR was implemented using the global SLR projections based on Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC, 2019) by the end of the Twenty-first century. The Intergovernmental Panel on Climate Change (IPCC) AR5 summarizes the relationship between the RCPs and SLR. There are several RCP scenarios, however, we selected two typical scenarios for this analysis. First, the RCP2.6, which relates to the Paris agreement for 2-degree target in mitigation. In addition, the RCP8.5, which reflects for the worst-case scenario. The future rise in global mean sea level (GMSL) differs depending on the

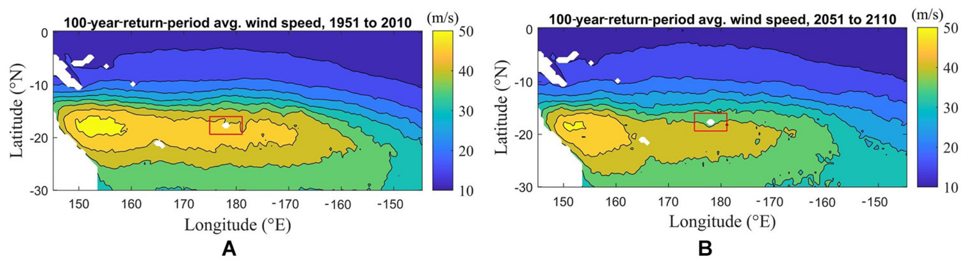


**FIGURE 4 |** Extreme wind speed at 100-year-return-period around Fiji, according to historical climate **(A)** and the warmer future climate **(B)** according to d4PDF climate projection (unit: m/s).

**TABLE 1 |** GMSL rise estimates depending on different RCP scenarios according to the Special Report on the Ocean and cryosphere in a changing climate (Oppenheimer et al., 2019).

| | RCP 2.6 | RCP 8.5 |
|---|---|---|
| GMSL in 2100 relative to the years 1986–2005 | +0.43 m (0.29–0.59 m) | +0.84 m (0.61–1.10 m) |

*The values in parenthesis indicate 95% confidence level.*

different radiative forcing from RCP2.6 to RCP8.5. As discussed in Chapter 4 of IPCC SROCC, the estimated sea level by the year 2,100 is 0.43 m under the RCP2.6 scenario and 0.84 m under the RCP8.5 scenario under medium confidence, compared to the years 1986–2005 (**Table 1**). In addition, according to the aforementioned report (Oppenheimer et al., 2019), there is a certain likelihood of a rise in the GMSL and an acceleration in the high confidence. For example, for the RCP8.5 scenario, the annual rate of SLR is predicted to be 15 mm/year by 2100. Meanwhile, there is high confidence that the dominant cause of GMSL since 1970 is anthropogenic forcing. In addition, anthropogenic drivers are not limited to the climatic drivers and may include demographic and urbanization trends. There is very high confidence that such drivers have played a significant role in negatively affecting the exposure and vulnerability of low-lying coastal communities to SLR and storm surge. In addition, there is high confidence that anthropogenic coastline modifications can outpace the SLR effects. There is a wide range of regional variability in the SLR speed, reaching up to 30%. Despite regional differences, the globally averaged SLR values were applied in this study, as there is no regional SLR projection available for the target region. To analyze the differences between the sea surface elevation depending on the SLR in detail, six low-lying territories in inhabited areas were selected (**Figure 2**).

These areas are located in territories that are prone to the combined effect of storm surge and SLR. The largest settlements are located in the southeastern and western parts of the island. Consequently, two locations in the most urbanized and low-lying areas in Nadi (location #1 in **Figure 3**) and Lautoka (location #2) were selected to represent the affected areas on the western coast. The affected areas on the populated southern coast were represented by areas in Suva (location #5) and Na Vasi (location #6). The northern coast does not have any bigger settlements, but has several low-lying areas, which were represented by areas in Draunivi (location #3) and Narewa (location #4). The eastern coast was not analyzed in detail even though it has some low-lying areas, as all populated areas are mostly limited to the capital (Suva) area.

## Population Data

The social impact of coastal flooding was estimated using the inundation model. The Gridded Population of the World, Version 4 (GPWv4) data provided by NASA Socioeconomic Data and Applications Center (SEDAC) was used in the model to estimate the impact of SLR and storm surge on the population [Center for International Earth Science Information Network (CIESIN), 2018]. The GPWv4 data models the distribution of the human population in most countries in the world, including Fiji. The GPWv4 is gridded with an output resolution of 30 arcs, or ∼1 km at the equator. These models have been used for vulnerability mapping, health dimensions of environmental change, and disaster impacts (Doxsey-Whitfield et al., 2015). The precision of the international boundaries of census data sets was compared against the Global Administrative Areas version 2 (GADMv2). The GPWv4 used in this study is a raster data collection, which includes the population data from the national population and housing censuses conducted between 2005 and 2014. The dataset used for Fiji population estimates was based on the Final Census conducted in 2007 by Fiji Islands Bureau and Statistics, 2008, with the national estimates adjusted to the United Nations World Population Prospects to avoid potential overreporting or underreporting (United Nations, 2013).

The population dataset of GPWv4 was interpolated linearly to the same grid system as the topography dataset, from 30 arcs to 3 arcs, as described in section Bathymetry and topography data. The population distribution was then compared to the topography and inundation maps in general, as well as to those in the selected areas. This enabled the direct estimation of the affected population numbers after flagging. Conclusions were made based on the vulnerability of Viti Levu Island. Since the spatial interpolation from 30 arcs to 3 arcs gives large biases, we paid attention to the uncertainties of the analysis for the vulnerability results. The population numbers acquired from GPWv4 enabled distinguishing the principal tendencies of the population distribution on Viti Levu Island.

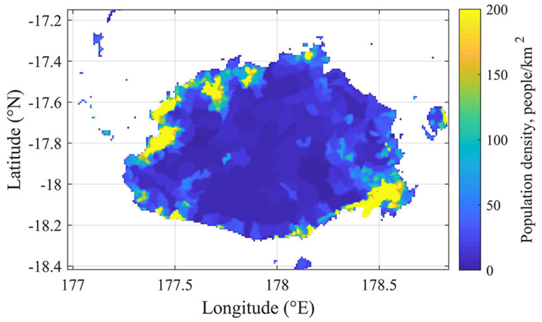


**FIGURE 5 |** The population density map of Viti Levu based on GPWv4 (unit: a number of people/$km^2$).

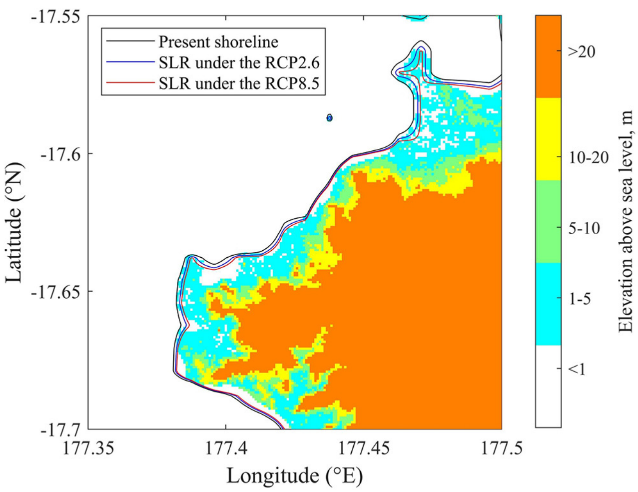


**FIGURE 6 |** Changes in the shoreline by SLR in location #2, Lautoka area, (see **Figure 3B**) under different SLR scenarios. The black line corresponds to the coastline under present climate condition, the blue line corresponds to the retreat of coastline due to SLR under the RCP2.6 scenario, while the red line corresponds to the shift in the shoreline due to SLR under the RCP8.5 scenario.

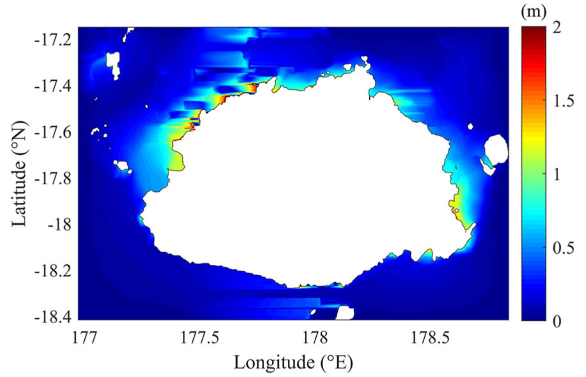


**FIGURE 7 |** Spatial distribution of the maximum storm surge level combining different wind directions (unit: m above MWL).

The population density in Viti Levu (58.8 people/$km^2$) slightly exceeds the national average (46.4 people/$km^2$). However, despite the relatively low population density, there are areas where the population density is higher than 200 people/$km^2$ and may exceed 5,000 people/$km^2$. Such areas are prevalent in the western, northwestern, and southeastern parts of the island, all of which are predominantly located in coastal zones (**Figure 5**). The highest population density was observed in the southeastern part of the island, which is home to the capital city of Fiji.

## RESULTS AND DISCUSSIONS

### Individual SLR and Storm Surge Contribution to Inundation

First, we examined the permanent inundation due to SLR by submerging the bathymetry and topography data. According to the RCP2.6 scenario, the SLR alone would cause an inundation of 20.5 $km^2$, or 0.2% of the total land area, while the RCP8.5 estimated that the inundation area would be approximately twice as large at 39.9 $km^2$ (or 0.38%) of the total land area. **Figure 6** shows an example of the inundation change by SLR estimated by RCP2.6 and 8.5 in location #2 (see its location in **Figure 3**) in the northwestern part of Viti Levu. Changes in the coastline in location #2 (Lautoka area), as shown in **Figure 6**, indicate that a higher SLR induces larger permanent inundation; however, the affected area is highly dependent on the local topographical and bathymetrical features. The details of local inundation characteristics are discussed later in the manuscript.

The storm surge heights greatly differ depending on the wind speed. To estimate the maximum inundation, we changed the wind directions over the island. **Figure 7** depicts a combined map for the maximum storm surge height in the simulations with four different wind directions. Owing to bathymetric and topographic features, the spatial distribution of the surface elevation was considerably smaller in the southern part of the island. However, extreme storm surges were estimated to be as high as 2.9 m on the eastern and northern coasts, while the storm surges were significantly more moderate in the southern part of the island, with a maximum estimated value of 1.42 m in the Suva area with an exception of the Vunanu area. In addition, a significant difference was observed in the total area (i.e., the marine and coastal areas where a certain sea surface elevation anomaly was observed). In all the modeled areas, for the southern wind, the total area where the sea surface was elevated above 1 m was merely 4.4 $km^2$; however, the total area was as large as 93.42 $km^2$ for the eastern wind, and as much as 184.55 $km^2$ for the western wind. In addition, all the wind directions except the southern direction were capable of generating surface elevation higher than 2 m. Furthermore, 2.69 $km^2$ of the total area had a sea surface elevation exceeding 2 m under the western wind, 1.07 $km^2$ under the eastern wind, and 0.54 $km^2$ under the northern wind. Differences in storm surge height for Viti Levu was due to the differences in the bathymetry and coastal morphological characteristics. The ocean area south of Fiji is noted for its

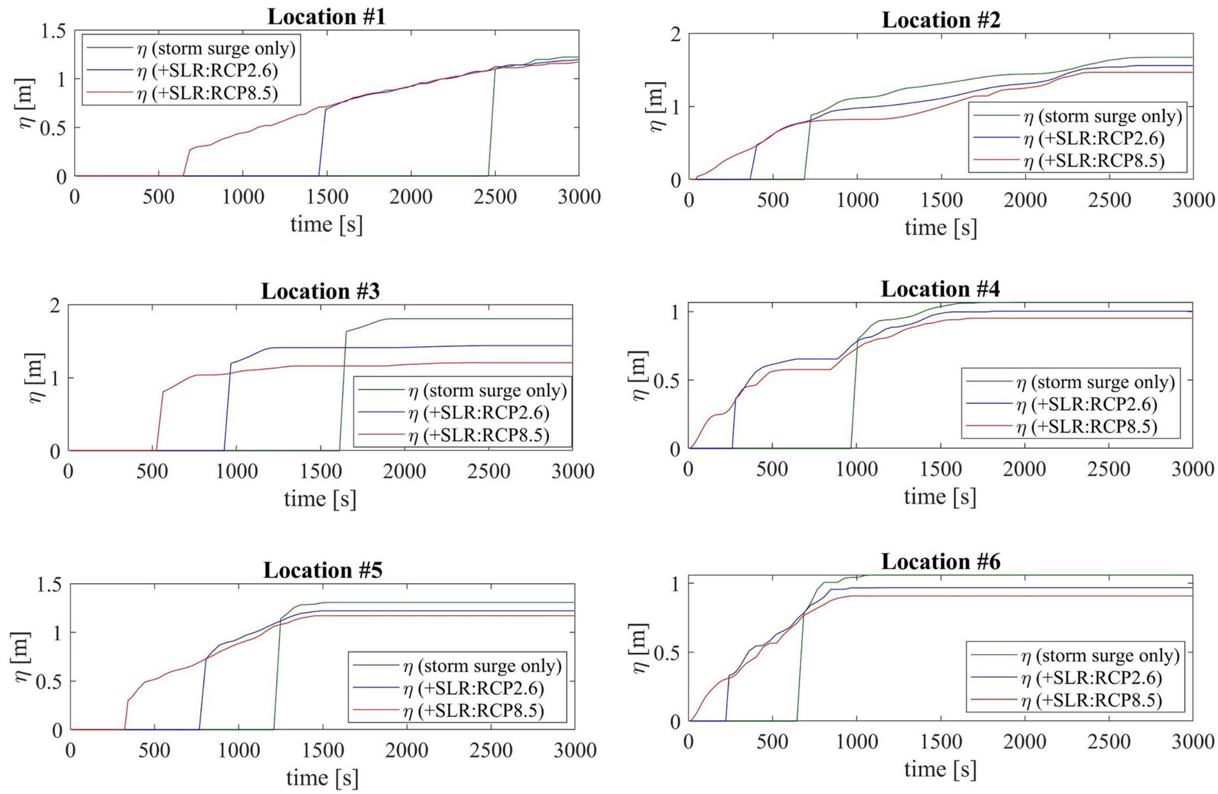


**FIGURE 8 |** Time series of surface elevation due to storm surge with and without SLR in selected locations. The green line corresponds to the maximum sea surface elevation above MSL in the case of storm surge alone. The blue line corresponds to the maximum sea surface elevation (above the future MSL) in the case of storm surge+RCP2.6 scenario. The red line corresponds to the maximum sea surface elevation (above the future MSL) in the case of storm surge+RCP8.5 scenario.

depth, while the coast is either very steep or barely elevated, thus preventing a higher storm surge height for extreme events. In contrast, the northern and western coasts are characterized mostly by shallow waters and either very less elevated or 1–2 m elevated coasts, thus, generating extreme storm surges.

It is important to note that the storm surge alone would lead to 7.29 $km^2$ (0.07%)–28.55 $km^2$ (0.28%) of inundated areas, depending on the wind direction. In addition, an average of 17.95 $km^2$ of the territory is going to be inundated due to the storm surge alone, with the western wind resulting in the largest inundations and the southern wind resulting in the smallest ones.

## Compound Effects of SLR and Storm Surge for Inundation

We investigated the compound effects of SLR and storm surge on the total inundation. First, we examined the time series of the sea surface elevation with respect to the future MSL. For this, we selected the wind direction that caused the highest storm surge for each location. **Figure 8** shows an example of the time series of $\eta$ at selected locations for the individual effect of the storm surge and those with the addition of the SLR for the RCP2.6 and RCP8.5 scenarios. As shown in **Figure 8**, the SLR decreased the time needed for coastal inundation and resulted in an earlier arrival of the peak surge. This is consistent with the results of Bilskie et al. (2016). In addition, relatively steep coasts (1 m or higher) offered favorable conditions for high storm surge-related surface elevation, as observed in Locations #2, #3, and #5 (see **Figure 3**) with maximum surface elevation of 1.67, 1.81, and 1.31 m, respectively. Meanwhile, locations #1, #4, and #6 exhibited more modest surface elevation values (i.e., 1.22, 1.07, and 1.06 m, respectively). The bathymetric configuration significantly affected the maximum surface elevation in locations #2 and #3. Depending on the location, the maximum elevation value was attained after 1,000–2,450 s. The maximum sea surface elevation for location #2 was achieved after 2,450 s, while that for location #6 with no simulated SLR (storm surge only) was achieved after 1,000 s. In addition, the saturation period was longer for the locations with no simulated SLR and for the locations with a larger height above sea level. The highest surface elevation values were observed in a model with no simulated SLR. Storm surges as high as 1.81 m were achieved for location #3 under the northern wind, followed by 1.67 m for location #2 under the western wind. The maximum estimated surface height for the other locations are as follows: 1.22 m for location #1, 1.07 m for location #4, 1.31 m for location #5, and 1.06 m for location #6. In comparison to the mean sea level, the estimated sea surface elevation was 8–22% lower for the SLR occurring under the RCP8.5 scenario compared to models with no SLR

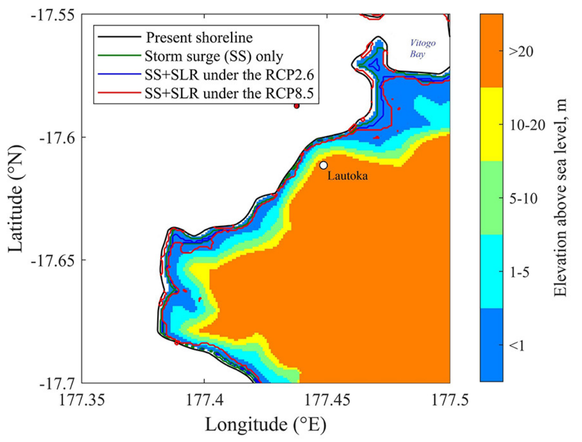


**FIGURE 9 |** Inundated area due to the compound effects in location #2, Lautoka area, (see **Figure 3B**). The black line corresponds to the coastline under present climate condition, the green line corresponds to storm surge inundation only, the blue and red lines correspond to the maximum inundation edge due to storm surge with SLR under the RCP2.6 and RCP8.5 scenarios, respectively.

simulation. Only location #1 recorded almost no difference regardless of the SLR scenario.

The compound effects of SLR and storm surge play a significant role in sea surface elevation. The inundated area was examined for all wind directions. The most devastating results for Viti Levu were observed for the western winds (88.53 km$^2$ of the inundated area), followed by the eastern, northern, and southern winds, wherein the estimated inundated area was 7.3, 42.8, and 79.16 km$^2$, respectively (out of the total area of 10,388 km$^2$). As expected, the narrow and shallow bay with a flat land area had the largest impact on the storm surge inundation.

In comparison, the northern part of Fiji showed significantly more inundated areas due to SLR, particularly under the western wind, as shown in **Figure 9**. It is important to note that low-lying areas, as well as shallow bathymetry are prevalent in these areas. In addition, it is important to note that some of the observed inundated areas are low-lying uninhabited small islets and rocks that are present in the bathymetry but were excluded from the topography dataset. Some of these areas are rocks separated from the mainland islands. Regardless, a relatively significant part of the Lautoka area was vulnerable to the individual effect of the SLR, including the northeastern part of Lautoka city and Vitogo Bay. Location #2 is noted for its low-lying coastline, which mostly lies below 1 m above mean sea level (AMSL). The elevation of a large part of the urbanized Lautoka area did not exceed 3 m AMSL. Therefore, SLR plays an important role in the compound surface elevation in such areas. In contrast, the SLR effect was almost negligible in the southern coast, wherein the storm surge effect was more significant, particularly for the Vunanu area under the eastern wind. In addition, the changes in the inundated area were minimal for the southern coast irrespective of the direction of the wind. Furthermore, most parts on the southern coast and the southwestern shore in particular, are noted for steep cliffs, thus making them less prone to the hazards of extreme events.

The compound effects by the SLR and storm surge changed the total inundated area of the island, however, the individual effect of these factors was relatively mild. As discussed in the previous section, the SLR inundated 20.5–39.9 km$^2$ of the coastal territory, whereas the total area of the island is 10,390 km$^2$. In contrast, without the SLR, the storm surge inundated only an average of 17.9 km$^2$.

**Figure 10** summarizes the compound effects of SLR and storm surge on the total inundation of Fiji. For the RCP8.5 scenario, the average compound effect was 82.99 km$^2$ of the inundated area, with relatively minor differences depending on the wind direction (79.16–88.53 km$^2$). Depending on the wind direction, the SLR contribution to the cumulative inundation was 45–50% (**Figure 10**). For the RCP2.6 scenario, the average compound effect was 48.27 km$^2$ of the inundated area, with the analogical differences depending on the wind direction (42.84–57.97 km$^2$). Depending on the wind direction, the SLR impact is reduced, since it contributes 35–47% to the cumulative effect. SLR is an important factor for the inundation of the northern areas. The individual effect of SLR on the inundated area is more significant than that of the storm surge when a different approach is used. When the storm surge scenario is used as a baseline, and the additional surface elevation levels from the RCP2.6 and RCP8.5 scenarios are assumed to be attributed to the SLR, the storm surge contribution to the compound effect becomes smaller. Under this interpretation, the storm surge alone contributes an average of 36% to the surface elevation (17-49%) when the SLR scenario is based on the RCP2.6, but only an average of 22% to the surface elevation (9–32%) when the SLR is based on the RCP8.5 scenario.

From the results, it can be concluded that the relationship between the inundation scope and SLR is not linear. This finding is similar to those of Bilskie et al. (2014) for the study on Mississippi and Alabama.

The significance of the SLR on the total inundation was confirmed by comparing the inundation depth in the selected locations under no SLR, RCP2.6, and RCP8.5 scenarios (1–6), as shown in **Figure 11**. The largest inundation was observed in location #2 under the RCP8.5 scenario, which was estimated to be submerged up to 1.42 m due to the compound effect. Other locations submerged above 1 m include location #1 (1.22 m), location #6 (1.05 m), and location #4 (1.00 m). Meanwhile, all observed territories were submerged below 0.8 m without SLR simulations, with the most significant inundation occurring in location #2 (0.79 m).

## Exposure: Population

In this section, the population affected by the total inundation discussed in the previous section is discussed with and without the storm surge effects. **Figure 12** shows the relationship between the population and the inundated area due to the storm surge and SLR. Despite the very long shoreline, the number of people estimated to be directly affected (i.e., would have their homes inundated) is limited. For the Viti Levu Island, SLR did not pose a significant threat to the island population. The total population estimated to be directly affected by the effects of SLR and storm

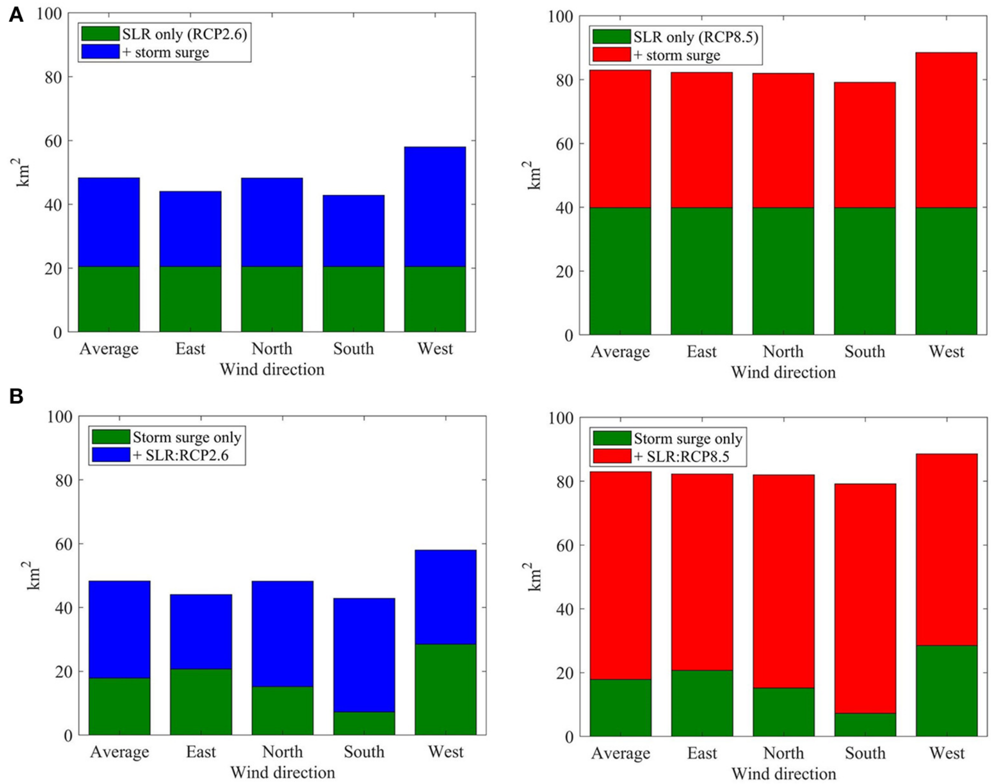


**FIGURE 10 |** Compound effects on the total inundation area by SLR and storm surge (left: RCP2.6 scenario, right: RCP8.5 scenario). **(A)** Contribution of storm surge to total inundation area, **(B)** Contribution of SLR to total inundation area.

surge was an average of 5,430 people. However, the indirectly affected population can be speculated to be significantly larger. In addition, the retreat of the coast in location #2 may presumably affect the local population more significantly than in other areas due to the lower altitude of the areas around the shore, as well as the population density.

The most potentially vulnerable areas for the population to the impact of SLR and storm surge are located on the western side of the island. Not only were these areas estimated to have the widest inundation scale, as shown in **Figure 10B**, but they are also known for a higher population density in locations #1 and #2 (**Figure 12**). This finding is consistent with that of McInnes et al. (2014), in which the northwestern part of the island was identified to possess the highest storm tide risk. The examined locations #1 and #2 have an estimated population of 23,080 and 70,700, respectively, out of which 430 and 3,060 people, were estimated to be directly affected by inundations, respectively. Despite not being subject to inundations as wide as that on the northern side, the capital Suva area is known to have the highest population density on the island, and was denoted as location #5. Approximately, 179,230 and 11,460 people inhabit the 5th and 6th locations, respectively, while the territories inhabited by 730 and 150 people, respectively, were estimated to be inundated. Meanwhile, the northern part of Fiji is known for having smaller settlements, and the vulnerability of the directly exposed population due to hazards is low. The 3rd and 4th selected locations have an estimated population of 660 and 5,990 inhabitants, respectively, and the directly exposed population accounted for 115 people altogether.

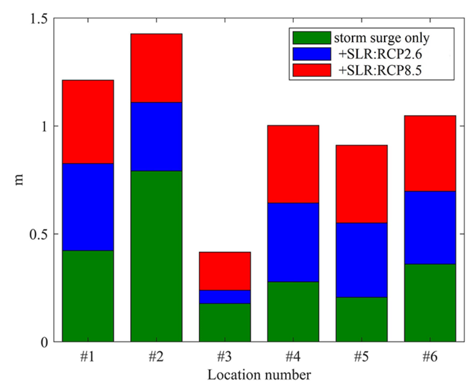


**FIGURE 11 |** Maximum inundation height in selected six locations (unit: m).

While the estimated directly affected population number is 5,430, it is worth noting that the urbanized territory is located very close to the potentially inundated area (**Figure 12**). In addition, the population living in proximity to the inundated area is ∼70,700. Since in certain cases, the inhabitants may become displaced due to loss of jobs when the coastal infrastructure is destroyed, it is important to consider this in further studies. Such inhabitants may have to flee even if their houses are not

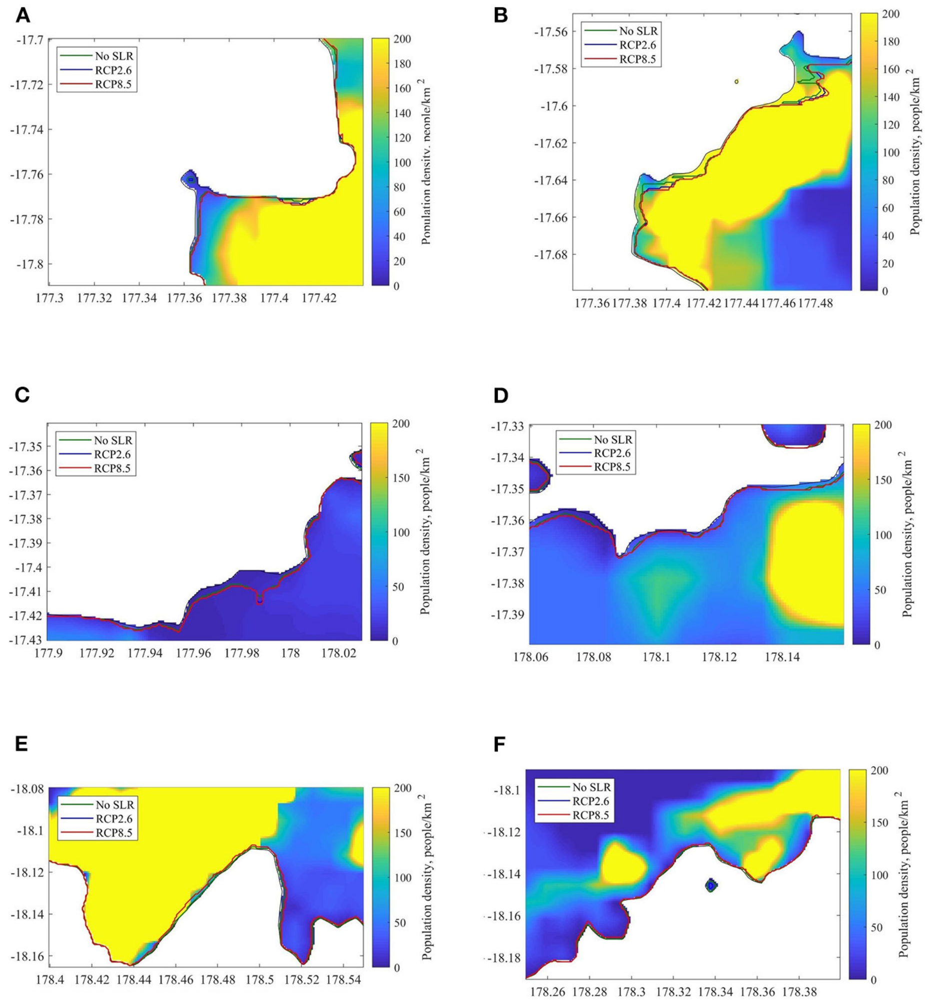

**FIGURE 12 |** Relationship between the population density and inundation area in the selected 6 locations. The area of the 6 locations are shown in **Figure 3B** (unit: a number of people/km$^2$). **(A)** Location #1, **(B)** Location #2, **(C)** Location #3, **(D)** Location #4, **(E)** Location #5, and **(F)** Location #6.

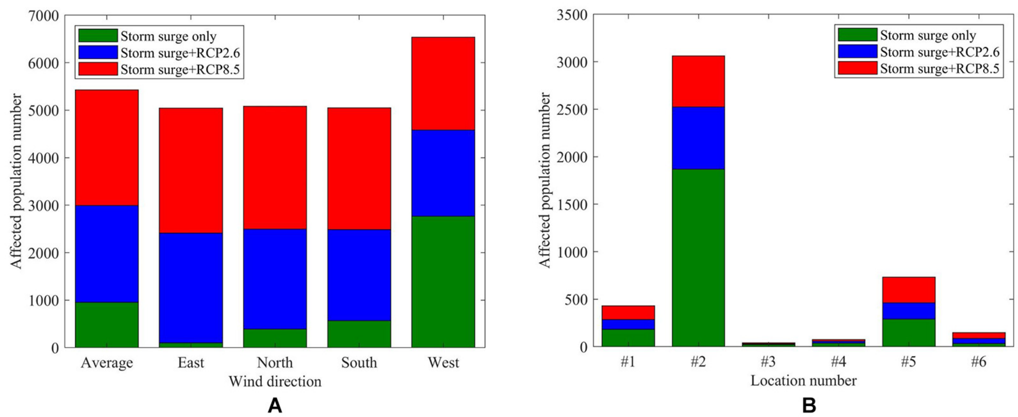


**FIGURE 13 |** Graphs showing the directly affected population scope trends under different wind directions **(A)** and in different selected locations **(B)**.

flooded or damaged after an extreme event. For example, the inhabitants whose income relies on the infrastructure near the coastline or where the coastal areas are extensively used such as in the agricultural sector, the shore recession and consequent soil degradation and salinization may lead to permanent displacement. In addition, some displaced people may return to their locations afterwards, while some displacement may be permanent. People who are forced to flee their home and are displaced either internally or outside their country are occasionally referred to as 'climate refugees' (Berchin et al., 2017). However, a limited number of studies regarding the relationship between climate change and human population displacement have been conducted, as this discourse is sometimes even considered controversial due to a lack of empirical studies (Mortreux and Barnett, 2009; Lilleør and den Broeck, 2011). Several sociological studies conclude that displaced people are subject to physical, economic, and social exclusion (Cernea, 2005), and are forced to abandon their usual ways of life (Berchin et al., 2017) and customs, with the vulnerability and exposure also depending on wealth and education. However, due to numerous complexities, the indirectly exposed population is beyond the scope of this study.

The SLR was confirmed to be a very significant factor for people displacement in all cases in this study. The population displacement numbers were three times higher under the RCP2.6+storm surge model, compared to the model with the storm surge alone. Consequently, the directly affected population numbers were 1.8 times higher in the RCP8.5 model than in the RCP2.6 model. In addition, the biggest difference was observed under the eastern wind. The difference in the number of the directly affected population between the no SLR model and that of the RCP8.5+storm surge differed by ∼50 times (**Figure 13A**). This could be explained by the very scarcely populated eastern coast of the island. Meanwhile, when comparing the selected locations, the difference in the displaced population numbers differed by approximately 1.8 times or more (i.e., close to the island average). The sharpest difference was spotted in the more populated locations #6 (4.4 times) and #5 (2.5 times). In contrast, another urbanized area (location #2) exhibited the smallest increase among all the observed locations (1.6 times, **Figure 13B**). This can be explained by the differences in tendencies to inhabit coastal areas.

## CONCLUSIONS

This study presents an impact assessment of coastal inundation by the SLR and storm surge on Viti Levu Island of Fiji. A numerical method was developed for computing the inundation area by the SLR and storm surge. Based on the analysis, the storm surge significantly increased the inundation area (hazard intensity) and the related affected population (exposure) depends on the topography and bathymetry.

The effects of the western wind direction equipped with the SLR effect on the western coast appeared to be the most disastrous due to the topographic and bathymetric characteristics of the island. Furthermore, the effect of the storm surge alone was limited, inundating 17.9 $km^2$ (or 0.17%) of the island territory, whereas the compound effect under the RCP8.5 scenario resulted in 4.7 times higher inundation values for the future climate condition. A narrow and shallow bay with a flat land area had the largest impact on the storm surge inundation. In conclusion, we found that the SLR accelerated the inundation of the island compared to the present climate situation. While the storm surge caused by extreme events is projected to decrease in future climate conditions, the sea level is expected to rise continuously with time. The most potentially vulnerable parts of the island are the western urbanized areas. The settlements on the western side are subjected to the highest storm surges with the largest inundated areas, while the settlements in the south are estimated to experience smaller scales of inundation. The results of the displaced people in the south are not negligible, as it is the most densely populated area on the island. While the inundated areas are estimated to pose a direct threat to a relatively small number of the island population (5,429), Viti Levu Island, and Fiji by extension can still be categorized as vulnerable to extreme events due to the importance of the coastal areas to the country's economy, especially if the SLR intensifies in the future. In contrast, the SLR plays an important role in the displacement, as the estimated directly affected population numbers differ five times between the SLR under RCP8.5 and that of the storm surge only. In summary, this study concludes that depending on the future scenario, the biggest island of Fiji may be vulnerable to the effects of climate change, and understanding the compound effects of SLR and storm surge is necessary for adaptation planning.

For future studies, it is important to include the characteristics of TC wind fields, tracks, and other parameters, although we considered the homogeneous extreme wind speeds blowing over the island. This study used the 1/100 years extreme wind fields based on the d4PDF ensemble dataset. The projection of the extremes by GCMs has a large uncertainty. Further analysis will be required using CMIP6 or other high-resolution projections. A limitation of the proposed model for vulnerability analysis is the use of interpolated data from a coarse 1 km resolution to 100 m scale of the population density data. The precise population data can improve the vulnerability analysis and related displacement estimations in coastal areas. In addition, this model did not consider human behavior when assessing the potentially displaced population, therefore a conservative discourse was followed, in which only people living in the potentially submerged areas are considered to be directly affected. Future studies may need to conduct more detailed research regarding the coastal morphology change due to SLR and storm surge inundation, particularly for smaller low-lying islands.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

AS: numerical simulation, validation, analysis of the results, preparation of the manuscript, and revisions. NM: supervising, coding of model, revisions, methodology, and the final editing. NF: SWE storm surge model stability and figures related to inundation. TS: input data for the storm surge model and the revision. TM: consultation regarding the coding and visualization of figures. All authors contributed to the article and approved the submitted version.

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# Communication Structures and Decision Making Cues and Criteria to Support Effective Drought Warning in Central Malawi

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Early warning systems trigger early action and enable better disaster preparedness. People-centered dissemination and communication are pivotal for the effective uptake of early warnings. Current research predominantly focuses on sudden-onset hazards, such as floods, ignoring considerable differences with slow-onset hazards, such as droughts. We identify the essential factors contributing to effective drought dissemination and communication using the people-centered approach advocated in the WMOs Multi-Hazard Early Warning System Framework (MHEWS). We use semi-structured interviews with key stakeholders and focus group discussions with small-scale farmers in the Mangochi and Salima Districts of Malawi. We show that the timely release of seasonal forecast, the tailoring of the drought warning content (and its timing) to agricultural decision making, and the provision of several dissemination channels enhance trust and improve uptake of drought warning information by farmers. Our analysis demonstrates that farmers seek, prepare, and respond to drought warning information when it is provided as advice on agricultural practices, rather than as weather-related information. The information was found to be useful where it offers advice on the criteria and environmental cues that farmers can use to inform their decisions in a timely manner. Based on our findings, we propose that by focusing on enhancing trust, improving information uptake and financial sustainability as key metrics, the MHEWS can be adapted for use in monitoring the effectiveness of early warning systems.

**Keywords: Malawi, people centered design, effectiveness, communication and dissemination, drought warning, extreme events forecasting, developing countries**

## INTRODUCTION

The intensification of climate-related disasters and their catastrophic impacts are increasingly affecting the most vulnerable populations (UN, 2019). To reduce the impacts disasters have, approaches are shifting from humanitarian response-driven strategies toward preparedness and resilience-building with local communities as part of Disaster Risk Reduction (DRR)

(Staal, 2015; UNDRR, 2015; Hilhorst, 2018), with an emphasis on early warning systems (EWS). The 7th global target of the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015) calls for substantial improvements in multi-hazard early warning systems. Dissemination and communication of warning information is a key and challenging aspect of such early warnings systems, and need to be developed effectively to help reduce the harm caused by extreme weather events (Taylor et al., 2018). Ultimately, the effectiveness of EWS depends on whether warnings trigger the taking of early preventative action by end-users (Rai et al., 2020).

To facilitate the development of warnings that are actionable, a people-centered paradigm has been promoted. The essential elements of this paradigm—community engagement, integration of local perceptions and information tailored to those at risk—are recognized to enhance trust in the warning information and increase its uptake (WMO, 2015, 2018). The MHEWS framework (WMO, 2018) has been developed by the WMO from the Sendai framework and provides guidelines on the development of an effective people-centered approach to communication and dissemination of early warning information. Aligned with the MHEWS, emerging approaches—such as impact-based forecasting and the use of adapted and local communication channels and services—have helped transform hazard-only forecast data into useful information for those at risk by incorporating peoples' perception of risks and needs and improving local understanding of a hazard's potential impact (Sivakumar, 2006; Luther et al., 2017; Taylor et al., 2018; WMO, 2018). Recent examples from Kenya and Zimbabwe—such as the development of local media (e.g., a local community radio), using local languages in communication and extension services, and integrating local knowledge—show that such approaches improve the contextualization of information, increase the sense of ownership in the messages delivered, and enhance trust, and thus uptake, of warning information (Sivakumar, 2006; Pulwarty and Sivakumar, 2014; Andersson et al., 2019). EWS user needs and their perception of risks are context-specific elements that must be considered to provide enough evidence of a threat and prompt early actions by those at risk (Choo, 2009; Parker et al., 2009; Pulwarty and Sivakumar, 2014). Context relevant social and environmental cues and criteria also closely relate to agro-climatic indices, measures of an aspect of the climate that has specific agricultural significance, as Mittal et al. (2020) (this issue, submitted) defined for Malawi. Environmental cues are environmental indicators that exhibit the hazard, and social cues relate to indicators present in the social environment of the user (Choo, 2009).

Current early warning systems have, however, mainly concentrated on hazards associated with immediate impacts, such as floods, earthquakes, and hurricanes, and less on slowly developing hazards such as droughts. For the latter, the development of early warning processes is challenging as drought definitions and perceptions vary from place to place (Monacelli et al., 2005). Drought is a hazard that has been characterized as a natural long-term phenomenon with cumulative impacts (Pulwarty and Sivakumar, 2014), initiated by a prolonged deficiency in precipitation (Villagrán de León et al., 2013; Pulwarty and Sivakumar, 2014). As a result of the deficient precipitation, a cascade of impacts on the surrounding environment and diverse societal and economic sectors can ensue; this makes droughts a context-specific hazard that is difficult to identify (Wilhite, 2000; Monacelli et al., 2005; Pulwarty and Sivakumar, 2014). As a result, drought risk management focuses on crisis-driven strategies rather than proactive approaches (Pulwarty and Sivakumar, 2014). Across Africa droughts represent one of the major life-threatening hazards with significant impacts on the agricultural sector (IPCC, 2019), warranting the need to develop effective systems to improve the uptake of drought warning information (Lumbroso et al., 2016). In this context, user-centric climate services have been promoted as a way to enhance drought resilience in agriculture (Villagrán de León et al., 2013; Roudier et al., 2014; Mungai, 2017; Mahon et al., 2019).

Climate services are primarily developed through National Hydrological and Meteorological Services (NHMS) (Sivakumar, 2006; Mahon et al., 2019) and help transform weather information into relevant warnings for end-users. Lack of funds, relevant skills, institutional and human capacities, and policy support are recognized as barriers to the development of such services (Sivakumar, 2006; Mahon et al., 2019). In addition, feedback from end-users though which the evaluation of EWS can improve its design, development and implementation, are lacking (Sivakumar, 2006). Climate information tends to be developed following a value chain approach, where weather data generated by climatic centers are (re)packaged through various actors and then fed to end-users without engaging them in the development process, causing information to lack of contextualization and thus limiting the uptake on climate information by communities (Vogel et al., 2019).

To contribute to drought preparedness strategies through the provision of actionable drought early warnings, this paper explores the key factors that contribute to effective drought warning communication and dissemination. Our study in Malawi reflects on these factors within the context of the people-centered-approach advocated in the MHEWS. It has been recognized that the implementation of the MHEWS in Malawi has been constrained by issues such as the late release of information by the government, the lack of accessibility (in terms of reception of information by end-users) and reliability of the information, as well as the lack of understanding of the information provided (Venäläinen et al., 2015; Šakić Trogrlić and van den Homberg, 2018). The development of a tailor-made drought warning communication and dissemination process is recognized as a major challenge (Government of Malawi, 2018) that needs to be addressed to encourage the uptake of drought warning information.

This paper first provides background information on the drought warning system in central Malawi, followed by a description of the methods used for data collection and analysis. The results section outlines the key factors that were found to contribute to effective drought warning communication and dissemination through an analysis of; (i) how drought warnings have been generated to meet farmers' needs; (ii) how they have been disseminated within the governmental and humanitarian sector actors and communicated to farmers; (iii) how farmers respond to the warning; and, (iv) how, why and if drought warnings are effective from a farmer's perspective. Finally, the discussion and conclusion section position these factors within the context of MHEWS framework, illustrating how the established process is aligned to the framework, as well as reflecting on how the framework can be built on and adapted for use in monitoring the effectiveness of early warning systems.

## STUDY AREA

Malawi has a sub-tropical climate comprising of a wet season from November until April, and a dry season from May to October. Precipitation is highly variable due to the topography of the country (Bucherie, 2019). Furthermore, the climate of Malawi is correlated to the ENSO effect (Šakić Trogrlić and van den Homberg, 2018). Malawi is listed as one of the poorest countries and most vulnerable to climate change (UNDP, n.d.). It is a country prone to disasters, where droughts constitute one of the major natural hazards causing food insecurity, which has led to the high involvement of humanitarian and non-governmental organizations (NGOs) (Šakić Trogrlić and van den Homberg, 2018). After endorsing the Hyogo Framework, Malawi has shifted its approach to disaster risk reduction to align with the Sendai Framework and focus on preparedness and resilience building with local communities to cope with food insecurity (Government of Malawi, 2018).

Although there is scarce literature available on the drought warning communication and dissemination process in Malawi (see Šakić Trogrlić and van den Homberg, 2018; Streefkerk, 2020), recent studies reveal that there is a mostly top down system in place for the dissemination of drought warning information (Streefkerk, 2020) from the national level to local level, though most authorities involved in the design of the drought warning remains at the national level. The drought early warning system consists of the provision of a seasonal forecast, first agreed upon at the Southern African Regional Climate Outlook Forum (SARCOF), and by the Department of Climate Change and Meteorological Services (DCCMS) in Malawi. SARCOF leads a regional climate outlook prediction process embraced by the Southern African Development Community (SADC). This community is composed of sixteen countries, including Malawi (WMO, n.d.). The seasonal forecast showing the rainfall predictions for the season is then downscaled to national level and disseminated by DCCMS through mainly the agricultural and disaster management departments to the local communities. Various means of dissemination such as organized gatherings, radio program, text messages, and word of mouth are used to ensure that a maximum number of farmers are reached. Nevertheless, the lack of staff capacity and the limited access by the population to mobile phones, radio sets, or internet limits the accessibility to drought warning information.

## METHODS

**Figure 1** provides an overview of our research methodology. We use the MHEWS framework (WMO, 2018) to structure our analysis. This was developed from the Sendai framework and provides guidelines on the development of effective communication and dissemination processes through a people-centered approach. The warning communication and dissemination element is one of the four elements of people-centered early warning systems and aims at ensuring that those at risk receive warning information in an understandable and useful way. The other three elements are the knowledge of disaster risk; the detection, monitoring, analysis and forecasting of the hazards and possible consequences; and, the preparedness and response capabilities (WMO, 2018). Within the warning communication and dissemination element, the guidelines in the framework (**Appendix 1**) are clustered in three dimensions: (i) the organizational set-up; (ii) the communication systems and equipment; and (iii) the effective communication of impact–based early warnings to prompt early actions by those at risk. As the MHEWS provides no clear distinction between communication and dissemination, for the purpose of this paper, we use the characteristics outlined by the EU IPR Helpdesk (Scherer et al., 2018) and adapt them to our context. Dissemination is defined as the means used to spread the warning information within official governmental and humanitarian channels to reach farmers, while communication relates to the strategy and measures in place to format the message in the most adapted way for farmers (end-users here). Although our focus is on the warning communication and dissemination element of EWS, this cannot be completely separated from the warning generation and the action taken by farmers on reception of drought warnings, which belong, respectively to the monitoring and warning elements, and to the response capability element of the MHEWS framework.

### Data Collection

The channels and the actors identified to be relevant to the dissemination and communication are based on Streefkerk (2020). To understand how drought warnings are communicated, focus group discussions (FGD) were carried out with five groups of small-scale farmers, two in the Salima district and three in the Mangochi district (refer to **Table 1**) (**Figure 2**). To build on Streefkerk (2020), we chose the same districts and the same group of farmers. Group sizes varied between 5 and 11 people, among which half-represented women. We carried out 25 semi-structured Key Informer Interviews (KII) with stakeholders including governmental bodies, UN agencies, and NGOs (i.e., CADECOM, Malawi Red Cross, NASFAM, Malawi Lake Basin Programme, Oxfam) in Lilongwe, Mangochi, and Salima districts. The selection of NGOs was guided by those that were identified by farmers as relevant to the communication and dissemination process.

#### Key Informer Interviews (KII)

KII were carried out either by a phone call or in person, and in English (with a translator where required) using an open-ended questionnaire (**Appendix 2**). Stakeholders were contacted via e-mail, and questionnaires were sent upon request prior to the meeting. Prior to the start of any interview, permission to record the interview was requested. Each interview lasted for around

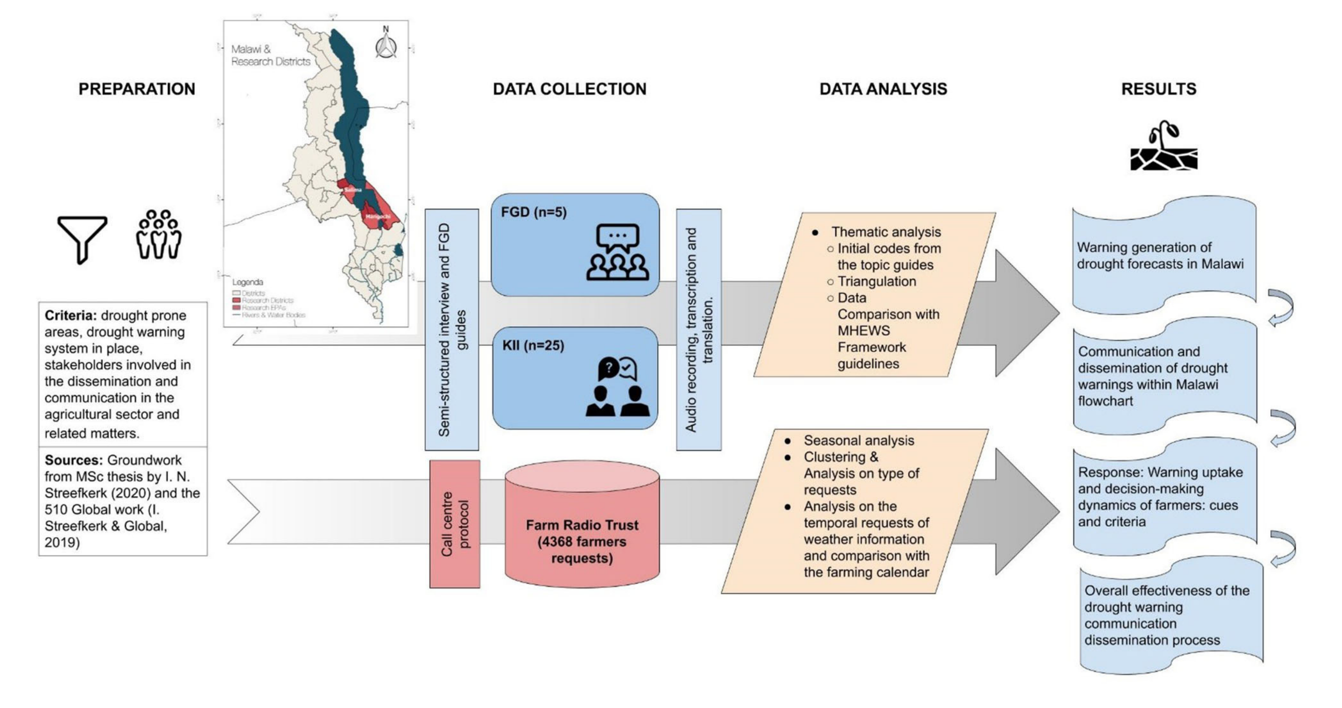


**FIGURE 1 |** Research methodology overview.

**TABLE 1 |** List of stakeholders that were either interviewed or part of the focus group discussions.

| Level | Stakeholders |
|---|---|
| National level | Farm Radio Trust<br>WFP<br>UNDP |
| District level | DoDMA District Desk Office–Salima<br>District Agricultural Development Office (DADO)—Salima<br>DoDMA District Desk Office—Mangochi<br>District Agricultural Development Office (DADO)—Mangochi<br>Meteorological District Office Mangochi |
| Area | Agriculture extension officer Maiwa (3 officers, interviewed in a group)<br>Agriculture extension officer Mbwadzulu (3 officers, interviewed in a group)<br>Agriculture extension officer Nankumba (2 officers, interviewed in a group) |
| Local | NGOs: Oxfam, CADECOM, Malawi Lake Basin, NASFAM, Malawi Red Cross (3 Members) |
| Local | Informal Cape Maclear (2) |
| Local- FGD | Farmers Salima: Location 1 and 2: Khombedza<br>Farmers Mangochi: Maiwa, Mbwadzulu, and Nankumba |

30–40 min. The information gathered through KII included state of current drought early warning systems, the information flow between different institutions and the communication of drought to other institutions, or end-users. At the district level, more in-depth questions on the process of contextualization of weather forecast at the district level and the use of climate information by farmers were asked. Interviews with NGOs and UN agencies focused on obtaining insight into their involvement in the dissemination and communication of drought warning in Malawi, as well as the uptake of the information by their own organizations to inform early actions. Discussion also included information on the organization structures and communication processes, and uptake of climate information by farmers.

## Focus Group Discussions

The consolidated criteria for reporting of qualitative research (COREQ) were used to guide the preparation of FGD strategy and reflect on the data quality (Tong et al., 2007). As such the following criteria were considered:

- The name and occupation of the facilitator (s) and translator;
- Background information on the translator such as the gender and experience;
- The number of participants, demographic data: names, the occupation, gender;
- Time of the day, the duration of the FGD;
- Observations on the communication dynamics;
- Observation on the quality of transcriptions.

Focus group discussions with farmers were carried out in Chichewa, the local language, and then translated and transcribed for analysis. In the first part of each session, a farming calendar was constructed with farmers and the discussions was held around the type and sources of information used for their decision-making process, under normal conditions. The second part of the session consisted of understanding how drought was perceived and understood by farmers, followed

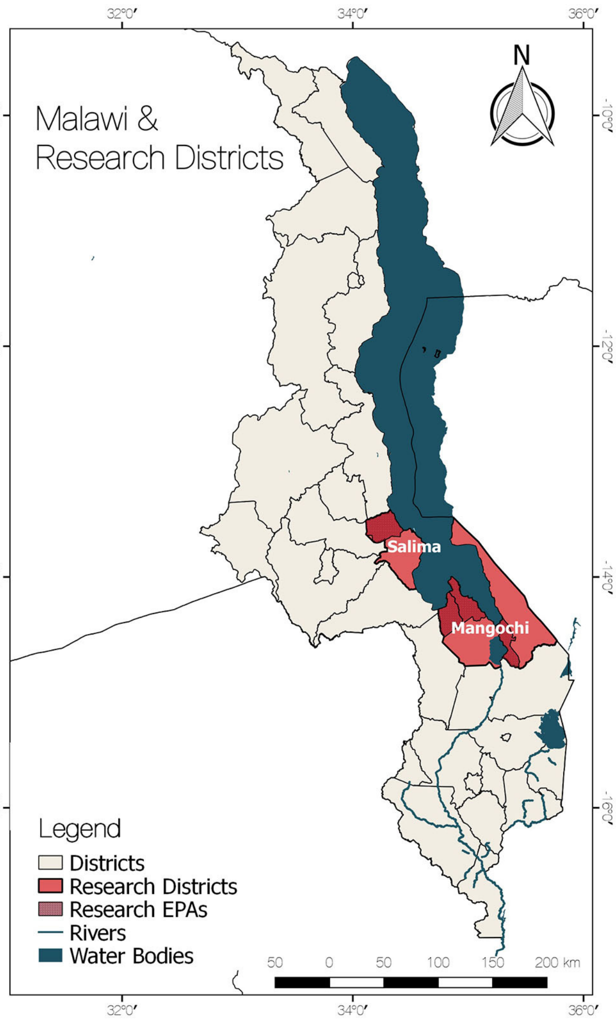


**FIGURE 2 |** Map of Malawi and districts considered in this research.

by how their farm decisions were influenced by drought warnings from different sources (**Figure 3**). The last part of the session consisted of a discussion on issues encountered and recommendations to improve the current early warning dissemination and communication (**Appendix 2**). Further information was gathered from the Farm Radio Trust (FRT) database collecting all farmers' questions. FRT categorizes these requests by Crop type/ Regional/District/Gender/Categories and Query. For this study, we focused on the tab "Categories" as it provides more details in terms of the nature of the request. Examples of categories are: Organic Manure, Pest and Disease Control, Livestock related, Weather information, Soil and Water conservation, Irrigation etc. Information from FRT was obtained for the period from November 2018 to November 2019, with the exception of the months of March and June 2019, where the records were not available.

One of the limitations of the study is that it depends predominantly on participant recall and perception, rather than on direct observations of EWS dissemination, communication, and uptake. We lack existing baseline data for pre- and post-EWS intervention comparison or the capacity for procedural monitoring, this is a point that we return to in the discussion, with regards to recommendations for EWS evaluation.

## Data Analysis

Our analysis of the drought warning generation, and its dissemination and communication is based on the qualitative method of data coding (Saldaña, 2016). In the context of a qualitative inquiry, a code is most often a word or short phrase that symbolically assigns a "summative, salient, essence-capturing, and/or evocative attribute to language-based or visual data" (Saldaña, 2016). By looking for patterns, similarities and/or relationships of what people say on a topic, information is clustered manually using Excel into a main code. Each code is composed of the various stakeholders' perspectives on that particular theme. The information is triangulated by checking it against the information provided by KII and validated. Findings were then compared with the MHEWS conceptual framework guidelines on the effectiveness of the warning dissemination and communication processes (**Appendix 1**) by looking if elements listed in the framework could be found in the system in place in Malawi.

Regarding the use of warning information, the MHEWS framework states that the impact-based warning needs to prompt action by the target group, but it does not provide more information regarding how to assess this element. Therefore, to analyze the use of drought warning information in farm decisions, the protocol developed by Doksæter Sivle and Kolstø (2016) was adapted for this study. This protocol was designed to analyze the use of weather information by the public in Norway by looking at the factors that affect the amount of information used, the type of information used, the dynamic that people follow to carry out different activities, and the evaluation of uncertainty. This analysis was based on identifying the criteria and associated indicators that people use to make their decision paths for various activities. In this study, the data analysis followed a similar protocol. Our analysis of the focus group discussions focused on (i) identifying the farming activities carried out under normal and drought conditions, (ii) determining the conditions (criteria) outlined by farmers that needed to be met to carry out each activity, and (iii) identifying the indicators (cues) that farmers used to decide whether those conditions are met. The source and type of information received is the same across the farmer groups, except for the presence and frequency of support provided by NGOs to different groups. Also, the extension officers in both districts have been trained through the Participatory Integrated Climate Services for Agriculture (PICSA) program (Dorward et al., 2015) implying that the information is communicated at consistent levels of comprehensibility to farmers in both districts. The program trains extension officers to interpret and understand the climate information and predictions to help them better explain the seasonal forecast to farmers. Regarding data from the FRT, weather related requests from the database were

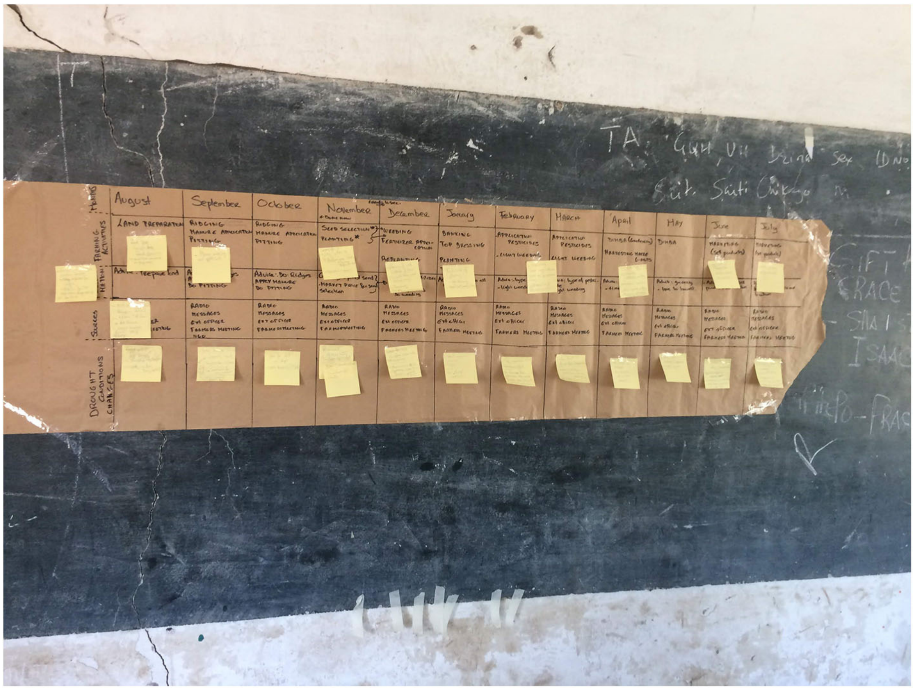

**FIGURE 3 |** The farming calendar that was built during focus group discussions with farmers. First row: Farming activities, Second row: Information received, Third row: Sources of information, Last row: Changes when there are drought conditions.

compiled and plotted to give a chronological view of the amount of requests during the farm season. This permitted to analyze whether, and if so when the weather information is more relevant to farmers.

Through analysis of the data from the FGDs and combining with the Farm Radio Trust data on the type of information requested by farmers, it was possible to assess whether and how the warning information was received, understood, and used by farmers. This improved our understanding of farmers' response to drought warnings.

## RESULTS

### Generation of Drought Warning

In Malawi, drought warnings targeting farmers are only developed through the seasonal forecast process. The process usually starts upon the release of the seasonal forecast by the Department of Climate Change and Meteorological Services (DCCMS). For the past 2 years, the seasonal forecast has been downscaled to the district level, and even to the area-specific administrative level for certain districts, before it is disseminated to various actors, as expressed by 15 out of 25 KII. At the National Content Development Committee (NCDC), 5 out of 25 KII explained that the data are then discussed among the various stakeholders (DAES, NASFAM, FRT, WFP etc.), and advisories for different districts, as well as mitigation measures to cope with different hazards, are formulated for farmers.

The seasonal forecast is provided at the district level in the form of a poster (**Figure 4**), in both English and local language "Chichewa." Tweleve out of twenty-five KII explained that the poster provides an estimate of the potential rainfall in the district, characterized by statements such as "above, below, or normal rainfall." When a statement "below normal" is issued, DCCMS associates it with the expected occurrence of dry spells. When a dry spell is expected to be prolonged during the rainy season for a period of 2–3 weeks and above, the message delivered to communities includes that potential drought conditions may occur, and, as such, drought mitigation measures are recommended *"When we disseminate to communities, we don't go deeper: we only say normal, below or above normal and then add the implications. If you have below normal: practice on conservation agriculture and technologies that encourage high moisture in the soil, early maturity seeds etc." (Governmental authorities).*

During an extreme year, these messages are reported to be issued more frequently. They consist of a warning that drought is coming and conservation agriculture measures should be taken. These types of drought warnings have been characterized by the providers as impact-based messages. *"For example we say if dry spells continue these are the impacts on the crops and this is what you should do" (Governmental authority).* However, based on the focus group discussions, all farmers describe the message as being solely an advice providing guidance on the most suitable farming practices for the seasonal forecast provided. Additional to the seasonal forecast, 10-day agro-meteorological bulletin, weekly

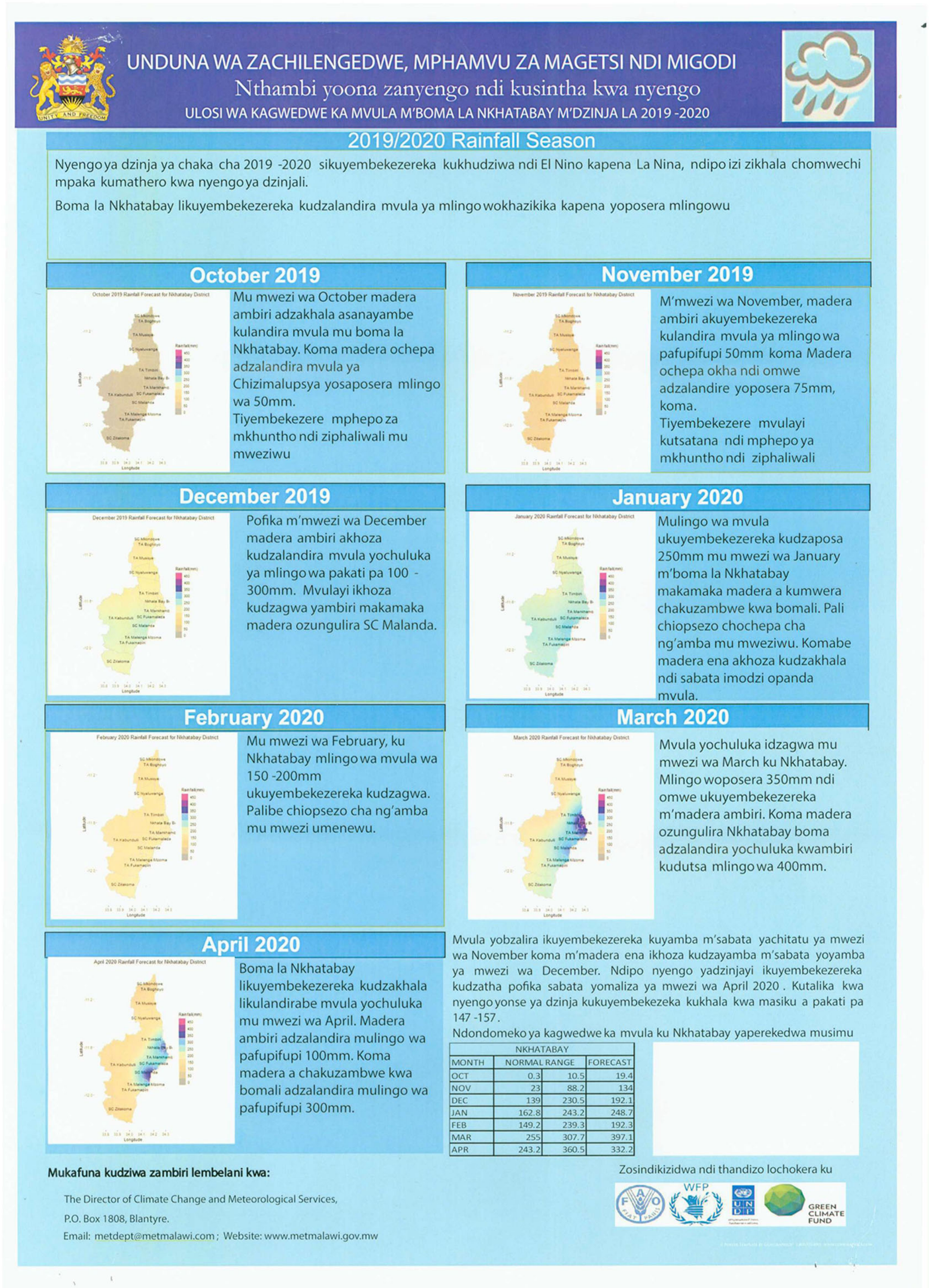


**FIGURE 4 |** Seasonal forecast for the Salima District 2019–2020.

weather statements, 5-day forecasts, and daily forecasts providing updates on rainfall and wind are disseminated through various channels, including radio, text-messages, newspaper, e-mails, WhatsApp groups, and on the DCCMS website. Other sources of dissemination include community gatherings, the use of loud-hailer via car or van around the village.

## The Dissemination and Communication Strategy

The process of dissemination of drought information is conceptualized in **Figure 5** and has been described by 19 out of 25 KII. Once the warning information has been generated, it is transmitted to the District Agricultural Development Office (DADO), the District Civil Protection Committee (DCPC), and district meteorological offices. Stakeholders from these organizations then gather in a district coordination meeting to adapt the climate information to their districts, and agree upon the strategy to disseminate information at the local level. National level structures also provide backstopping support to these dissemination strategy meetings at district level. We identified two channels through which information is disseminated: the agricultural advisory channel and the disaster risk management advisory channel (**Figure 5**). In the agricultural advisory channel, information is passed on to the agricultural extension officers, who then pass it on to lead farmers and communities. In the disaster risk management advisory branch, DCPC has the role of disseminating information to the Area Civil Protection Committee (ACPC) and Village Civil Protection Committee (VCPC), which then provide the information to communities. As one government stakeholder explains; *"(...) after that we communicate with communities through the structures from district level up to community level. [There are] civil protection committees responsible for all disaster related issues (...). At TA level, there is an area civil community and at village level a community civil committee. Those committees: disseminate the climate information and any weather related information. At TA and village they disseminate what the district gives. But then it depends, sometimes they meet and plan together as a community and combine the guidance given by district and adapt it with communities."*

In Malawi, humanitarian agencies are extensively involved in disaster response related matters and in the dissemination of information. As described by 16 out of 25 KII, NGOs are involved mainly in the implementation of plans at the area and local administrative levels. Their role varies depending on the aim of each NGO. In contrast, UN agencies like UNDP and WFP are more directly involved in the production of climate information at national and district level, rather than at area and local level (apart from supporting the local disseminators, where necessary). For drought preparedness and warning communication, the main support provided by humanitarian agencies and NGOs is to release funds that these organization have received from donors to support food security measures. These funds help the drought warning development through enabling stakeholders meetings, the production of seasonal forecast posters, capacity building on the understanding and interpreting seasonal forecast, and increased access to information by reaching areas where extension officers cannot go. *"In DRR, we work with local government structures: district counsels (with CPC), ACPC and VCPC). We provide support to those structures through capacity building." (NGO). "We provide financial support to contingency plans for certain districts, training of committees and governmental staff." (NGO).*

Our finding from the FGD show that the main channels used for the communication of drought warnings were in order of usage frequency community gatherings, extension officers, NGOs, certain radio programmes, and text-messages. Of these, in all focus group discussions, farmers preferred as channels, extension officers, and radio. Extension officers facilitate communication amongst farmers during community gatherings, while the Farm Trust Radio (and other local radio broadcasters) has a greater reach to farmers and communities. The contribution of Farm Trust Radio is greatly appreciated, as shared during FGD: *"We want any communication about weather changes to be through radio [as] it's very easy for us to know the information"* and "*the best mode of communication is the radio because it [is] easy and faster.*" NGOs were found to coordinate with extension officers and use similar channels to help spread warning information. However, the presence of NGOs is sporadic, as lead farmers have to rely on other channels more readily available. *"NGOs come and go, they appear and disappear (...) NGOs don't have EPA on the ground, they use DADO extension officers and they only support when they have money. The dissemination of information is mainly done by extension officers, NGOs are sometimes part of it but not systematically." (Governmental authority).* As a whole, it was found that a clear communication strategy to the farmers does not exist. As highlighted in FGDs, climate information is disseminated by multiple means to ensure maximum accessibility. However, the type of information, its provider and its timing are not defined *a-priori* as pointed out by a humanitarian agency: *"The dissemination is the main challenge institutions need to work with, it needs to be clear with the different procedures, need to come up with a strategy to disseminate those information. There is no dissemination in place for drought, it is done but there is a need for a proper strategy, rather than people talking about it from place to place."*

Furthermore, based on discussions with extension officers, the preference of farmers for extension services has increased since the introduction of Participatory Scenario Planning (PSP) and the Participatory Integrated Climate Services for Agriculture (PICSA) training and provision of participatory tools. "*The training permits farmers to understand how weather works and make decisions with the current forecast. (..) for the training, lead farmers were very happy and understand better rainfall patterns. "(Governmental authority).* The PICSA training under WFP is relatively recent in the Mangochi and Salima districts (last 2 years) and 11 out of 25 KII (8 being extension officers) expressed that it has increased the ability of extension officers—and hence also farmers—to get a better understanding of how weather information relates to farming activities. In addition, through the participatory tools provided, advice on farming practices that is adapted to the individual can be generated. These services are primarily provided during community gatherings and are the main strategy in place to contextualize information and engage communities in the development of the drought early warning. Based on feedback obtained from extension officers and farmers, the output of these services is promising as it provides understandable advice that has increased farmers trust, favoring the uptake of drought warning information. *"There is a difference*

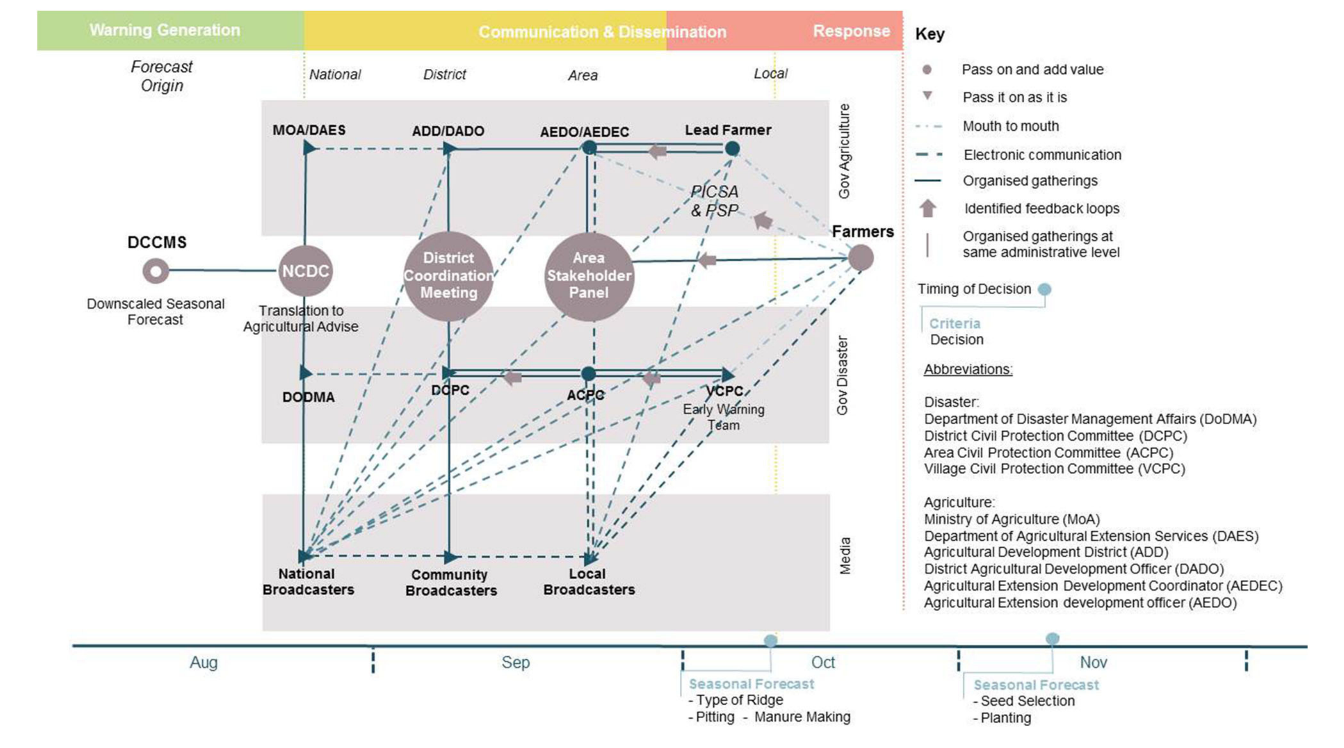


**FIGURE 5 |** Flowchart representing the organizational set-up and the dissemination and communication processes in place for drought warnings.

*since the PICSA training. We used to transmit the information as it is and it was based on assumption. Now there is more information, and there is a higher understanding. Now farmers are better trained but not yet they are able to adapt to the weather forecast. They use the advice that is being given." (Governmental authority).*

Feedback mechanisms were found at the Area-Local administrative level (**Figure 5**) and mentioned by 4 KII involved at these administrative levels. For farmers the first contact with mandated authorities is during community gatherings with the extension officers or VCPC members. At the area stakeholder panel and village agriculture committee, farmers are also present and can give feedback. As explained by governmental officials *"[the area stakeholder panel] is a forum where all agricultural staff and small-scale farmers and medium farmers, commercial farmers and NGOs representatives collaborate and talk to each other"* and "*VCPC go to communities with issues to discuss.*" Farm Radio Trust has also developed a call center aimed mainly at supporting farmers by answering their requests and getting their feedback. No information was provided on whether these feedbacks are discussed during the National Warning Content Committee.

## Warning Uptake and Decision-Making Dynamics

Farm Radio Trust data showed that 3,090 out of 3,292 (94%) of requests were related to farmers seeking advice on farming practices, and only 202 (6%) to weather information. Weather information consists of requests on weather updates and rainfall forecast. Despite the small number of requests for weather information, the trend over 2018–2019 shows higher demand for weather-related information between November and May, with the highest peak in February (**Figure 6**). As outlined in the farming calendar (**Table 2**), this coincides with the period where most farming activities occur. From June until August crops are mainly sold and therefore weather conditions are less relevant. February follows the main planting season that ends in January making weather conditions critical to crop development (**Table 2**). This suggests farmers seek weather-related information when it is most relevant to their activities, demonstrating the importance of timeliness of information.

**Table 2** shows the decision-making processes described by FGDs. Highlighted in gray are farming activities associated with measures taken to mitigate drought impacts. Criteria correspond to the conditions necessary to take the decision to carry out a farming activity. Cues correspond to the environmental and social indicators and to the advices provided with the seasonal forecast, that are used to inform if criteria are met (Doksæter Sivle and Kolstø, 2016).

Overall, the decision-making process follows the cropping cycle, with decisions being made on either what activity should be done, or when to carry out an activity. Decisions made were related due to the interdependence of farming activities. For example, farmers replant when the first-planted crops fail. Another criterion for replanting could be good soil health after harvesting, allowing for an additional crop. Decisions such as the type of ridging, seed selection, pitting, manure application, and dimba (gardening for personal food provision) are conservation

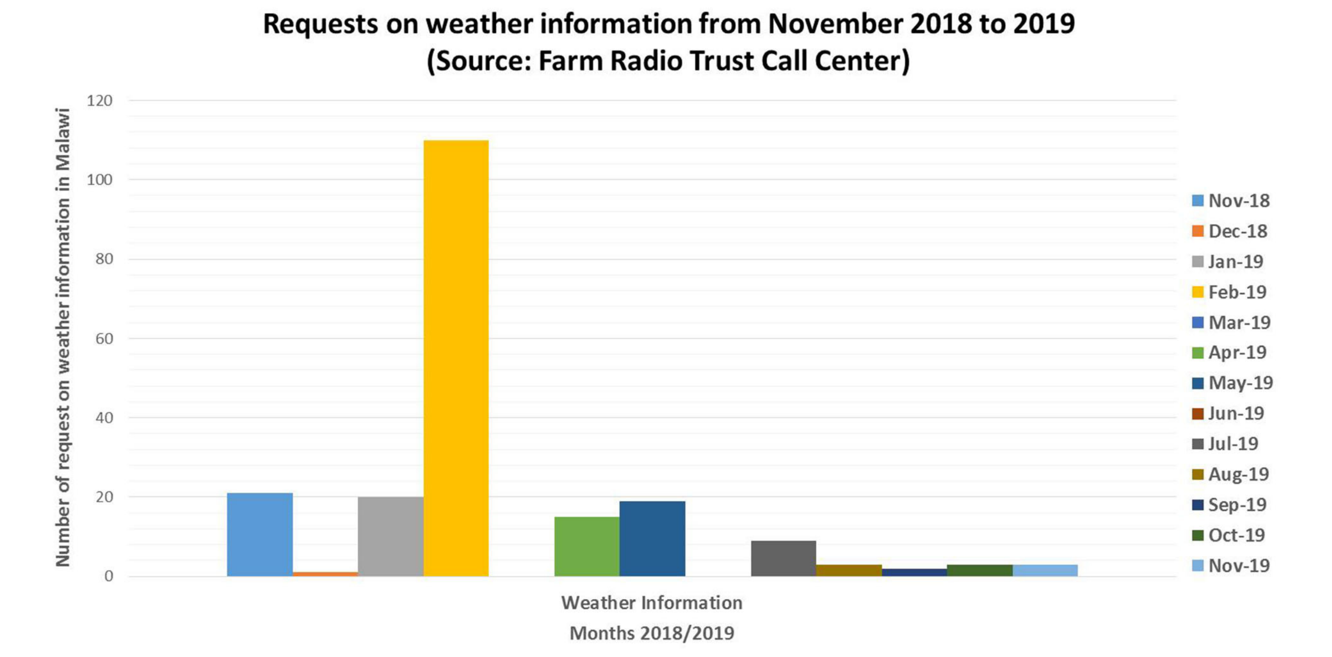


**FIGURE 6 |** Requests by farmers on weather information from November 2018 to 2019.

agriculture activities that are carried out when the amount of rainfall is forecasted to be below normal rainfall and a subsequent development of droughts is envisaged (criteria).

Criteria and cues were found to be very similar from one farmer group to another. To further analyze the decision-making dynamics, information from the different FGD were combined on the basis of the farming activity. This analysis permitted to distill how farmers respond to the information. The results from the farming calendars (**Table 2**) show that the decision making by farmers consists of two types of decision "what to do" and "when to do it" (**Table 2**), as explained previously. To decide upon how to carry out these activities farmers use various cues that come from either the guidance in the form of advisories or weather information based on local observations (environmental cues) (**Table 2**). To assess how the warning information, primarily in the form of advisories, is used we analyzed which sources of information were used for the decisions to carry out farm activities. To do this, we calculated the number of correlations between the types of decision (when/what) and the associated source of information (environmental cues/advice) used to take this decision. Results were plotted on **Figure 7**, and show a clear correlation between "What to do–Advice" and "When to do it–Environmental cues." Social cues were not mentioned by farmers. These results could be explained by the fact that farmers respond well to the guidance provided in comparison to the weather updates. According to farmers, the uptake of the weather updates is low because of a lack of access. This analysis thus demonstrates that farmers respond to drought warning information when it is provided as advice on agricultural practices, rather than weather-related information.

## DISCUSSION

The shift toward people-centered systems has been promoted as a key mechanism to enhance trust and improve uptake of warning information for the end-users to take appropriate disaster preparedness measures (Pulwarty and Sivakumar, 2014; WMO, 2015, 2018). Malawi has adopted this new approach in the development of its early warning communication and dissemination systems (Government of Malawi, 2018). Focusing on end users trust in, and uptake of, early warning information as key measures of success of this dissemination and communication, we identify four characteristics of effective people-centered EWS: (i) a sectoral system focusing on agriculture and farmers' needs, (ii) the provision of several dissemination channels, (iii) the provision of local dissemination services, and (iv) the timely provision of relevant information.

However, we also recognize that there is more work to be done in the monitoring and evaluation of EWS communication and dissemination. Here, we adopt trust and uptake as metrics of the effectiveness and rely heavily on stakeholder perceptions and recall as approaches for capturing these metrics. Efforts to better conceptualize the multidimensional nature of trust and action at the science-policy-practice interface (Stern and Coleman, 2014), can help to guide such efforts. Similarly the purposeful design of EWS implementation for evaluation, and the use of longitudinal and action-research methodologies that can directly observe, monitor and attribute changes in behavior associated with EWS, can help build a more robust evidence base around what works (Tall et al., 2018).

**TABLE 2 |** Example of decision-making dynamics for farmers in Mangochi.

| FGD | What/when | Farming activities | Criteria | Cues | Months |
|---|---|---|---|---|---|
| 3 | When | Land preparation | Dry conditions prevailing | Environmental cues: High heat (relative) | August |
| 3 | When | | | Environmental cues: Tree regeneration | August |
| 3 | When | | After ceremonial activities | Traditional: Always in August | August |
| 3 | What | Ridging | Normal weather predicted | Advice to carry out normal ridging | September/October |
| 3 | What | Ridging | Drought weather predicted | Advice to carry out box ridging | September/October |
| 3 | When | Ridging | Dry conditions prevailing | Environmental cues: High heat (relative) | September/October |
| 3 | When | Manure making | Drought weather predicted | Advice to carry out this farming activity | October |
| 3 | When | Manure application | Dry conditions prevailing | Environmental cues: Dust storm for signs of rainfall, high heat (relative) and tree regeneration | October |
| 3 | When | Pitting | Drought weather predicted | Advice to carry out this farming activity | September/October |
| 3 | When | Pitting | Dry conditions prevailing | Environmental cues: High heat (relative) | September/October |
| 3 | What | Seed selection | Weather prediction: Drought or normal | Advice on type of seeds | November/December |
| 3 | What | Seed selection | Best quality (grading) | Advice from extension officers or other media and personal observations | November/December |
| 3 | What | Seed selection | Market prices | Advice from extension officers or other media | November/December |
| 3 | When | Planting | Enough Rain (moist soil) | Environmental cues: High heat and Thunderstorms | November/December |
| 3 | When | Weeding | Presence of weeds | Environmental cues: Bad weeds | December |
| 3 | What | Fertilizer app | Type of crops planted and weather prediction | Advice on what fertilizer to use | December |
| 3 | When | Fertilizer app | Soil moist and after planting | Environmental cues: The soil is seen moist and not dry | December |
| 3 | What | Replanting | Weather forecast | Advice on what to replant | December/January |
| 3 | When | Replanting | Failure of seeds | Environmental cues | December/January |
| 3 | When | Replanting | Enough moisture content left | Advice on when to replant | December/January |
| 3 | When | Banking | After Planting and need for heavy rainfall | Advice on when to start banking (and how) | January |
| 3 | When | Top dressing | Soil moist and after planting | Environmental cues and advice on when to carry out top dressing | January |
| 3 | When | Thinning | N/A | N/A | January |
| 3 | What | Application pesticide | Type of pests present | Advice on what pesticide to apply | February/March |
| 3 | When | Application pesticide | Dry conditions prevailing | Environmental cues: No rainfall but need moist soil so during the dry spell 1–2 weeks | February/March |
| 3 | When | Light weeding | Presence of weeds | Environmental cues: After heavy rains | February/March |
| 3 | What | Dimba (gardening) | Drought weather predicted | Advice on what to plant for Dimba | April/May |
| 3 | When | Dimba (gardening) | Drought weather predicted | Advice on when to start Dimba | April/May |
| 3 | When | Harvesting | Dry conditions prevailing | Environmental cues: Dry and crops ready for harvesting | April |
| 3 | When/To whom | Marketing (selling products) | Market | Advice on when to start selling products, what they should keep for themselves and linking farmers with buyers | June/July |

*N/A means Not Available. Environmental cues are based on local knowledge from farmers. Advices are given by extension officers or other media based on the rainfall patterns from the seasonal forecast.*

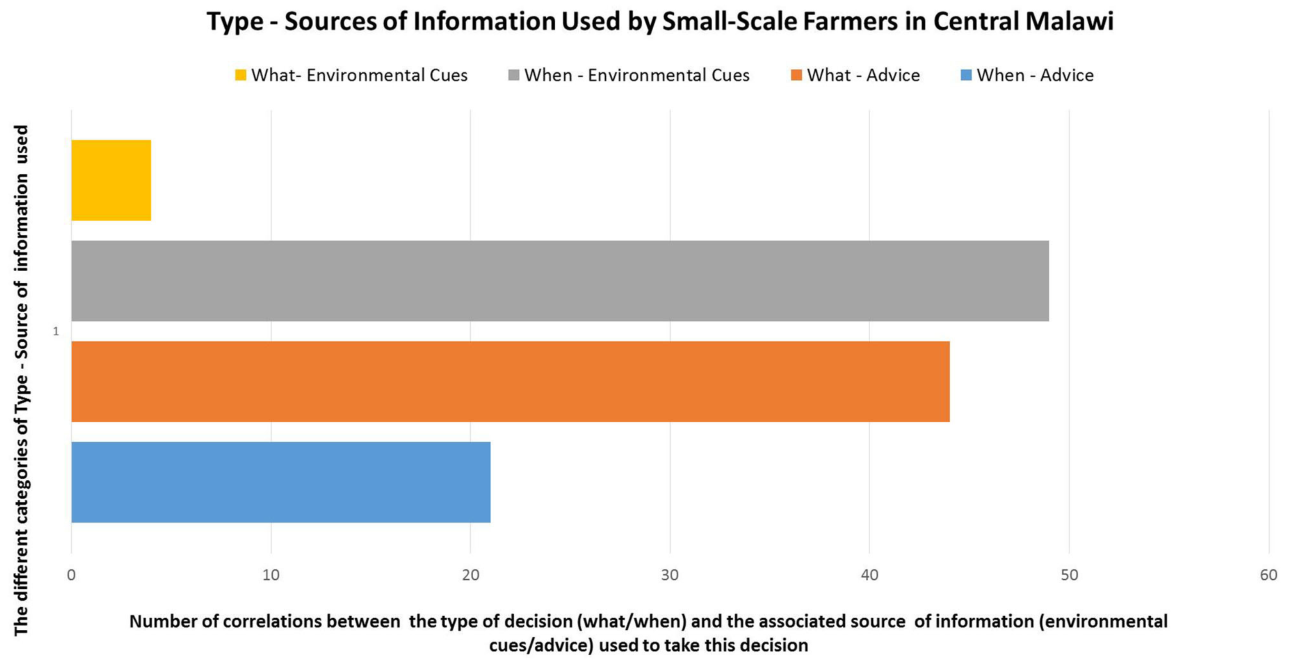


**FIGURE 7 |** The type and sources of information the most used for farming decisions.

## Sectoral System Focusing on Agriculture and Farmers' Needs

The drought warning dissemination and communication process was found to be, to a certain extent, tailored to farmers' needs through a sectoral system focused on agriculture. Indeed, based on the focus group discussions it was found that only information relating to drought mitigation measures were used and found relevant. The timing to carry out farming activities is based on farmers' own environmental indicators. The drought warning information is embedded within the climate information provided by DCCMS and disseminated upon the release of the seasonal forecast through a value chain approach in climate services, which is also found in other such processes in Africa (Sivakumar, 2006; Mahon et al., 2019; Vogel et al., 2019). The communication process covers a creation/conceptualization of the warning information to the district context and the dissemination strategy consists of transferring this information within the governmental and humanitarian channels. During this process, the warning information provided consists of an impact–based seasonal forecast downscaled to the district context and based on scientific knowledge. At the local level the communication process consists of the translation of those advisories by the district administrative level entities to communities to enable an understanding of what these advisories mean for their farming practices. During this process, a bridge between scientific and local knowledge and the integration of local perception on drought and risk is attempted to enable an understanding of the warning information and enhance an uptake on drought warnings.

In the MHEWS framework, the distinction between dissemination and communication is not explained (WMO, 2018) and the different functions expected to be accomplished under these two mechanisms are not elaborated. The form of engagement of end-users is mentioned to be key when developing a people-centered approach, as supported by (Steen, 2011), and we argue that observing procedural participation, as well as behavior change (Tall et al., 2018) of different stakeholder groups involved in communication and dissemination processes, can contribute to the evaluation of people-centered EWS approaches.

## Dissemination Channels, Accessibility, and Trust

The accessibility of information—which encompasses a consideration of the channels through which information is provided and whether or not end users have the means (technology, contact with extension officers, etc.) to receive information—is critical for effective EWS. However, if accessibility is to be adequately understood and evaluated, it is important that there is a focus on both the means of information provision and the ways in which these are accessed (or not accessed) by end users.

The MHEWS framework (WMO, 2018) emphasizes the need to develop multiple channels to reach as many people as possible. This may increase the likelihood that information is received, in one form or another, and help to add greater perceived credibility to that information, providing that the multiple channels offer information that is consistent (the opposite affect may be true if information is inconsistent). However, a simple counting of the number of information channels, does not pay adequate attention to questions of what information is being received, through which channels, and by whom.

A variety of channels were found to be operational in Malawi. However, not all provide messages that are specific to the geographic context and the farming activities and decision-making needs of the farmers. Our results suggest that this has a significant bearing on the extent to which farmers are able to utilize that information.

Moreover, end users place varying levels of trust in different information sources, both because of the extent to which the information is context specific (Molinari and Handmer, 2011) and because of their perceptions of the information generators and providers associated with it. In reality it may be difficult to distinguish between trust placed in the process of producing climate information (what Stern and Coleman (2014) describe as procedural trust) and the information itself (what Stern and Coleman (2014) describe as rational trust) by the end-users, but this is an important aspect of their experience of different information and information sources.

Whilst the number of active information channels might provide a useful indicator of the extent to which information reaches end users, effectively evaluating EWS requires a more nuanced analysis of both accessibility and trust in information.

## Provision of Local Dissemination Services

Similar to Kenya and Zimbabwe, the development and empowerment of local services through PICSA and PSP, agricultural extension services, local radio, and lead farmers were found to be highly appreciated as a communication and dissemination strategy in Malawi. These were identified as a key mechanism in establishing trust in the drought information (Sivakumar, 2006; Pulwarty and Sivakumar, 2014; Andersson et al., 2019). The uptake in Malawi has improved since localized and downscaled climate information is provided. The sense of proximity to the information—by communication coming from sources known to end-users, or through the contextualization of warning content to the local situation—creates a sense of ownership and trust that results in a higher uptake of drought warning information (Pulwarty and Sivakumar, 2014; Andersson et al., 2019). The affinity to local services improved since the development of the PICSA program as this has provided higher competencies to extension officers to communicate and interpret the information. This in turn enables farmers to better understand and use the climate information provided. This study reveals, however, that challenges remain in enabling an effective communication and contextualizing information at the local level. For instance Kniveton et al. (2015) argue for the integration of climate information with local knowledge systems, but also acknowledge the challenges given the inherent uncertainty of weather and climate information. Local knowledge varies from one place to another and is poorly documented, making the co-production of EWS with farmers difficult from the national stakeholder perspective. Furthermore, with regards to the understanding of the nature of drought, this study found disparities in drought perception between the producer of climate information and the farmers. Droughts are mainly described by mandated authorities, UN and NGOs as a prolonged lack of rainfall following the planting season for a duration of 2–3 weeks or more. Perceptions of the farmers coincide with this definition. However, additional hazards such as fall army worms and even floods are considered as elements causing drought to farmers in Mangochi district though this was not found to be the case in Salima district. This disparity in drought perception clearly shows a need to actively engage farmers to avoid inadequate early farming actions when a drought warning is issued. In addition, these differences in drought perceptions highlight the need to clearly characterize what constitute a drought in the context Malawi, and re-adjust the communication strategy for the farmers and communities.

## Timely Provision of Relevant Information

This study shows that the uptake of drought warnings is associated with the downscaling of weather information to the district and area administrative level and the provision of the seasonal forecast in a timely manner. The drought warnings delivered are characterized as impact-based information, complemented by advisory information on farming practices, the location and the timeline for farming practices to mitigate droughts. Though only scarcely relevant impact information was included, contextualization to the local situation is believed to increase the understanding and trigger the taking of early actions by end-users (Choo, 2009; Potter et al., 2018). However, our results show that the element that is considered most relevant is the guidance provided on (drought) mitigation measures such as conservation agriculture or farming practices. The drought warning is not used by farmers for decision-making related to timing of their activities. Daily or weekly weather updates are not often used as cues because farmers are not able to access them via the channels through which they are communicated, or because there is a lack of trust in those updates that are received. Weather updates contain weather-only information and are provided uniformly across all sectors, without the sector-specific guidance considered most relevant in drought warnings. However, discussions at Cape Maclear with fishermen, pointed out that there the weather updates are closely paid attention to. This may be because they will go out on the lake to fish only when the weather conditions are adequate, and the information is therefore considered as highly relevant to them. The direct relevance of the information to the risk assessment of the end users, in this case, is well-understood and explains the high use of weather updates to decide upon fishing or not. For farmers, the relationship between forecast information and the outcomes of their responses (i.e., their decisions about land management) are less straightforward. Daily weather updates are not translated into farming information and advice, which can explain a lack of uptake by farmers. Data from FRT showed that few requests (6%) were made for the weather updates and thus supports the fact that this information is not widely used to cue the carrying out of most farming activities. Only following the planting season, the weather updates are considered relevant and important, and are therefore requested more frequently.

We point out that the MHEWS framework (WMO, 2018) does not include a way to assess this important component of understanding. Molinari and Handmer (2011) propose a behavioral model to quantify warning effectiveness. The MHEWS framework does assess understanding indirectly via the ability of tailor-made impact-based information to prompt the taking of action. In Malawi, the actions we found to have been taken show that, indeed, drought warning mitigation guidance is used in the decision-making process of farming activities. However, this does not necessarily imply that drought warnings are understood; it just shows that advice on improving farming practices as a whole is used in the decision-making. Clear links between drought warnings and understanding may be difficult to establish by looking only at the action taken by farmers, particularly given that the perception of drought may differ.

### The Dependency on Humanitarian and NGO Assistance

Overall, the timely provision of relevant drought warning information has triggered the uptake of early action by farmers. However, the accessibility to these services is limited to areas where there is NGO and humanitarian support. We found that these organizations provide extensive financial support to enable the development of these services. For instance, the PICSA training is supported by WFP or UNDP, while other projects provide funds that enable extension officers to access remote regions and to have more capacities to meet communities needs. The high financial dependency on humanitarian and NGO assistance tends to be, however, project-oriented and implemented for a certain period, jeopardizing the long-term development and provision of warning information to farmers (Harvey et al., 2019). This support is sporadic in time and space, thus bringing into question the sustainability and effectiveness of the drought early warning communication and dissemination at the country level. While the dissemination and communication process tends to align mostly to the guidelines in the MHEWS framework (WMO, 2018) when supported by donors, the question this raises to the sustainability due to this specific dependency is not elaborated in the framework.

## CONCLUSION

The timely provision of downscaled information, complemented with tailored advice has been shown to improve the uptake of warning information as witnessed by our analysis in the districts of Mangochi and Salima in Malawi. A people-centered approach is useful for enhancing trust and enabling an effective uptake of drought warning information. Focus group discussions and interviews supported by literature permitted us to identify that trust in, and uptake of, drought EWS in Malawi is enhanced by proximity. Relevance of information is achieved through the inclusion of local context and communication through locally recognized channels such as well-trained and trusted agricultural extension officers, lead farmers, and Farm Radio Trust.

The MHEWS framework supports a people-centered approach to the generation, communication, and dissemination of EWS, but it has some limitations as an evaluation tool for the effectiveness of EWS. Drawing on our findings, we argue that further disentangling the dissemination and communication processes within EWS, and observing participation, behavioral change and trust by stakeholders across these distinct processes can contribute to understanding what works, where and why in people-centered EWS approaches.

From the data collected, the adoption of a people-centered approach to early warning shows that this has improved the tailoring of drought Early Warning Systems to farmers' needs, and contributed to the perception by farmers interviewed in Malawi that the information provided is useful. Information provided that contained advisories on what actions farmers should take are of most use as farmers requested and responded to that information more readily than advisories on when to take actions. While improvements toward a people-centered-approach for drought EWS were identified, a high dependency on financial support from donors and lack of available funds at local levels for such initiatives was found. Although further introduction of digital communication methods could help reduce costs, other key elements such as training of agricultural extension officers and logistics also depend on donor funding. This is problematic for the further development and sustainability of these systems. Financial sustainability is currently not strongly embedded in the MHEWS framework. This should, however, be included as they may well jeopardize the effectiveness of the approach.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because all data available are qualitative and confidential. Participants are identifiable and therefore data cannot be shared. Requests to access the datasets should be directed to Alexia Calvel, alexia.calvel@gmail.com.

## ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

AC: main writer of the article based on M.Sc. Thesis. MW, MH, and ACF supervised and contributed to the writing of the article. IS, NM, SW, CB, and CL helped to improve the conceptualization of the field work and research work and contributed to the writing.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2020.578327/full#supplementary-material

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# The Implications of Extreme Weather Events for Attaining the Sustainable Development Goals in Sub-Saharan Africa

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Sub-Saharan Africa is among the regions that contribute least to global climate change, yet it is among the most vulnerable to its impacts due to low levels of economic and technological development. The frequency and magnitude of extreme weather events in the region are rising at a faster rate than the population capacity to deal with the attendant disasters. This paper interrogates some emerging and existing evidence of the potential for extreme weather events to obviate countries' attainment of the Sustainable Development Goals (SDGs). Whilst previous studies have assessed the vulnerabilities of sub-Saharan African (SSA) countries to extreme weather events on specific sectors, a comprehensive assessment of the implications of these extreme events for attaining the SDGs remains largely untouched. This paper assesses the impacts of flooding, extreme heat and drought on five key SDGs—Zero hunger (Goal 2), Good health and well-being (Goal 3), Quality education (Goal 4), Clean water and sanitation (Goal 6), and Sustainable cities and communities (Goal 11). Based on empirical cases from different SSA country contexts, and guided by the SDG targets and indicators, we discuss the main interactions between extreme weather events and different SDGs, emerging with a framework for the climate change—sustainable development nexus. Such an assessment, with regard to specific national and local case studies, would inform policy formulation and implementation, research and investment toward sustainable development in the region. Integrating resilience strategies into national development policies will offer sub-Saharan African countries the opportunity to reduce the impacts of extreme weather events on attaining their targets for sustainable development towards Agenda 2030.

**Keywords: extreme event, sustainable development goals, Sub-Saharan Africa, food security, health and wellbeing, water and sanitation, quality education, sustainable cities and communities**

## INTRODUCTION

Over the past two decades, African countries have experienced some remarkable economic growth, yet the continent is still home to over half of the world's poor population (Sustainable Development Goals Center for Africa (SDGC/A), 2019). As part of efforts to eradicate global poverty and ensure well-being for all, United Nations member states adopted the 2030 Agenda for Sustainable Development in September, 2015 (United Nations, 2015). Prior, to that the African Union had adopted the Agenda 2063 as a comprehensive programme of action toward inclusive and sustainable development for the continent. Like all other relevant regional and multilateral programmes of action, the UN Sustainable Development Goals (SDGs) integrated the AU Agenda 2063 in its development and so both agenda are aligned (United Nations, 2015). Sub-Saharan Africa remains one of the least developed regions globally in socioeconomic terms. Sub-Saharan Africa comprises four major regions; West Africa, Central Africa, East Africa, and Southern Africa. There is an appreciable distinction between North Africa and the other regions toward the attainment of various SDGs (AU, ECA, AfDB, and UNDP, 2018). Various assessments of the progress of sub-Saharan African countries toward achieving the SDGs identify that the targets are somehow ambitious and may require enhanced commitment and targeted resource allocation (Nhamo et al., 2019). Emerging research and anecdotal evidence indicate that climate change and its attendant extreme weather events adversely impact development and human well-being globally. Indeed, climate change and its impacts can potentially erode the gains made from investments made by governments into education, health, water, and food security to enhance population development. However, while sub-Saharan African governments are actively pursuing their human development agenda by focusing on harnessing the potential of a demographic dividend from their youthful populations, climate change seems a remote concern for many (Ezeh, 2016). Considering that extreme weather events associated with climate change have considerable impacts on key thematic developmental issues, the paucity of studies on the implication of these extreme events for attaining the SDGs in SSA is a cause for concern.

According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), mean annual temperatures have increased over the past half century and are projected to increase by over 2°C by the end of the century (Niang et al., 2014). According to the 2018 IPCC Special Report on global warming, temperatures will reach 1.5°C above pre-industrial times between 2030 and 2052 (IPCC, 2018). Africa is one of the continents most likely to be adversely impacted by the manifestations of extreme climate variability even though it is among the lowest contributors to anthropogenic climate change. Climate change occurs over decades or centuries, however, short term extreme weather events are experienced periodically by populations. In fact, the frequency, duration, and magnitude of extreme events, including droughts, flooding, and extreme heat, have increased over the past half century (Niang et al., 2014). This increase in extreme events is unmatched by the capacity for governments and populations to effectively manage the consequences. Limited capacity due to poor infrastructure, inefficient governance mechanisms, informality and lack of preparedness are harbingers of disastrous effects of extreme events in many sub-Saharan African countries. Though with less confidence than for temperature, it is projected that the frequency of extreme rainfall days will increase over western and eastern Africa while general warming over recent past decades signal deficient rainfall and severe drought risks in parts of southern and eastern Africa (Niang et al., 2014; IPCC, 2018). The lack of an effective adaptation policy and disaster response space in many sub-Saharan African countries suggest a lack of capacity to effectively deal with the impacts of extreme weather events, thus hampering efforts toward the attainment of the SDGs. In spite of this, few studies assess the implications of extreme weather events for achieving the SDGs by sub-Saharan African countries. Even though some studies examine the impact of climate change or extreme weather events on individual sectors of development such as food security (Connolly-Boutin and Smit, 2016; Tumushabe, 2018), water (Ziervogel, 2018; Nhamo et al., 2019), and health (Codjoe and Nabie, 2014; Dovie et al., 2017; Codjoe et al., 2020) among others there is no study that attempts to holistically address the challenges extreme weather events present to the attainment of the SDGs across the sub-Saharan African region. Given the foregoing, this paper attempts to answer the question, "How will extreme weather events impact the attainment of the Sustainable Development Goals by African countries?"

## EXTREME WEATHER EVENTS AND THE SDGS

This paper focuses on the impacts of extreme weather events on five thematic issues including food, health, education, water and sustainable living in communities. These five key issues are not only development outcomes but are also in themselves means through which key development agenda such as poverty eradication and gender equity can be attained. These issues are at the core of sustainable development and are directly affected by the impacts of extreme weather events.

### Zero Hunger (Goal 2)

Goal 2 of the SDGs aims to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture" (**Box 1**). As shown in **Box 1** below, the aim of the SGDs is to exceed eradicating hunger to include the ambitious targets of adequate nutrition and food safety (FAO, 2019). Recent evidence shows that, after years of continual decline until 2015, food insecurity and undernourishment are on the rise in many sub-Saharan African countries and the region has the highest burden of global food insecurity (FAO, 2019). All four SSA regions have severe food insecurity at levels more than twice the global average (Sustainable Development Goals Center for Africa (SDGC/A), 2019). Food insecurity levels are particularly highest in Central Africa and East Africa. In Central Africa, food insecurity has been worsened by rapid population growth, poverty, harsh environmental conditions, and political instability (Tumushabe, 2018). With this level of food insecurity in the region, therefore, it is important to assess the extent to which extreme climate events impede efforts toward attaining specific targets of the SDG 2.

Food production, which is at the core of food availability and specific to targets 2.3 and 2.4, is one of the targets most sensitive to extreme weather events. In low-income contexts, particularly in sub-Saharan Africa, where much of the food production is rain-fed, the implications seem more dire (FAO,

**BOX 1** | SDG Goal 2: Zero hunger (United Nations, 2015).

Targets:

By 2030,

2.1 end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious, and sufficient food all year round
2.2 end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women, and older persons
2.3 double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists, and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets, and opportunities for value addition and non-farm employment
2.4 ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters and that progressively improve land and soil quality
2.5 maintain the genetic diversity of seeds, cultivated plants, and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional, and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed

2018). The lack of sophisticated crop production and storage technologies or infrastructure contribute immensely to food losses in SSA (Nyo, 2016). Climate change and variability continue to extensively impact the already deficient crop, livestock, and fisheries production, as well as change the prevalence of crop pests and diseases (Campbell et al., 2016). In arid and semi-arid areas of SSA, where temperatures are projected to increase over the next century, erratic rainfall and increased evapotranspiration threaten to exacerbate the impacts of droughts for agro-pastoralism which is the mainstay of about 80% of rural populations across SSA (FAO, 2018). Severe droughts in the Horn of Africa in the 2015–16 period devastated livelihoods for many households, particularly millions of pastoralists living in Ethiopia and Kenya (Tumushabe, 2018). Droughts significantly impact agricultural production systems, be they irrigated or rainfed.

Another impact of extreme weather events on food production is by creating suitable environment for pest breeding and migration. In mid-2019, unusual tropical cyclones in the Arabian peninsula led to an outbreak of desert locusts who thrived and migrated through Yemen and into East Africa by the end of 2019, facilitated by yet other tropical cyclones, wreaking havoc for local farmers and economies who were both unprepared and lacked the capacity to deal with the plague (Salih et al., 2020). Though the desert locusts have been in existence for eons, this outbreak has been spurred by unusual tropical cyclones in East Africa and the Near East, creating favorable conditions for the locusts to reproduce rapidly and migrate over long distances (Kennedy, 2020). This is an indirect impediment to the attempts by affected communities and countries to attain Target 2.4 attributable to the occurrence of extreme events.

Combined agro-ecologic and economic models of all regions in the world project that SSA will most likely be biggest bearer of the brunt of climate change impacts, generating the lowest incomes from agriculture (Schmidhuber and Tubiello, 2007). The IPCC in its AR5 on Africa declared with high confidence that climate change would result in yield losses for major cereal staples across SSA (Niang et al., 2014). Generally, analyses of rainfall patterns between 2004 and 2016 over the continent indicate that there has been shortening of growing season length in Southern Africa and West Africa (FAO, 2018) while days of extreme precipitation are projected to be more frequent (IPCC, 2018). Flooding across the Sahel is also associated with destruction of cropland for thousands of populations (Tschakert et al., 2010). Flooding can also lead to the loss of livestocks and stored crop produce (Fiorillo et al., 2018).

Livelihood diversification seems a feasible economic adaptation strategy, however, some livelihood activities that are not sensitive to extreme events may adversely impact the environment (Niang et al., 2014). Also, while shifting from agriculture to other economic activities may improve income for households, it may lead to a reduction in agricultural outputs for countries and the region and ultimately a higher dependency on food imports. In Ghana, for instance, small scale farmers have transferred or lost farmlands and farms (including cocoa farms) to small-scale gold miners or even diversified from farming to mining, sometimes illegally (Boadi et al., 2016). This has implications for overall food price hikes due to production shortage amidst higher demand from miners and the general population. Usually, net producers of food crops will gain from price hikes due to food shortage as a result of extreme events (Grimm, 2011). However, majority of the SSA population engaged in agriculture are smallholder farmers who practice subsistence farming (Yaro, 2013) and lack the capacity to exponentially increase production.

To effectively reduce poverty, therefore, there is the need to enhance climate resilience in agricultural production to improve food availability and improve household incomes of farming communities. Also, the more affordable food becomes on the market the more accessible it will be and the lower the proportion of households' incomes that will be spent on food, leaving more disposable income to be spent on other needs and services.

Some African countries, with support from development partners and donor agencies, have undertaken programmes to increase the resilience of populations chronically affected by extreme weather shocks. For example, the Government of Malawi secured funding from the Green Climate Fund with the assistance of UNDP to expand early warning systems and climate information to communities in food-insecure districts[1] The government, with support from the FAO also secured funds to support selected communities against food crop and livestock loss by providing improved seed varieties, increasing access

[1]https://www.dodma.gov.mw/index.php/projects/m-climes-project.

to water resources and livestock vaccinations[2] It behooves on governments to provide safety nets for perpetually vulnerable communities to safeguard against crop and livestock production loss in order to attain food security for all.

**BOX 2** | Goal 3: Good health and well-being (United Nations, 2015).

Targets:

By 2030,

3.1 reduce the global maternal mortality ratio to <70 per 100,000 live births
3.2 end preventable deaths of newborns and children under 5 years of age, with all countries aiming to reduce neonatal mortality to at least as low as 12 per 1,000 live births and under-5 mortality to at least as low as 25 per 1,000 live births
3.3 end the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases and combat hepatitis, water-borne diseases, and other communicable diseases
3.4 reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being
3.5 Strengthen the prevention and treatment of substance abuse, including narcotic drug abuse and harmful use of alcohol
3.6 halve the number of global deaths and injuries from road traffic accidents
3.7 ensure universal access to sexual and reproductive health-care services, including for family planning, information and education, and the integration of reproductive health into national strategies and programmes
3.8 Achieve universal health coverage, including financial risk protection, access to quality essential health-care services and access to safe, effective, quality, and affordable essential medicines and vaccines for all
3.9 substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination

## Good Health and Well-Being (Goal 3)

SDG 3 aims at ensuring health lives and promoting well-being for all people at all ages (**Box 2**).

The IPCC AR5 affirms with high confidence that climate change has significant influence on human health (Smith et al., 2014). Extreme weather events impact the socioeconomic and environmental determinants of health, causes of disease as well as the healthcare systems. Under-five mortality rates are highest in SSA and many countries, based on observed trends, many not be likely to reach the targets by 2030 [Sustainable Development Goals Center for Africa (SDGC/A), 2019].

Extreme weather events have direct and indirect effects on health across SSA. Due to variability in climate and environmental conditions by sub-region and country, the potential impact on health in each country is largely dependent on local environmental conditions as well as existing health systems. One of the key targets is to eradicate epidemics of vector-borne diseases including some whose vectors are influenced by extreme weather events. Flooding is associated with an increased outbreak of diarrhoeal diseases in urban areas of many SSA countries (Abu and Codjoe, 2018; Okaka and Odhiambo, 2018). In most African cities, where water vendors supply water to households using water tankers, the risk of pathogenic infections is higher. Flooding devastates health facility infrastructure and disrupts access to healthcare in SSA countries where health infrastructure are rarely climate-resilient (Codjoe et al., 2020).

A major omission from the SDGs is the inclusion of deaths associated with extreme events. Floods in East Africa between April and June, 2020 directly resulted in tens of deaths in Kenya, Rwanda, Somalia, and Uganda, at the same time as they were hit by locust invasion and were at the early stages of the global coronavirus disease pandemic[3]. Floods cause accidents and fatal injuries to affected populations due to inadequate early warning systems, poorly coordinated disaster risk preparedness, response, and management in many SSA countries. They can also exacerbate existing health hazards particularly in urban areas. In 2015, in Ghana, flooding exacerbated the disaster caused by leakage from a fuel station in the capital city, Accra, leading to fire outbreak that left over a 150 dead, many more injured dead and about $100 million in asset losses in its wake (Erman et al., 2018). This example demonstrates the poor accident control mechanisms in efforts to "substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination (Target 3.9)" which are exacerbated by the occurrence of flooding.

Besides, flooding, like drought, can cause severe emotional and psychological distress for displaced households or those that lose loved ones and properties. Severe droughts can cause devastating impacts that can lead to emotional distress for individuals. The sight of dead cattle and failed crops following a drought can be a source of great emotional distress for farming households (Babugura, 2008). Acute water shortage can cause great emotional and physical distress for people, particularly women, who have to trek over long distances to collect water for household consumption and use (Arku and Arku, 2010; Asaba et al., 2013; Graham et al., 2016). Based on models of yellow fever transmission across countries in West, East, and Central Africa that incorporate future temperature projections that assume a 1.5°C temperature increase between 2030 and 2050, and keeping vaccination rates constant at 2018 levels, temperature increases by year 2050 will lead to increase in force of infection particularly in Central and East Africa. Similarly, mortality due to yellow fever is projected to increase under RCP scenarios 4.5, 6.0, and 8.5. This has the potential to increase the yellow fever burden across all endemic regions (Gaythorpe et al., 2020).

Extreme heat potentially increases temperature-related morbidity in many parts of SSA where housing quality is low and occupational conditions are dire. In South Africa, extreme heat impacts the domestic environment in informal settlement houses made of inferior poorly-insulated materials increasing heat-related stress and sleeplessness (Chersich et al., 2018). In a study of the impacts of climate change on occupational stress, manual workers from two sites in South Africa (Johannesburg and Upington) associated extreme summer temperatures with reduced productivity and myriad of poor health outcomes

[2]http://www.fao.org/emergencies/fao-in-action/stories/stories-detail/en/c/1180394/.

[3]https://www.bbc.com/news/world-africa-52571322#:$\sim$:text=Flooding%20as%20a%20result%20of,have%20killed%2016%20in%20Somalia.

including dehydration, skin irritations, burning eyes, headaches, exhaustion, sinus problems, and dizziness among others (Mathee et al., 2010). The working conditions of manual workers is similar across the sub-region with many occupational activities conducted outdoors or in the open.

In addition, extreme heat affects the delivery of healthcare for many in urban heat islands across the region. A study in Ghana revealed that many health facilities are poorly designed to be resilient to high indoor temperatures and may lack adequate cooling systems, thereby increasing both patient and health worker irritability as well as affecting drug quality (Codjoe et al., 2020). Health facilities must be designed to provide optimum room temperature as well as sited with proper drainage systems to ensure access during flooding. Particular communities noted for vulnerabilities to disease outbreaks and other health challenges should be specifically targeted for early warning systems, public health education and interventions. It is to be noted that good health and well-being are greatly linked with water and food security, thus, efforts must be strengthened to improve access to safe water and sufficient nutritious food for all.

## Quality Education (Goal 4)

Goal 4 of the SDGs is for governments and stakeholders to "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" (United Nations, 2015) (**Box 3**). Education is vital for the psychosocial and economic development of children and youth. While many SSA countries have endeavored to improve enrolment rates it is still unclear the extent to which there is equity in access and quality of education.

Extreme weather events potentially impede the attainment of this goal by affecting school attendance and dropout rates through their impacts or critical livelihood resource such as water and food. Analyses of school enrolment and attendance data from primary schools and climate (temperature and rainfall) data between 1970 and 2006 in the arid Zamfara State in Northern Nigeria, show that school attendance is low during drought and high when the rains come (Adejuwon, 2016). Household water collection is typically the responsibility of women and children in many rural communities across the region. Hence, during droughts, school attendance is affected when school time is spent fetching water and with prolonged droughts, dropout rates increase. This reflects the indirect impacts of droughts on Goal 4.5 which seeks to "eliminate gender disparities in education and ensure equal access to all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples and children in vulnerable situations." Improving water availability for water-scarce communities will help remove this barrier to school attendance for young girls.

On the other hand, household income from crop and livestock production drops in times of drought and affects the households' capacity to afford school expenditure. School enrolment and attendance is further affected when schoolchildren have to take up extra household chores when their guardians migrate or work extra hours, engage in economic activities to augment household income or migrate altogether with their parents for succor (Babugura, 2008). Dropping out of school and absenteeism disproportionately affects more girls than boys even within same communities.

**BOX 3** | Goal 4: Quality education (United Nations, 2015).

Targets:

By 2030,

4.1 ensure that all girls and boys complete free, equitable, and quality primary and secondary education leading to relevant and effective learning outcomes
4.2 ensure that all girls and boys have access to quality early childhood development, care, and pre-primary education so that they are ready for primary education
4.3 ensure equal access for all women and men to affordable and quality technical, vocational, and tertiary education, including university
4.4 substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship
4.5 eliminate gender disparities in education and ensure equal access to all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples and children in vulnerable situations
4.6 ensure that all youth and a substantial proportion of adults, both men and women, achieve literacy and numeracy
4.7 ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development

Not only enrolment is affected by droughts, learning outcomes can be somehow impacted by droughts. Thus, drought experiences can be linked with the attainment of Target 4.6 to "ensure that all youth and a substantial proportion of adults, both men and women, achieve literacy and numeracy" and Target 4.7 to "ensure that all learners acquire the knowledge and skills needed to promote sustainable development" particularly in rural areas. A comparative study among girls from drought-affected and unaffected rural Zimbabwe, found that, in spite of advancing in school due to automatic grade progresssion, droughts were associated with worsened learning and leadership test outcomes, suggesting adverse mental health consequences of droughts (Nordstrom and Cotton, 2020). The effects of drought especially for education gendered considering that social roles and responsibilities are gendered for children of school-going age.

Besides droughts, flooding contributes significantly to educational outcomes. Flooding can have direct destructive impacts on school buildings and can lead to internal displacement which affects education in many countries. However, the effects of flooding, though sudden, has shorter durations of effect on education. Evidence from Eswatini shows that flooding may not keep people out of school for long, as rebuilding after floods is much faster compared with severe droughts (International Displacement Monitoring Centre, 2020).

It is clear that droughts, extreme heat, and flooding can adversely affect the efforts toward attaining the targets of the SDGs on education. This relationship, as demonstrated with the examples above, is indirect through the direct impacts of drought on Goals 1 (No poverty), 2 (Zero hunger), and 6 (Clean water and sanitation). Therefore, to consolidate gains made by investment into increasing access to education, governments must specifically target communities affected by drought or by perennial floods with interventions to increase in times of extreme weather events. Interventions toward enhancing water, food, and livelihood resilience will impact school attendance and completion especially for young girls.

## Clean Water and Sanitation (Goal 6)

SDG 6 seeks to "ensure availability and sustainable management of water and sanitation for all" (**Box 4**). Beside safe water being a physiological need for human survival, it is essential for human well-being and socio-economic development and ecosystem sustainability.

Attaining water security is central to the SDGs. This is a very critical goal which directly underlies other goals including no poverty, zero hunger, good health and well-being, oceans, and biodiversity. In spite of increased access to safe drinking water and improved sanitation in SSA over the past two decades, the regional coverage rate is lowest for any region with less than half the global average with remarkable disparities between and within countries (AU, ECA, AfDB, and UNDP, 2018). In fact, by 2015 which is the baseline for the SDGs, whereas about 89% of the global population were served by at least basic water services—an improved water source within 30 min' round trip to collect water—this was only true for about 58% of the SSA population (WHO UNICEF, 2017). Only 24% of SSA population had access to safely managed water sources compared with the global average of 71% while about two-thirds of the 159 million people dependent on surface water sources for drinking were in SSA (WHO UNICEF, 2017).

Precipitation, surface and ground water resources are unequally distributed across the region, with significant limitations in the Sahelian regions of West Africa, and in Southern and East Africa. Preexisting conditions of water scarcity in these regions challenge the resilience of populations toward achieving water security. Climate change is a key challenge toward the attainment of water security particularly in arid and semi-arid regions of SSA and for urban slums without adequate pipe systems. The availability, quality, and stability of water resources for human consumption are adversely impacted by the occurrence of extreme weather events in many SSA countries. A huge proportion of infectious disease burden and child mortality is attributable to unclean water and poor sanitation. Achieving water security is indirectly linked to the attainment of other goals related to education, gender equality, sustainable cities and communities, energy, jobs, etc. (Mugagga and Nabaasa, 2016).

Droughts directly affect SDG Target 6.1 which aims to "achieve universal and equitable access to safe and affordable drinking water for all." Droughts can result in severe water crisis for both rural and urban communities, particularly for rural households dependent on surface water or rainwater harvesting and underground water sources. Besides the stress for water encountered by rural communities in semi-/arid area, there is the increasing evidence of the impact of droughts and extreme heat on urban water supply in urban areas. A 2018 study in Accra with officials of the city water treatment facility reported about an 18% shortfall in water production where there is little rain resulting in intermittent water supply to residents (Gough et al., 2019). The non-availability of water during droughts is directly linked to the attainment of SDG Target 6.2 which requires that populations "achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations." There is evidence of drought affecting household water use relating to sanitation and hygiene, even in sophisticated cities such as Cape Town (Ziervogel, 2018; Matikinca et al., 2020). Cape Town recorded a record-breaking period of drought between 2015 and 2018 since the 1930s (Enqvist and Ziervogel, 2019; Matikinca et al., 2020). This led to household changes in water use, such as reducing number of times showered, collecting water from showering and using that to flush toilets. Indeed, the occurrence of such extreme events potentially undermine efforts to increase access to safe drinking water for all even if more and more households are connected to urban water supply systems. In fact, the Southern African Development Community (SADC) region is no stranger to extreme events with increasingly significant variability in temperature and rainfall (Ziervogel, 2018).

Flooding is associated with contamination of water bodies from pathogens as well as chemicals used in farming and fishing. Flooding leads to overland flow with the potential to contaminate sources of water supply for treatment plants thus posing a challenge to the provision of safe and affordable water for all people (Rickert et al., 2019). Implementation of strict regulatory regimes is not without challenges in many SSA countries due

**BOX 4** | Goal 6: Clean water and sanitation (United Nations, 2015).

Targets: By 2030,

6.1 achieve universal and equitable access to safe and affordable drinking water for all
6.2 achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
6.3 improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
6.4 substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
6.5 implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
6.6 protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes

to the informality and rapid urbanization that outstrip the regulatory capacity of city authorities and governments.

In this regard, the UNDP, in partnership with the government, has initiated an Adaptation Fund project to help rehabilitate existing dams and build new multi-purpose dams where feasible in parts of semi-arid Northern Ghana[4] This initiative which also includes boreholes, solar irrigation, rainwater harvesting, and irrigation systems in a sustainable water management approach also supports all-year farm productivity toward the attainment of targets 2.3 and 2.4. It also underscores the need for multi-purpose water intervention resources whilst ensuring an integrated water management system to enhance availability and ensure equitable access to water and efficient water-use.

## Sustainable Cities and Communities (Goal 11)

SDG 11 seeks to "make cities and human settlements inclusive, safe, resilient, and sustainable" (**Box 5**). Sub-Saharan Africa is the most rapidly urbanizing region though it is the least urbanized region of the world, with an urban share of about 40% in 2018 from 13% in 1950s (UN, 2019). Since the year 2000, the annual urban population growth in sub-Saharan Africa has averaged around 4%. That notwithstanding, the patterns and trends of urbanization have followed different trajectories in different countries.

**BOX 5** | Goal 11: Sustainable cities and communities (United Nations, 2015).

Targets: By 2030,

11.1 ensure access for all to adequate, safe, and affordable housing and basic services and upgrade slums
11.2 provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities, and older persons
11.3 enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries
11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage
11.5 Significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations
11.6 Reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management
11.7 Provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities

Urbanization in the region is mainly driven by internal migration, natural increase and, to a little extent, by decentralization and area reclassification. Commonly, the rapid urbanization due to migration into existing urban areas or cities is characterized by rapidly increasing population in peripheral informal settlements and the informal sector that is not matched by commensurate urban development, governance, resource allocation, and service provisioning. Hence, there seems to be a deficit in the provision of quality housing, water and sanitation, health, education, transport, and other modern services to make cities safe and comfortable to live in. Sub-Saharan African cities are plagued by social, economic, and health challenges which have implications for health and well-being of urban populations (Serdeczny et al., 2017). These include poverty, unemployment and hazardous economic activities, lack of housing and poor housing conditions and poor access to electricity, water and sanitation services and poor healthcare. For instance, the conurbation along the coast of West Africa from Benin City to Accra, with its fulcrum being Lagos, is potentially the single largest footprint of urban poverty by 2020 (Davis, 2006).

Flooding presents a great challenge for attaining Target 11.5 which is to "reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations." Flood disasters wreak widespread havoc for urban communities, particularly those in informal settlements. The earlier referred to June 3rd flood disaster in Accra affected over 50,000 inhabitants destroying livelihoods and properties and displacing hundreds. Two years after the disaster, the most vulnerable households in informal settlements had yet to recover from the impacts of the disaster (Erman et al., 2018) and 5 years after the disaster flooding persists in the affected areas with massive devastation. In the first half of 2020 alone, flash flooding resulted in 100s of deaths across cities such as Lagos, Mogadishu, Abidjan, Bangui, Nairobi, and others. The floods left in their wake many properties, houses, and power lines destroyed. Such experiences demonstrate the potential for flooding to disrupt access to safe housing, health, transport, and other basic service to improve sustainable livelihoods in lums.

The rapid uncontrolled expansion of SSA cities also pose a risk factor for managing extreme heat impacts. A study of land surface temperature in four African cities (Lagos, Nairobi, Addis Ababa, and Lusaka) revealed high urban heat island intensities with 3–4°C warmer surface and air temperatures in up to 1 km radius of city centers relative to surrounding areas (Simwanda et al., 2019). Extreme heat events have the potential to exacerbate the challenges associated with urban heat islands such as discomfort to humans and poor health outcomes due to heat. Extreme heat in urban settlements increase the need for indoor cooling which may require more expensive energy consumption, particularly for vulnerable and poor persons who live in crowded spaces and densely populated informal settlements. In Accra and Tamale in Ghana, increased energy demand for cooling exerts additional pressure on electricity supply at a time when the extreme heat wears out transmission cables and transformers, leading to

[4]https://www.adaptation-fund.org/project/increased-resilience-to-climate-change-in-northern-ghana-through-the-management-water-resources-and-diversification-of-livelihoods/.

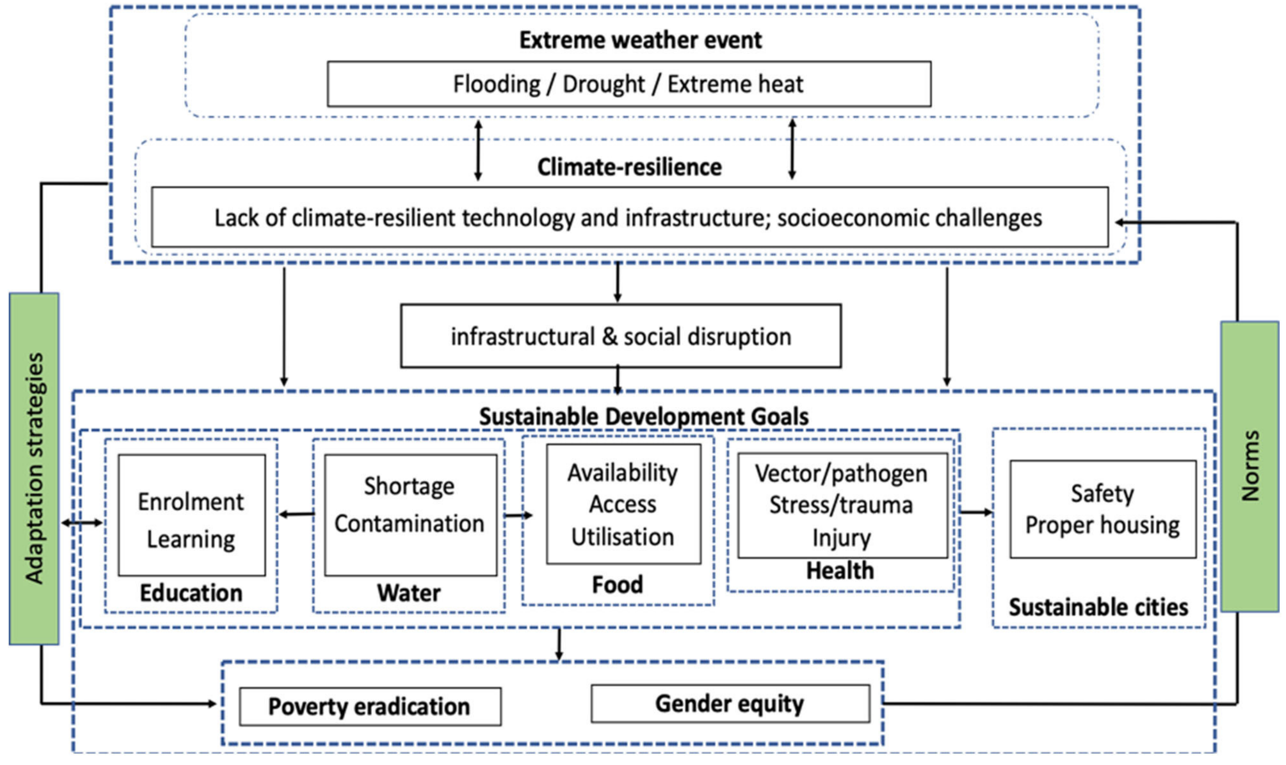


**FIGURE 1 |** Links between extreme weather events and sustainable development goals. Source: Authors' construct.

**TABLE 1 |** Extreme events and impacts on specific SDG Targets.

| | Extreme Event | | |
|---|---|---|---|
| **Impact on SDG Targets** | **Extreme droughts** | **Floods** | **Extreme heat** |
| Direct impacts | 2.4<br>6.1, 6.2, 6.4 | 3,3, 3.9<br>6.1, 6.3, 6.4<br>11.5 | 11.1 |
| Indirect impacts | 2.1, 2.3<br>3.3<br>4.5, 4.6, 4.7 | 3.1, 3.8<br>4.6, 4.7 | |

intermittent power supply and load shedding when production capacity is low (Gough et al., 2019; Codjoe et al., 2020).

The siting of urban infrastructure must take into consideration their resilience against extreme heat and flooding especially. A comprehensive approach to building sustainable cities and communities incorporates climate resilience in urban service provisioning.

## DISCUSSION AND CONCLUSION

This study highlights the implications of extreme weather events for sustainable development in the sub-Saharan African context. The study draws examples of the impacts of flooding, drought and extreme temperatures on achieving the sustainable development goals related to food security, health, education, water and sanitation, and sustainable cities and communities. It is evident from the aforementioned evidence that for SSA countries to remain on course toward attaining the targets of the sustainable development goals, attention must be paid to building resilience against extreme weather events as these have the potential to erode the gains made in investments into health, food, water, education, and urban infrastructure.

**Figure 1** illustrates the pathways through which extreme weather events impact the attainment of the SDGs in Ghana. This is a modified framework by Codjoe et al. (2020) which showed the links between extreme weather events and health in poor urban areas. In fact, it is evident that human actions or inactions in the context of SSA potentially amplify the risks and vulnerabilities associated with extreme weather events. The framework from this study indicates that there exist poor infrastructure that are not climate resilient together with socioeconomic challenges in many sub-Saharan African countries. This makes them sensitive to the impacts of flooding, droughts, and extreme temperatures. The disruption of these existing infrastructure and socioeconomic conditions create problems in various sectors including food security, water and sanitation, education, health and sustainable cities and communities. Evidently, extreme events have direct impacts on attaining the targets for SDG 6 related to water and sanitation with implications for different goals including SDGs 1, 3, 4, and 11 (**Table 1**). Indeed, this supports the proposition that water is central to the realization of the SDGs on the African continent (Mugagga and Nabaasa, 2016). For instance, flooding interrupts housing conditions, road access, and educational infrastructure. This adversely impacts both access to and the utilization of school and health care services with implications for future poverty reduction. Droughts interact with lack of adequate water supply infrastructure to impact water availability. Water unavailability has implications for food security as well as health, education and living in sustainable communities. Without adequate water for household use, especially in rural areas, women and girl children are per social norms in some setting responsible for collecting water. This may adversely impact girl children's time spent at school or even their enrolment as well as impact the ability of older women to engage in other economic activities, thus affecting gender equity and poverty reduction.

The evidence presented in this paper shows that, in sub-Saharan Africa, flooding, drought, and extreme temperatures obviate successful attainment of the sustainable development goals. By focusing on examples from sub-Saharan Africa, this review contributes some evidence to guide policy formulation and implementation. Given the poor state of infrastructure, extreme weather events potentially exacerbate harsh living conditions and interfere with key development sectors that can contribute toward alleviating poverty and improving well-being for all persons in sub-Saharan African countries. The consequences of extreme weather events for development are dire for sub-Saharan African countries and reducing these risks is not without challenges for a region with among the highest poverty rates in the world. Different countries in different parts of the region will experience the effects of individual extreme weather events on the attainment of the SDGs differently because climatic conditions and existing levels of socioeconomic and human development differ. Similarly, countries differ in policy formulation and implementation of disaster risk management, adaptation and resilience strategies toward the impacts of extreme weather events. Early warning systems differ by country and even within countries the implementation of these may not be equitably distributed. It is important to note that even though sociocultural norms and traditions may deepen the vulnerability of women, children, and other vulnerable groups, lack of resilience, and appropriate adaptation strategies could further reinforce the existing norms and values that create inequalities and inequity for these groups. Concerns about gender mainstreaming in the climate change and development discourse have largely been based on rhetoric with very little active representation in decision-making and policy implementation (Simon and Leck, 2015).

The investments into various sectors of development notwithstanding, progress toward attaining sustainable development depends, to some extent, on building resilience to extreme weather events. It is important for governments and development partners in the sub-Saharan African region to incorporate climate-resilience strategies into all sectors of development as they are largely interrelated. There arises a greater need to further examine the extent to which extreme weather events potentially disrupt efforts toward the attainment of the sustainable development goals for sub-Saharan Africa.

## AUTHOR CONTRIBUTIONS

All authors conceptualized the research, did the literature search, and drafted the manuscript.

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# Analysis of Climate Change and Extreme Climatic Events in the Lake Victoria Region of Tanzania

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The understanding of climate change impacts and the associated climate extreme events at regional and local scales is of critical importance for planning and development of feasible adaptation strategies. In this paper, we present an analysis of climate change and extreme climate events in the Lake Victoria region of Tanzania, focusing on the Kagera and Geita regions. We use daily simulated climate variables (rainfall and minimum and maximum temperatures) from the Coordinated Regional Climate Downscaling Experiment Program Regional Climate Models (CORDEX_RCMs) for the analysis. Extreme climate event, rainfall, and minimum and maximum temperatures time series during historical (1971–2000) climate condition are compared to future climate projection (2011–2100) under two Representative Concentration Pathway (RCP): RCP 4.5 and RCP 8.5 emission scenarios. The existence, magnitude, and statistical significance of potential trends in climate data time series are estimated using the Mann–Kendall (MK) non-parametric test and Theil-SEN slope estimator methods. Results show that during historical (1971–2000) climate, the Lake Victoria region of Tanzania experienced a statistically significant increasing trend in temperature. The annual minimum and maximum temperatures in the Kagera and Geita regions have increased by 0.54–0.69°C, and 0.51–0.69°C, respectively. The numbers of warm days (TX90p) and warm nights (TN90p) during the historical climate have increased, while the numbers of cold days (TX10p) and cold nights (TN10p) have decreased significantly. However, in future climate condition (2011–2100) under both RCP 4.5 and RCP 8.5 emission scenarios, the Lake Victoria region is likely to experience increased temperatures and rainfall. The frequency of cold events (cold days and cold nights) is likely to decrease, while the frequency of warm events (warm days and warm nights) is likely to increase significantly. The number of consecutive wet days, the intensity of very wet days, and the number of extreme wet days are likely to increase. These results indicate that in future climate condition, socioeconomic livelihoods of people in the Kagera and Geita regions are likely to experience significant challenges from climate-related stresses. It is, therefore, recommended that appropriate planning and effective adaptation policies are in place for disaster risk prevention.

**Keywords: climate change, climate variability, extreme climate indices, extreme weather, impact**

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## INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) assessment reports indicate that it is very likely that climate change has influenced the increase of the frequency and intensity of extreme weather and climate events (IPCC, 2007, 2013). The projections for the future from the climate models indicate further increases in the frequency and intensity of extreme weather and climate events that relate to temperature and rainfall (Kundzewicz, 2016). These events have damaged residential, commercial, and government/municipal buildings and caused destruction of material assets within the building and destruction of public infrastructures (roads and bridges) (NCEI, 2017). Moreover, extreme weather and climate events are projected to damage many socioeconomic sectors such as water, health, transport, agriculture, and food security in different regions of the globe, particularly in developing countries (Sarker et al., 2012; IPCC, 2013; Curtis et al., 2017).

For instance, it is projected that due to climate change, millions of people in Africa are likely to face increased water stress (IPCC, 2013), and in some African countries, yields from rain-fed agriculture could decline (FAO, 2017; Benjamin et al., 2020). Agriculture production and access to food in many African countries will be severely impacted. This could affect all dimensions of food security and exacerbate malnutrition.

In East African countries, climate change has already affected weather patterns and hydrological cycles. Several studies over East Africa region indicated that temperatures have increased, rainfall in particular, the long rains that are historically considered important for agriculture activities in the region have declined by later onset and earlier cessation (Wainwright et al., 2019; Borhara et al., 2020), the frequency and intensity of extreme weather events such as persistent drought and floods have increased (Kijazi and Reason, 2009a,b; Chang'a et al., 2017; Nicholson, 2017), the unpredictability of rainfall seasons has increased, and sea rise and coastal erosion have been noticed over many coastal regions (Tumbo et al., 2010; Liwenga et al., 2014; Mubaya et al., 2014). These events have affected water availability, food security, human health, and other socioeconomic livelihoods (Opiyo et al., 2014).

Tanzania as one of the East African countries faces greater challenges both in proneness to significant impacts of climate change and the ability to address the impacts (URT, 2007, 2012; Kijazi et al., 2019). The country's economy heavily depends on rain-fed agriculture, which is sensitive and mostly affected by increasing erratic climate change and variability (Ehrhart and Twena, 2006; Enfors and Gordon, 2008; Müller et al., 2011). The main crops that are grown in Tanzania include maize, cassava, millet, bananas, sweet potatoes, cotton, coffee, and sorghum, which have been reported to decline in productivity due to climate change and variability (URT, 2008; Munishi et al., 2010; Rowhani et al., 2011; Kangalawe, 2012). A recent study by Luhunga (2017) examined the impact of inter-seasonal variability of maize production in the Wami-Ruvu Basin of Tanzania and found that rainfall, maximum temperature, and solar radiation are the most important climate variables that determine inter-seasonal variation in maize yields.

The future climate projections of Tanzania are likely to present several challenges to the agriculture sector. For instance, the projected increase in temperatures in many regions as indicated by Luhunga et al. (2018) are likely to influence wilting and drying of plants and multiplication of pest, weeds, and diseases that would result in increased costs of crop production and failure in crop yields. Also, warmer temperatures are likely to cause an eruption of new pests, parasites, and diseases that would affect the agriculture sector severely. The trends of increased frequency of very wet days and extreme wet days, as was found by Chang'a et al. (2017), are likely to influence nutrient leaching, washing away of topsoil, waterlogging, pests, disease outbreaks, and infrastructure damage that would result into low crop yields and disruptions of the food supply chain.

The only approach toward devising actionable adaptation and mitigation strategies to the impacts of climate change is through conducting robust climate analysis to characterize and understand the historical and future climate conditions.

This requires a detailed analysis to characterize the whole spectrums of inherent natural variability of the climate system, including extreme climate events that are of interest for economists and investors (Christensen and Christensen, 2003). Moreover, climate analysis at a higher temporal and spatial resolution is required to provide evidence that would properly guide the formulation of adaptation and mitigation strategies. This paper provides a detailed analysis of climate change in the Lake Victoria region of Tanzania focusing on two regions: Kagera and Geita regions. These regions have complex spatial and temporal climate patterns largely modulated by the presence of Lake Victoria. This has made the government of Tanzania identify Kagera and Geita as priority areas for addressing the vulnerability from the impacts of climate change in Tanzania.

## DATA AND METHODOLOGY

### Study Region

The study areas are the Kagera and Geita regions located in the northwestern part of the Lake Victoria region of Tanzania (**Figure 1**). These regions are experiencing significant climate-related stresses such that the government of Tanzania through Food and Agriculture Organization (FAO) Tanzania is developing a funding project proposal titled "Enhancing Climate Change Resilience in Kagera and Geita regions of Tanzania." The developed project proposal will be submitted to access about USD 30 million from the Green Climate Fund as a grant to promote Climate-Smart Agriculture (CSA) practices and other forms of Agro-based innovations for adaptation benefits and mitigation contributions, support sustainable ecosystem management to ensure the flow of ecosystem goods and services for adaptation and mitigation, promote diversification of communities' livelihood in the context of the changing climate, and support Agro-meteorological infrastructure and services for climate resilience.

The Kagera and Geita regions experience bimodal rainfall patterns (**Figure 2**). This rainfall pattern is controlled by the movement of the Intertropical Convergence Zone (ITCZ), which moves southward in October and reaches the southern parts of

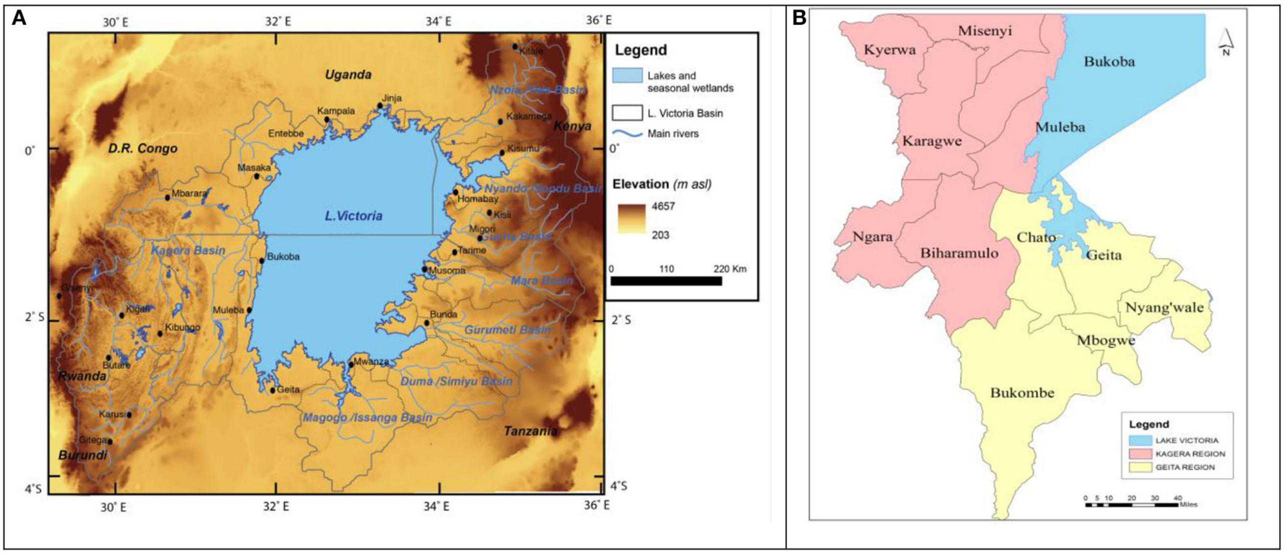


**FIGURE 1 |** The topographical map of the Lake Victoria region **(A)** adopted from Olaka et al. (2019) and **(B)** in the Kagera and Geita regions in the western parts of the Lake Victoria region of Tanzania.

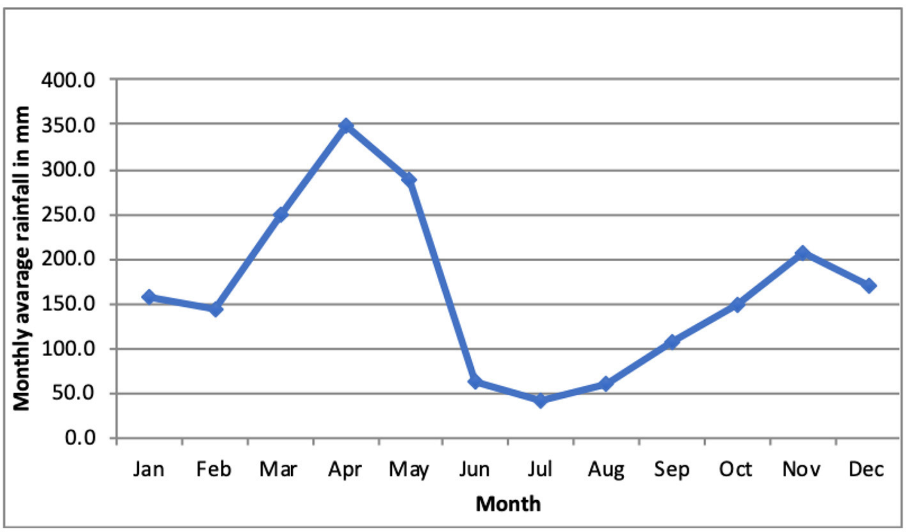


**FIGURE 2 |** Long-term (1971–2000) observed annual cycle of rainfall in Bukoba, a district of the Kagera region.

the country in January or February and reverses northward in March, April, and May. This movement makes the Kagera and Geita regions receive two distinct seasonal rainfalls—the short rainfall season that starts in October and continues through December (OND) and the long rainfall season that starts in March and continues through May (MAM) (Agrawala et al., 2003; Luhunga et al., 2016).

## Data

### Model Data

Tanzania has very few weather stations (28-synoptic weather stations) that are sparsely distributed over complex topographical terrain. Many places, especially in the Kagera and Geita regions, have no weather stations to monitor weather and climate patterns.

The only synoptic weather station that is used to monitor weather patterns in the Geita region is located at Mwanza region that is about 124–125 km apart. On the other hand, the Kagera region has one synoptic weather station that is located in Bukoba district. This station has long-term climate data series. These climate data series, however, have been impacted adversely with inhomogeneity caused by the change of instruments due to their damage or failure and change of land use cover surrounding the weather station in Bukoba.

**TABLE 1** | The Coordinated Regional Climate Downscaling Experiment (CORDEX)–Regional Climate Models (RCMs) and their driving General Circulation Models (GCMs).

| No. | RCM | Model center | Short name of RCM | GCM |
|---|---|---|---|---|
| 1 | HIRHAM5 | Danmarks Meteorologiske Institut (DMI), Danmark | HIRHAM5 | 1. ICHEC-EC-EARTH |
| 2 | Rossby Center Regional Atmospheric Model (RCA4) | Sveriges Meteorologiska och Hydrologiska Institut (SMHI), Sweden | RCA4 | 1. MPI-M-MPI-ESM-LR<br>2. ICHEC-EC-EARTHCNRM<br>3. CNRM-CERFACS -CNRM-CM5 |
| 3 | Regional Atmospheric Climate Model, version 2.2 (RACMO2.2T) | Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands | RACMO22T | 1. ICHEC-EC-EARTH |

To overcome the problem of data availability, especially over areas with a limited number of weather stations, Luhunga et al. (2016) evaluated the possibility of using climate simulation from the Coordinated Regional Climate Downscaling Experiment program Regional Climate Models (CORDEX-RCMs) to represent the climate condition of Tanzania. They found that CORDEX-RCMs perform better to represent observed historical climate conditions in many regions and therefore can supplement observation in areas that have no weather stations. In this paper, we use climate simulations from five high-resolution RCMs listed in (**Table 1**) to analyze climate change over the Kagera and Geita regions. The data are obtained from https://esgf-data.dkrz.de/projects/esgf-dkrz/ and are quality controlled and can be used to the terms of use (http://wcrp-cordex.ipsl.jussieu.fr/).

The RCMs indicated in **Table 1** run at a spatial resolution of latitude 0.44° and longitude 0.44°. To obtain climate variables at specific regions or districts, a statistical downscaling approach using the inverse distance weighted average interpolation techniques was used to obtain climate simulation for relevant regions or districts especially when multiple districts are found inside one grid point of the RCMs (Hartkamp et al., 1999; Ly et al., 2013; Luhunga et al., 2016). The outputs from the RCMs for the reference period (1971–2000) and future climate projections (2011–2100) under two Representative Concentration Pathway (RCP) RCP 4.5 and RCP 8.5 emission scenarios are used for the analysis.

## Methodology

In this paper, climate change has been analyzed by detecting the trend and significance of the trend in climate variables (rainfall and minimum and maximum temperatures) time series. SEN slope estimator method has been used to compute the gradient of the trends in climate data series. For detailed description on how the SEN slope method is used to compute the gradient of the trend in climate variables, the reader may consult Van Beusekom et al. (2015) and Byakatonda et al. (2018). Descriptive statistics such as moving average, standard deviation, and coefficient of variation (CV) are used to discern the change in climate variables.

Future (2011–2100) projections of climate variables (rainfall and minimum and maximum temperatures) are compared with climate variables in the reference period (1971–2000). The comparison is based on determining the departure of future climate during the present (2011–2040), mid (2041–2070), and end (2071–2100) centuries from climate condition in the reference period (1971–2000). The extreme climate indices are computed using RClimDex software. For detailed description on the computation of extreme climate indices using RClimDex, the reader may consult Zhang and Yang (2004) and Zhang et al. (2005). The RClimDex software is highly recommended by the World Meteorological Organization (WMO) to be used in computation of climate indices that are used to characterize climate extremes over different regions. The RClimDex software is used widely in computations of extreme climate indices using outputs from climate models, for instance, Gujree et al. (2017) have used outputs from RCM as input into RClimDex to compute 27 climate extreme indices in the Kashmir Valley of India, and Saddique et al. (2020) have used outputs from the General Circulation Models (GCMs) as inputs into RClimDex for computation of extreme climate indices in the Jhelum River Basin of India. In this study, RClimDex software is used to compute 17 climate indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) to characterize climate extremes over the Lake Victoria region. The computed indices presented in this study are percentile-based indices that relate to either temperature or rainfall. Percentile indices that relate to temperature include the occurrence of cold nights (TNp10), occurrence of warm nights (TNp90), occurrence cold days (TXp10), and occurrence of warm days (TXp90). The percentile indices that relate to rainfall are very wet days [which represent the amount of rainfall falling above the 95th (R95p)] and extreme wet days [which represent the amount of rainfall falling above 99th (R99p)].

Other indices that have been calculated include the absolute based indices that represent the minimum or maximum values of climate variables within a season or year. These indices include the maximum daily maximum temperature (TXx) and the maximum daily minimum temperature (TNx), the minimum daily maximum temperature (TXn) and the minimum daily minimum temperature (TNn), and the maximum 1-day precipitation amount (RX1day) and the maximum 5-days precipitation amount (RX5day). Furthermore, we have computed duration indices that include the Warm Spell Duration Index (WSDI); the number of Consecutive Dry Days (CDD) index, which is the length of the longest dry spell in a year; and the number of Consecutive Wet Days (CWD) index, which is defined as the longest wet spell in a year. The future changes in extreme climate events indices are analyzed by calculating the difference between extreme climatic events indices in present (2011–2040), mid (2041–2070), and end (2071–2100) centuries under two emission scenarios (RCP 4.5 and RCP 8.5) relative to the baseline period (1971–2000).

It should be noted that the use of the output from an individual climate model to analyze climate change over a particular region or location is subject to several uncertainties that arise from either the driving GCM or RCM (Northrop and Chandler, 2014; Qian et al., 2016; Luhunga et al., 2018). These uncertainties are overcome through the use of outputs from the multi-model ensemble average in the analysis. In this study, we constructed the ensemble average using five RCMs (RACMO22T and HIRHAM5 both driven by ICHEC-EC-EARTH, RCA4 driven by three GCMs: MPI-M-MPI-ESM-LR, CNRM-CERFACS-CNRM-CM5, and ICHEC-EC-EARTH) (**Table 1**) and used their outputs for climate change analysis.

## RESULTS AND DISCUSSION

The results on climate change and extreme climate events in the Lake Victoria region of Tanzania are presented and analyzed here in two subsections. The first subsection presents the analysis of climate condition and extreme climate events in the Lake Victoria region during the historical (1971–2000) climate condition, while the second subsection presents an analysis of climate condition and extreme climate events during the present (2011–2040), mid (2041–2070), and end (2071–2100) under two RCP (RCP 4.5 and RCP 8.5) emission scenarios. The data used for the analysis were obtained from ensemble average of five RCMs used in the CORDEX. These models were evaluated on their ability to reproduce the historical climate condition over different regions in Tanzania and found reasonable model skill, suggesting their potential use in representing the climate condition in different regions of Tanzania (Luhunga et al., 2016). However, it is important to mention here that although the outputs from RCMs are used in this study or have been used in other previous studies (Tölle et al., 2018; Almazroui, 2019), their results should be interpreted to account for the inability of the models to represent small-scale processes that play a role in modulating the intensity and magnitude of extreme climate events.

### Analysis of Historical (1971–2000) Climate Condition and Extreme Climate Events in the Lake Victoria Region

#### Analysis of Annual Cycle of Rainfall and Minimum and Maximum Temperatures

All districts in the Geita and Kagera regions receive a bimodal type of rainfall, with two peaks of rainfall, a primary maximum is in April and a secondary maximum is in November. The short rainy season starts from October and ends in December, while the long rainy season starts from March and continues through May. The long rainy season (MAM) in both regions (Geita and Kagera) ranges from 151.56 to 314.52 mm, while the short rainy season (OND) ranges from 39.42 to 182.83 mm. The driest months in the Geita and Kagera regions start from June and continue through September (**Figure 3A**).

In the historical (1971–2000) climate condition, the analysis of seasonal rainfall in the Geita and Kagera regions revealed a decreasing trend of rainfall. For instance, rainfall in the long rainy season exhibited a non-statistically significant decreasing trend of 2.46 mm (in March) with the trend of −0.082 mm/year to 22.08 mm (in April) with the trend of −0.736 mm/year (**Table 2**). However, an increasing trend of rainfall is observed in May (**Table 2**). This has been observed in both regions (Geita and Kagera). In the short rainy season, in October, rainfall in two districts (Bukombe and Mbogwe) exhibited a statistically significant decreasing trend of −1.163 mm/year and −1.164 mm/year, respectively (**Table 2**). In December, however, all districts in the Geita region except Chato exhibited a non-statistically significant decreasing trend of rainfall in the range of −0.33 mm/year to −0.520 mm/year. It is interesting to note that statistically significant increasing trends in rainfall are observed in most districts during June. This is an indication that rainfall season during March, April, and May (MAM) is shifting toward June. This indeed has been observed in Bukombe, Mbogwe, Bukoba rural, Karagwe, Kyerwa, Missenyi, and Muleba districts, where statistically significant increasing trends in rainfall during June were observed. In general, seasonal rainfall in both MAM and OND seasons showed a decreasing trend in both the Geita and Kagera regions. However, it is important to note that for most parts in the Kagera and Geita regions, the trends in rainfall are not significant.

All districts in the Geita region have seasonal minimum temperature in the range of 14.38°C to 18.45°C and the maximum temperature in the range of 23.25°C to 28.48°C (**Figures 3B,C**), while all districts in the Kagera region have seasonal minimum temperature in the range of 12.32–16.41°C and the maximum temperature in the range of 22.51–27.61°C (**Figures 3B,C**). The monthly minimum temperature in the Geita region exhibited a statistically significant increasing trend from January to April ranging from 0.01°C (in April) to 0.59°C (in March). These significant increases in temperature could affect agriculture activities in Geita, as an increase in temperature reduces grain yield in rice, wheat, and groundnut (Kaur and Hundal, 2010). Furthermore, Luhunga (2017) indicated that an increase in temperature shortens the length of growing season of maize crops (*Zea mays*). Statistically significant increased trends in minimum temperature in the range of 0.02–1.03°C/year are observed in the Geita region from September to December. It should be noted that both rainfall seasons (MAM and OND) minimum and maximum temperatures have increased significantly during the historical climate. These increasing trends in seasonal minimum and maximum temperatures are observed mainly in long-term rainfall season (MAM) as well as in short-term rainfall season (OND) (see **Table 3** for minimum temperature). This increase in temperature in the main rainfall season could have impacts in agriculture, as higher temperatures reduce the length of the growing season of many crops (Kaur and Hundal, 2010; Luhunga, 2017; Luhunga et al., 2016). Moreover, the observed significant increase in temperature could influence the multiplication and eruption of new crop diseases, for instance, Velásquez et al. (2018) indicated that an increase in temperature increases the incidence of plant diseases such as rice bacterial and sheath blight, increases the incidence of leaf spot and rhizomania that affect the production of sugar

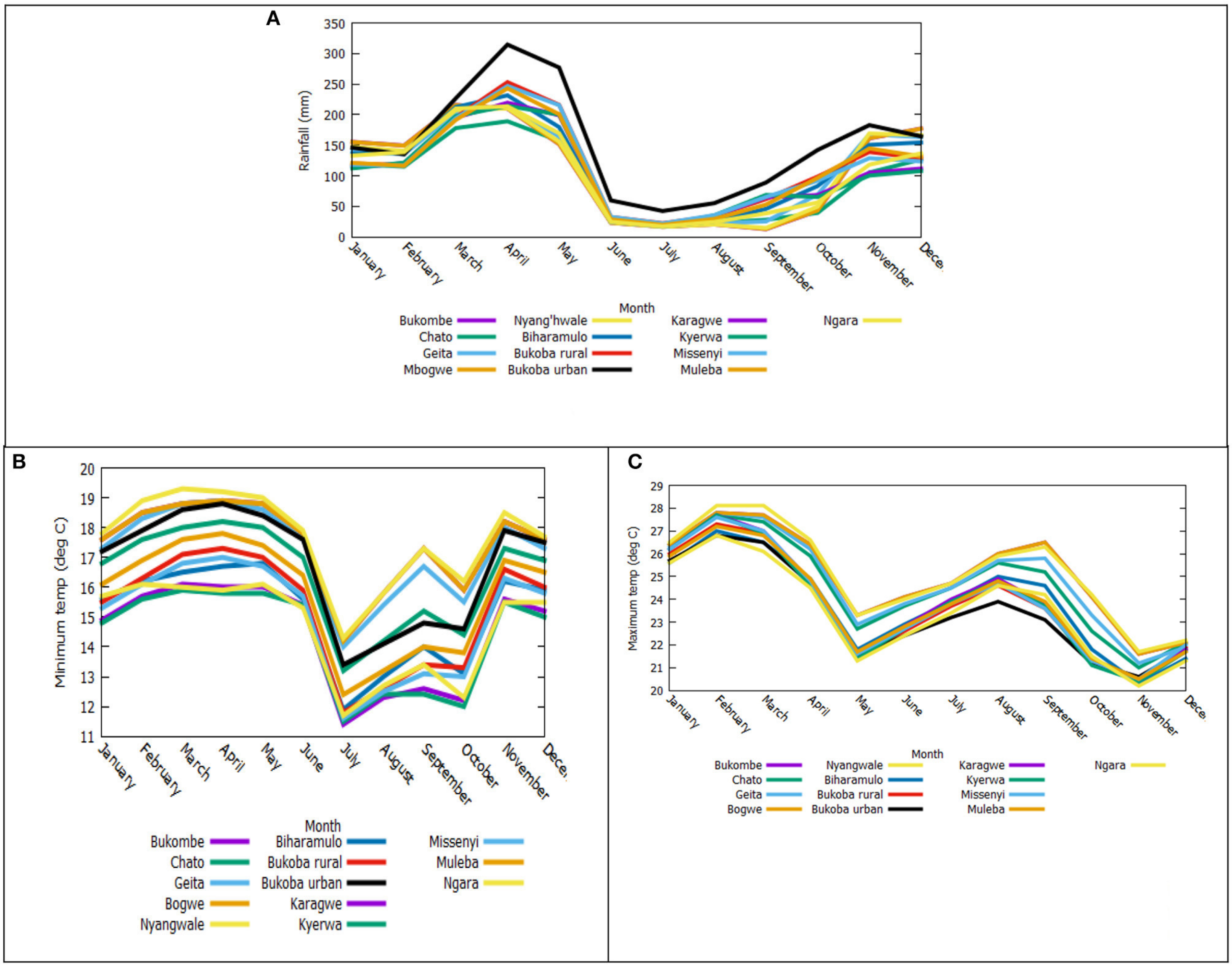


**FIGURE 3 |** The annual cycle of rainfall and minimum and maximum temperatures in the Kagera and Geita regions during the historical climate (1971–2000). **(A)** Rainfall. **(B)** Minimum temperature. **(C)** Maximum temperature.

beet, and increases sugarcane infection by the *Colletotrichum falcatum*. It should be noted that the statistically significant increased gradients in minimum and maximum temperatures in the Kagera and Geita regions are the evidence of climate change over those regions, since the main signal of climate change is an increasing trend in temperatures at local, regional, and global levels (Chang'a et al., 2017; Osima et al., 2018).

## Analysis of the Interannual Variation of Rainfall and Minimum and Maximum Temperatures

**Table 4** indicates the annual total of rainfall and annual mean minimum and maximum temperatures in the Kagera and Geita regions during the historical climate (1971–2000). This table indicates that the annual minimum temperature in the Kagera and Geita regions ranges from 13.8°C (in Karagwe district) to 17°C (in Nyang'hwale district). While the maximum temperature ranges from 25.1°C (in Bukoba urban) to 26.8°C (in Nyang'hwale district). Annual rainfall total in the Geita and Kagera regions ranges from 626.3 mm (in Geita district) to 839.8 mm (in Bukombe district).

To analyze how rainfall and minimum and maximum temperatures are involved during historical (1971–2000), the CV within annual rainfall and minimum and maximum temperature time series was computed (**Table 4**). Furthermore, time-series graphs and trend analysis were performed (**Figures 4A–C**). It is found that annual rainfall in most districts of the Kagera and Geita regions has decreased during the historical climate condition (1971–2000) (**Figure 4A**). Ten out of 13 districts exhibited a nonsignificant decreasing trend in rainfall during the historical climate (**Table 4**), while three districts (Bukoba rural, Bukoba urban, and Karagwe) have experienced a nonsignificant increasing trend in rainfall during the historical climate condition. In general, the non-statistically significant decreasing trends of rainfall in the Kagera and Geita regions

**TABLE 2 |** The gradient of the annual cycles of rainfall during the historical climate condition (1971–2000).

| | Ensemble | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEN's slope of rainfall (mm/year) | | | | | | | | | | | | |
| **Districts Month** | **Bukombe** | **Chato** | **Geita** | **Mbogwe** | **Nyang'hwale** | **Biharamulo** | **Bukoba rural** | **Bukoba urban** | **Karagwe** | **Kyerwa** | **Missenyi** | **Muleba** | **Ngara** |
| January | −0.264 | 0.091 | −0.102 | −0.263 | −0.154 | −0.114 | 0.241 | 0.208 | −0.128 | −0.192 | 0.127 | 0.256 | −0.192 |
| February | 0.301 | −0.227 | 0.071 | 0.293 | 0.379 | −0.188 | 0.130 | 0.147 | 0.205 | 0.303 | 0.174 | 0.135 | −0.162 |
| March | −0.098 | −0.239 | −0.204 | −0.082 | 0.369 | −0.506 | −0.384 | −0.629 | −0.353 | −0.354 | −0.437 | −0.451 | −0.151 |
| April | −0.723 | −0.537 | −0.543 | −0.736 | −0.505 | −0.662 | −0.507 | −0.273 | −0.696 | −0.647 | −0.388 | −0.568 | −0.509 |
| May | 0.299 | 0.428 | 0.219 | 0.267 | 0.044 | 0.686 | 0.215 | −0.227 | 0.570 | 0.510 | 0.281 | 0.438 | 0.631 |
| June | 0.018 (+) | 0.042 | 0.038 | 0.020 (+) | 0.023 | 0.047 | 0.287 (*) | 0.666 | 0.284 (*) | 0.285 (*) | 0.312 (*) | 0.229 (*) | 0.072 |
| July | −0.001 | −0.006 | −0.001 | −0.001 | −0.001 | −0.007 | −0.206 (+) | −0.649 (*) | −0.101 (*) | −0.082 (*) | −0.180 (*) | −0.160 (*) | −0.004 |
| August | −0.025 | −0.126 (+) | −0.079 | −0.028 | −0.033 | −0.137 | −0.168 | −0.215 | −0.167 | −0.192 | −0.188 | −0.177 | −0.123 |
| September | −0.126 | −0.339 | −0.300 | −0.128 | −0.282 | −0.235 | −0.022 | −0.334 | 0.060 | 0.085 | −0.039 | −0.003 | −0.357 |
| October | −1.163 (*) | −0.307 | −1.045 | −1.164 (*) | −1.047 | −0.132 | 0.616 | 0.877 | 0.050 | −0.109 | 0.406 | 0.688 | −0.039 |
| November | 0.453 | 0.174 | 0.334 | 0.447 | 0.331 | 0.461 | 0.658 | 0.624 | 0.410 | 0.056 | 0.724 | 0.256 | −0.112 |
| December | −0.357 | 0.004 | −0.338 | −0.346 | −0.520 | −0.238 | 0.126 | 0.206 | 0.004 | 0.140 | 0.152 | 0.135 | −0.437 |

*(*) trend significant at α = 0.05, and (+) trend significant at α = 0.1.*

**TABLE 3 |** The gradient of the annual cycles of minimum temperature during the historical climate condition (1971–2000).

| | Ensemble | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEN's slope of rainfall (°C/year) | | | | | | | | | | | | |
| **Districts Month** | **Bukombe** | **Chato** | **Geita** | **Mbogwe** | **Nyang'hwale** | **Biharamulo** | **Bukoba rural** | **Bukoba urban** | **Karagwe** | **Kyerwa** | **Missenyi** | **Muleba** | **Ngara** |
| January | 0.02 (*) | 0.02 (*) | 0.50 (+) | 0.02 (*) | 0.02 (*) | 0.02 (**) | 0.02 (+) | 0.01 | 0.03 (*) | 0.03 (**) | 0.02 (+) | 0.02 (+) | 0.02 (*) |
| February | 0.02 (+) | 0.01 | 0.31 | 0.02 (+) | 0.02 (*) | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.02 (+) |
| March | 0.02 (**) | 0.03 (***) | 0.59 (**) | 0.02 (**) | 0.02 (**) | 0.03 (***) | 0.03 (**) | 0.03 (**) | 0.04 (***) | 0.04 (***) | 0.03 (***) | 0.03 (***) | 0.03 (***) |
| April | 0.01 | 0.01 (*) | 0.22 | 0.01 | 0.01 | 0.02 (**) | 0.02 (*) | 0.01 (*) | 0.02 (***) | 0.02 (***) | 0.02 (*) | 0.02 (*) | 0.02 (***) |
| May | 0.01 | 0.01 | 0.24 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 (+) | 0.02 (*) | 0.01 (+) | 0.02 | 0.02 (+) |
| June | 0.01 | 0.01 | 0.41 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| July | 0.01 | 0.01 | 0.32 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 (*) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| August | 0.01 | 0.02 (*) | 0.41 | 0.01 | 0.01 | 0.03 (*) | 0.02 (*) | 0.02 (*) | 0.02 (*) | 0.02 (*) | 0.02 (*) | 0.02 (*) | 0.03 (*) |
| September | 0.02 (*) | 0.02 (**) | 0.57 (+) | 0.02 (*) | 0.02 (*) | 0.02 (**) | 0.01 (*) | 0.01 (*) | 0.02 (**) | 0.02 (**) | 0.02 (*) | 0.02 (*) | 0.02 (**) |
| October | 0.04 (**) | 0.03 (***) | 1.03 (***) | 0.04 (***) | 0.03 (***) | 0.03 (***) | 0.03 (***) | 0.03 (***) | 0.03 (***) | 0.02 (***) | 0.03 (***) | 0.03 (***) | 0.03 (***) |
| November | 0.02 (***) | 0.03 (***) | 0.65 (**) | 0.02 (***) | 0.02 (**) | 0.03 (***) | 0.02 (***) | 0.02 (**) | 0.03 (***) | 0.03 (***) | 0.02 (***) | 0.03 (***) | 0.03 (**) |
| December | 0.02 (**) | 0.02 (**) | 0.62 (**) | 0.02 (**) | 0.03 (**) | 0.02 (*) | 0.02 (*) | 0.02 (**) | 0.02 (+) | 0.02 (+) | 0.02 (*) | 0.02 (*) | 0.02 (*) |

*(***) trend significant at α = 0.001, (**) trend significant at α = 0.01, (*) trend significant at α = 0.05, and (+) trend significant at α = 0.1.*

**TABLE 4 |** Distribution of climate variables [changes in mean rainfall, minimum and maximum temperatures, gradient of change, and their coefficient of variation (CV)] during historical (1971–2000) climate conditions.

| | Ensemble | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **District** | **Change in maximum temperature (°C)** | **Change in minimum temperature (°C)** | **SEN's slope of rainfall (mm)** | **SEN's slope of maximum temperature (°C/year)** | **SEN's slope of minimum temperature (°C/year)** | **SEN's slope of rainfall (mm/year)** | **Mean annual maximum temperature (°C)** | **Mean annual minimum temperature (°C)** | **CV in maximum temperature (%)** | **CV in minimum temperature (%)** | **Mean value (mm)** | **CV in rainfall (%)** |
| Bukombe | 0.69 | 0.69 | −36.33 | 0.023 (**) | 0.023 (**) | −1.211 | 26.7 | 16.8 | 1.1 | 1.8 | 839.8 | 7.1 |
| Chato | 0.63 | 0.6 | −32.13 | 0.021 (**) | 0.020 (**) | −1.071 | 26.2 | 15.7 | 1.1 | 1.9 | 626.3 | 7.4 |
| Geita | 0.63 | 0.66 | −54.24 | 0.021 (**) | 0.022 (**) | −1.808 | 26.4 | 16.5 | 1.1 | 1.8 | 848.7 | 8.0 |
| Mbogwe | 0.69 | 0.66 | −34.29 | 0.023 (**) | 0.022 (**) | −1.143 | 26.7 | 16.8 | 1.1 | 1.8 | 840.6 | 7.1 |
| Nyang'hwale | 0.66 | 0.57 | −38.64 | 0.022 (**) | 0.019 (**) | −1.288 | 26.8 | 17.0 | 1.1 | 1.7 | 826.2 | 7.8 |
| Biharamulo | 0.66 | 0.6 | −36.69 | 0.022 (**) | 0.020 (**) | −1.223 | 25.5 | 14.5 | 1.2 | 2.2 | 902.8 | 5.1 |
| Bukoba rural | 0.57 | 0.54 | 20.61 | 0.019 (**) | 0.018 (**) | 0.687 | 25.4 | 14.6 | 1.1 | 1.9 | 922.9 | 6.5 |
| Bukoba urban | 0.51 | 0.54 | 16.11 | 0.017 (**) | 0.018 (**) | 0.537 | 25.1 | 16.1 | 1.0 | 1.6 | 1,338.8 | 7.4 |
| Karagwe | 0.66 | 0.57 | 1.38 | 0.022 (**) | 0.019 (***) | 0.046 | 25.5 | 13.8 | 1.1 | 2.0 | 784.5 | 5.2 |
| Kyerwa | 0.66 | 0.6 | −18.03 | 0.022 (**) | 0.020 (***) | −0.601 | 25.4 | 13.7 | 1.2 | 2.1 | 775.8 | 6.0 |
| Missenyi | 0.57 | 0.57 | 24.18 | 0.019 (**) | 0.019 (**) | 0.806 | 25.5 | 14.3 | 1.1 | 2.0 | 895.3 | 6.1 |
| Muleba | 0.57 | 0.57 | −7.53 | 0.019 (**) | 0.019 (**) | −0.251 | 25.5 | 15.1 | 1.1 | 1.9 | 879.5 | 6.5 |
| Ngara | 0.66 | 0.63 | −26.58 | 0.022 (***) | 0.021 (***) | −0.886 | 25.2 | 14.0 | 1.2 | 2.2 | 784.5 | 5.1 |

*(***) trend significant at $\alpha = 0.001$, (**) trend significant at $\alpha = 0.01$, and (+) trend significant at $\alpha = 0.1$.*

are in agreement with what was reported by Luhunga et al. (2016) that rainfall in all regions in Tanzania is decreasing with a nonsignificant trend.

The analyses of interannual variation in minimum and maximum temperatures indicate that minimum and maximum temperatures have increased significantly in all districts (**Table 4**). This could be due to the impacts of global climate change. The observed increase in both minimum and maximum temperatures could have adverse impacts on the agriculture sector by increasing the incidences of crop diseases; for instance, Velásquez et al. (2018) indicated that maximum temperature of 35°C and minimum temperature of 27°C are most favorable for *Xanthomonas oryzae* bacteria to colonize rice, temperatures between 26 and 31°C are ideal for papaya ringspot virus (PRSV) to infect papaya. Therefore, adaptation strategies need to be put in place to reduce the impacts, especially to temperature-sensitive crops.

To understand the influence of climate change on interannual variation of climate variables (rainfall and minimum and maximum temperatures) over the Kagera and Geita regions, we examine the CV. The CV of <20% is classified as less variability, 20% < CV < 30% as moderate, CV > 30% as high, CV > 40% as very high, and CV > 70% as extremely high variability. **Table 4** indicates the annual rainfall total, annual mean minimum and maximum temperatures, and their respective CV. It can be seen from the table that climate variables (rainfall and minimum and maximum temperatures) over the Kagera and Geita regions are consistent during the historical climate condition (1971–2000). The annual minimum temperatures across districts are more consistent when compared to annual maximum temperatures. Annual rainfall is more variable across the districts when compared to temperatures (**Table 4**).

To understand the influence of climate change on the trend of climate variables over the Kagera and Geita regions, we examine the gradient of change of rainfall and minimum and maximum temperatures from 1971 to 2000. **Table 4** shows the gradient of annual total rainfall, annual mean minimum and maximum temperatures, and their trends calculated from 1971 to 2000 climatological reference period. It is found that all districts in Kagera and Geita are dominated by increasing trends of minimum and maximum temperatures that are statistically significant at 99 and 99.9% confidence limit. From 1971 to 2000, the annual maximum temperature has, however, been increased at 99.99 significance level only at one district (Ngara) out of 13 districts. These results compare with what was reported by Chang'a et al. (2017) that the country has experienced a widespread statistically significant increase in temperature extremes consistent with the global warming pattern. The annual mean minimum temperature during historical climate (1971–2000) has increased at a 99.9% significance level at three districts (Ngara, Kyerwa, and Karagwe) out of the 13 districts. Increasing trends in the minimum and maximum temperature at statistically significant level of 99% are found in 12 districts for annual mean maximum temperature and 10 districts for the annual mean minimum temperature. These results provide very strong to strong evidence that minimum and maximum temperatures in the Kagera and Geita regions are increasing significantly. These

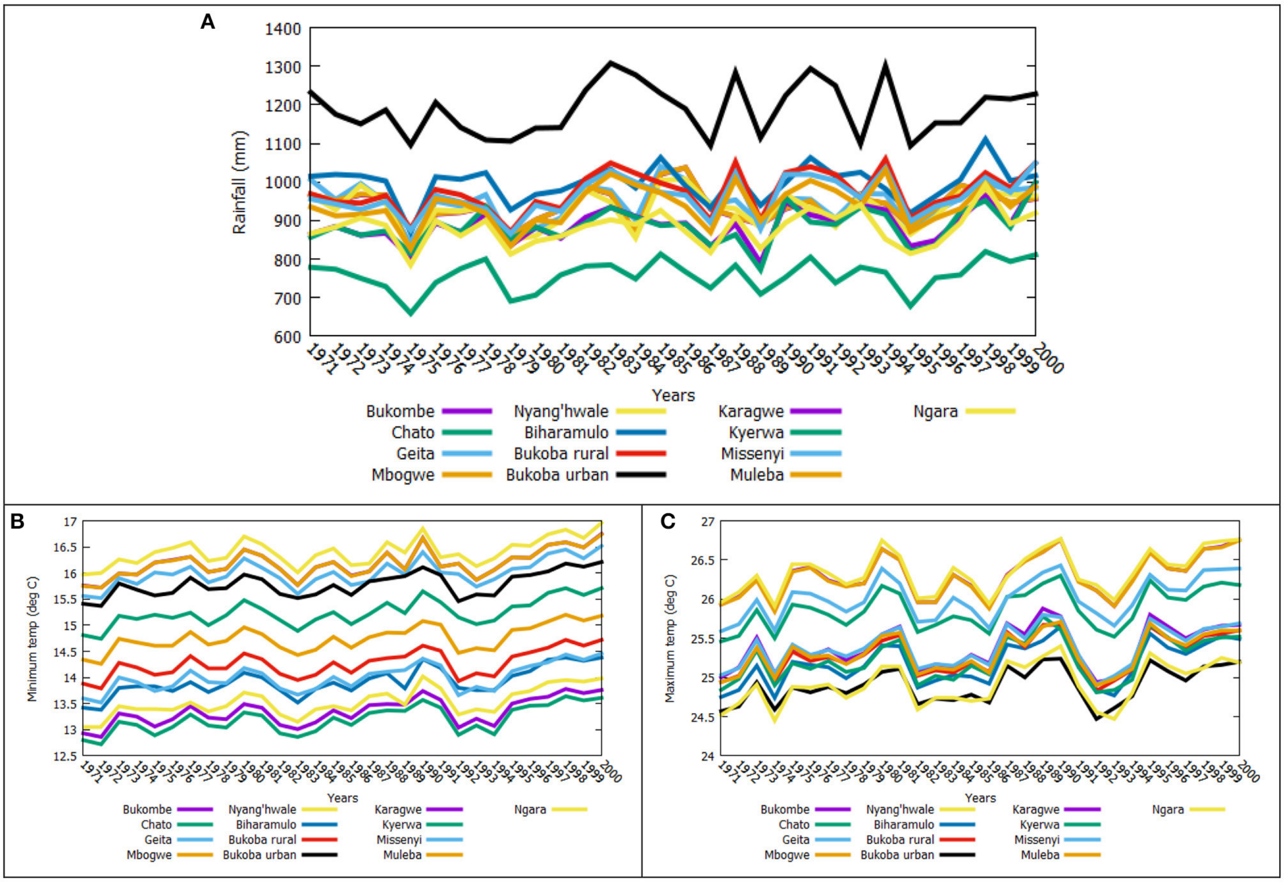


**FIGURE 4 |** The interannual variation in rainfall and minimum and maximum temperature. **(A)** Annual rainfall. **(B)** Annual minimum temperature. **(C)** Annual maximum temperature.

increases are associated with the impacts of climate change in the respective regions and districts. In general, during historical climate (1971–2000), minimum temperature has increased, ranging from 0.54°C in both Bukoba urban and Bukoba rural to 0.69°C in Bukombe. While maximum temperature has increased in the range of 0.51°C in Bukoba urban to 0.69°C in Bukombe (**Table 4**).

## Extreme Climate Indices Related to Rainfall and Temperature

One of the impacts of climate change is to increase the intensity, duration, and frequency of extreme climate events. This has contributed to the damage of properties and destruction of the environment and infrastructure in many regions. In agriculture, extreme climate events have contributed to crop failure, decreased crop yields, post-harvest loss, and disruptions of food supply chain especially from point of production (farm) to the marketplace (consumers). Here, the extreme climate indices in the Kagera and Geita regions during the historical climate condition (1971–2000) are analyzed. **Table 5** indicates trends in extreme climate indices related to frequency, duration, and intensity.

It can be seen from **Table 5** that all districts experienced a decreasing trend in cold days (TX10p). This implies that during the historical climate, daytime temperatures are becoming warmer and decrease the possibilities of having a day with cool temperatures. The decreased trend in cold days in the Geita and Kagera regions during the historical climate condition ranged from 0.21 days/year to 0.28 days/year. Missenyi district experienced a higher decreasing trend in cold days of 0.28 days/year at 95% significance level. The number of cold nights in the Kagera and Geita regions during historical climate indicates a decreasing trend. Kyerwa experienced the highest decreasing trend in cold nights of 0.48 days/year at 99.99% significance level. It is important to note that the number of cold days and cold nights in the Kagera and Geita regions have decreased at a very high significance level. This is a piece of strong evidence that climate change is taking place over those regions, as the IPCC (2013) concluded that due to climate change, the number of cold days and cold nights will decline in many regions of the world.

The number of warm days (TX90p) during historical (1971–2000) climate condition is presented in **Table 5**. It can be seen

**TABLE 5 |** Climate extreme indices during the historical climate condition (1971–2000).

| Districts | TX10p | TN10p | TX90p | TN90p | R95p | R99p | TXx | TXn | TNx | TNn | RX1 | RX5 | CDD | CWD | WSDI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chato | −0.27 (**) | −0.41 (***) | 0.33 (*) | 0.49 (***) | 0.66 | 0.11 | 0.02 (*) | 0.00 | 0.02 (+) | 0.02 (*) | 0.00 | 0.00 | 0.30 | 0.18 | 0.00 |
| Nyang'hwale | −0.26 (*) | −0.40 (**) | 0.34 (*) | 0.39 (**) | 0.04 | 0.00 | 0.03 (**) | 0.01 | 0.02 | 0.02 (**) | −0.02 | 0.05 | −0.19 | 0.09 | 0.00 |
| Biharamulo | −0.26 (**) | −0.45 (***) | 0.30 (*) | 0.52 (***) | 0.72 | 0.63 | 0.02 (*) | 0.00 | 0.02 (+) | 0.01 | 0.01 | 0.02 | 0.71 | 0.12 | 0.0001 (*) |
| Karagwe | −0.22 (+) | −0.46 (***) | 0.29 (+) | 0.56 (***) | 1.01 | 0.34 | 0.03 (**) | 0.02 (*) | 0.04 (***) | 0.02 (*) | 0.03 | 0.06 | 0.55 | 0.32 | 0.00 |
| Kyerwa | −0.24 (+) | −0.48 (***) | 0.30 (+) | 0.53 (***) | 0.63 | 0.17 | 0.03 (***) | 0.02 (+) | 0.04 (**) | 0.01 (+) | 0.02 | −0.01 | 0.56 (+) | 0.46 (+) | 0.00 |
| Missenyi | −0.28 (*) | −0.40 (**) | 0.28 (+) | 0.54 (***) | 1.18 | 0.58 | 0.02 (*) | 0.02 | 0.02 (**) | 0.01 (*) | −0.01 | 0.08 | 0.13 | 0.50 (*) | 0.0001 (**) |
| Ngara | −0.21 (*) | −0.45 (**) | 0.36 (*) | 0.54 (***) | 0.76 | 0.35 | 0.03 (*) | 0.00 | 0.03 (*) | 0.01 | 0.03 | 0.06 | 0.76 (+) | 0.07 | 0.00 |

*(***) trend significant at $\alpha = 0.001$, (**) trend significant at $\alpha = 0.01$, (*) trend significant at $\alpha = 0.05$, and (+) trend significant at $\alpha = 0.1$.*
*CDD, consecutive dry day; CWD, consecutive wet day; WSDI, warm spell duration index; RX1day, maximum 1–day precipitation amount; RX5day, maximum 5–day precipitation amount; TXx, maximum daily maximum temperature; TNx, maximum daily minimum temperature; TXn, the minimum daily maximum temperature; TNn, minimum daily minimum temperature.*

that all districts experienced a statistically increasing trend in warm days (TX90p) in the range of 0.28–0.36 days/year. Ngara experienced the highest increasing trend in warm days during the historical climate condition. The numbers of warm nights (TN90p) have increased significantly in the Kagera and Geita regions. These results are important, first, to discern or prove that climate change is happening in the Kagera and Geita regions and, second, to prepare appropriate adaptation strategies as the increase in daytime and nighttime temperatures would affect crop growth and can influence the development and eruption of new crop diseases.

The numbers of very wet days (R95p) and extreme wet days (R99p) indicate an increasing trend in all districts. These could have impacted by influencing sporadic flooding events in the Kagera and Geita regions. However, it is important to note that the numbers of very wet days and extreme wet days during the historical climate condition are non-statistically significant.

The extreme climate indices related to intensity are presented in **Table 5**. These indices include the monthly maximum value of daily maximum temperature (TXx), the monthly minimum value of daily maximum temperature (TXn), monthly maximum value of daily minimum temperature (TNx), the monthly minimum value of daily minimum temperature (TNn), maximum 1-day rainfall (RX1day), and maximum 5-day rainfall (RX5day).

Results from the trend analysis (**Table 5**) revealed that there is an increasing trend of TXx in all districts at the Geita and Kagera regions. Nyang'hwale, Karagwe, Kyerwa, and Ngara showed a positive increase in TXx of 0.03°C/year. This can be translated to an increase of 0.9°C at the end of the year 2000. Chato, Biharamulo, and Missenyi showed a positive increasing trend in TXx of 0.02°C/year. The trend analysis for TXn for two districts (Karagwe and Kyerwa) showed a statistically significant increasing trend of 0.02°C/year. Chato and Biharamulo, however, showed no trend in TXn. Based on the presented results in **Table 5**, TNx and TNn showed an increasing trend in most districts. The highest significant trend in TNx of 0.04°C/year is observed in Karagwe and Kyerwa. In general, these results indicate that the intensity of extreme temperature has increased significantly in the Geita and Kagera regions. Therefore, the adaptation plan must be put in place to reduce the impact of increased intensity of extreme temperature events. On the other hand, the maximum average 1-day (RX1day) rainfall revealed an increasing trend at four districts, Ngara, Kyerwa, Karagwe, and Biharamulo with 0.03, 0.02, 0.03, and 0.01 mm/year, respectively. This implies that there was an increased intensity of maximum 1-day rainfall in those districts during the historical climate condition. It is interesting to find the trend of maximum 5-days rainfall (RX5day) in all districts except Kyerwa, which showed a decreasing trend in RX5day rainfall of 0.01 mm/year. These results are important in devising adaptation strategies to come with increased intensity of 1-day and 5-days maximum rainfall in the Kagera and Geita regions.

The extreme climate indices related to duration are presented in **Table 5**. These indices include consecutive dry days (CDDs), consecutive wet days (CWDs), and warm spell duration index (WSDI). The presented results in **Table 5** reveal that there was an increasing trend in the duration of CDDs in all districts except Nyang'hwale, which showed a non-statistically significant decreasing trend in CDD of 0.19 days/year. The highest CDD of 0.76 and 0.71 days was observed at Ngara and Biharamulo, respectively. It is important to note that Ngara and Kyerwa observed a statistically significant increasing trend in consecutive dry days at 90% significance level. The analysis of WSDI showed almost no changes in most districts. However, a lower statistically significant increasing trend in WSDI is observed Biharamulo and Missenyi.

## Analysis of Future (2011–2100) Projection of Climate Condition and Extreme Climate Events in the Lake Victoria Region

Based on the detailed analysis of the historical climate condition in the Kagera and Geita regions, here we present the future projection of climate change in the Kagera and Geita regions. These changes in climate variable are assessed by comparing the future climate condition during the present (2011–2040), mid (2041–2070), and end (2071–2100) centuries under two emission scenarios (RCP 4.5 and RCP 8.5) relative to the historical climate condition (1971–2000). The detailed analysis of projected climate in the Lake Victoria region is presented in the following subsections.

## Analysis of the Projected Change in Temperature (Minimum and Maximum Temperatures)

The projections of change in minimum temperature in the Kagera and Geita regions during the present (2011–2040) century under RCP 4.5 and RCP 8.5 emission scenarios are presented in **Table 6**. This table indicates that all districts will experience increased minimum temperature during the present century under both RCP 4.5 and RCP 8.5 emission scenarios. For instance, during June–July–August–September (JJAS) season, Chato, Biharamulo, and Ngara are likely to experience increased minimum temperature in the range of 1.0–1.5°C. Moreover, the minimum temperature is likely to increase during March–April–May (MAM) season in the range of 0.8–1.3°C. In October–November–December (OND) season, minimum temperature is likely to increase in the range of 1.0–1.2°C. Under RCP 8.5 emission scenario, it is evident from **Table 6** that during the October–November–December (OND) season, Karagwe, Kyerwa, and Missenyi are likely to experience an increase in the minimum temperature in the range of 1.3–1.4°C. In general, all districts are likely to experience an increase in the minimum temperature predominantly in the main rainfall season MAM and OND. These results are consistent with a previous study by Luhunga et al. (2018), who indicated that the minimum temperature over the Lake Victoria Basin is projected to increase under both RCP 4.5 and RCP 8.5 emission scenarios. Moreover, the study by Osima et al. (2018) revealed increasing trends in temperatures in the entire Greater Horn of Africa in the future climate under both 1.5 and 2°C warming. The presented increases in minimum temperature are likely to affect the agriculture sector, as higher temperature reduces the length of the growing season of maize crops (Luhunga et al., 2016). Furthermore, higher temperature increases the incidence of crop disease outbreaks (Velásquez et al., 2018). Therefore, there is an urgent need to plan adaptation strategies on the projected change in minimum temperature in different districts in the Kagera and Geita regions.

The changes in minimum temperature during the mid (2041–2070) century under RCP 4.5 and RCP 8.5 emission scenario are presented in **Table 6**. Like in the present century, all districts are likely to experience increased temperature during the mid (2041–2070) century under both RCP 4.5 and RCP 8.5 emission scenarios. In JJAS season, all districts are likely to experience increased minimum temperature in the range of 1.6–2.3°C under RCP 4.5 emission scenario and the range of 2.7–3.2°C under RCP 8.5 emission scenario. In the end century (1971–2100), see **Table 6**, minimum temperatures are likely to increase up to 5.1°C in Biharamulo, Karagwe, Missenyi, and Ngarain in the JJAS season. These results agree with previous studies (Luhunga et al., 2018, Osima et al., 2018) that indicated that the Lake Victoria Basin will experience increased temperature in the future climate.

The projected changes in maximum temperature during the present century under RCP 4.5 and RCP 8.5 emission scenarios are presented in **Table 7**. This table reveals that all selected districts are likely to feature increased maximum temperature in the range of 0.7–1.2°C during the present century. The maximum temperature is likely to increase by 4.4°C in the end century under RCP 8.5 emission scenario (**Table 7**).

The projected percentage changes in rainfall during the present century (2011–2040) under RCP 4.5 and RCP 8.5 are presented in **Table 8**. This table indicates that in OND season, rainfall is expected to increase during the present climate. In mid (2041–2070) and end (2071–2100) centuries under both RCP 4.5 and RCP 8.5, see **Table 8**, all districts are likely to experience higher increased rainfall during OND season than in MAM season. It is interesting to find that all districts are likely to experience a decreased amount of rainfall in March. This is an indication that the MAM season is expected to shrink and become April and May (AM) season. On the other hand, the OND season is expected to extend to February and form an (ONDJF). This has been seen during present, mid, and end centuries (**Table 8**). These results are consistent with what has been reported in previous studies, for instance, Borhara et al. (2020) showed that there is a maximum rainfall decline in Tanzania during the long rainy (MAM) season and an increasing trend of rainfall during the short rainy (OND) season. Nicholson (2017) conducted a detailed review on climate and climate variability of rainfall over Eastern Africa and revealed that the long rains have been declining and the short rains have been increasing. Ogega et al. (2020) indicated that in the future, climate rainfall events over East Africa are projected to decline during MAM and increase during OND. The study by Wainwright et al. (2019) revealed that the projected decline in long rains during MAM is due to later onset of long rains influenced by the anomalously warmer Sea Surface Temperatures (SSTs) South of Eastern Africa that delay the north movement of the ITCZ and earlier cessation influenced by a decline of surface pressure over Arabia and warmer North Arabian Sea that pull the ITCZ northward outside the country. The presented results in this study are important, and special attention especially by farmers is needed when they plan their farming activities.

## Analysis of Projection of Changes in Extreme Climate Indices

The projected changes in extreme temperature indices in the Lake Victoria region under both RCP 4.5 and RCP 8.5 emission scenarios are presented in **Table 9**. All extreme temperature indices would increase in the present century (2011–2040) under both RCP 4.5 and RCP 8.5 emission scenarios. At the present century, the warmer indices TXx and TNx are likely to increase at the rate of 0.02 and 0.03°C/year, respectively, under RCP 4.5 scenario. Under RCP 8.5 scenario, the warmer indices TXx and TNx are likely to increase at the rate in the range of 0.02–0.04°C/year and 0.03–0.05°C/year, respectively. These results are consistent with the findings of Peng et al. (2019), who indicated that the warmer indices at night (TNx) would increase at a higher rate than warmer indices at daytime under both RCP 4.5 and RCP 8.5 scenarios. It is also observed that the higher the RCP, the larger the increasing rates, and this reveals the necessity of developing adaptation strategies on the climate change to reduce the impacts of

**TABLE 6 |** Projected change in minimum temperature (°C) in the Kagera and Geita regions during the present (2011–2040), mid (2041–2070), and end (2071–2100) century for Representative Concentration Pathway [a](RCP) 4.5 scenario and [b]RCP 8.5 scenario.

| Seasons | Month | Chato | | | Nyang'hwale | | | Biharamulo | | | Karagwe | | | Kyerwa | | | Missenyi | | | Ngara | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 |
| JF | January | 1.1[a] | 2.0[a] | 2.3[a] | 1.0[a] | 1.8[a] | 2.2[a] | 1.2[a] | 2.1[a] | 2.4[a] | 1.3[a] | 2.1[a] | 2.5[a] | 1.3[a] | 2.2[a] | 2.5[a] | 1.2[a] | 2.1[a] | 2.5[a] | 1.1[a] | 2.0[a] | 2.3[a] |
| | | 1.2[b] | 2.6[b] | 4.5[b] | 1.0[b] | 2.4[b] | 4.1[b] | 1.3[b] | 2.7[b] | 4.6[b] | 1.3[b] | 2.8[b] | 4.8[b] | 1.3[b] | 2.8[b] | 4.8[b] | 1.3[b] | 2.8[b] | 4.9[b] | 1.2[b] | 2.7[b] | 4.5[b] |
| | February | 1.0[a] | 1.7[a] | 2.4[a] | 0.9[a] | 1.6[a] | 2.1[a] | 1.0[a] | 1.8[a] | 2.5[a] | 1.1[a] | 1.9[a] | 2.6[a] | 1.1[a] | 2.0[a] | 2.7[a] | 1.1[a] | 1.9[a] | 2.6[a] | 1.1[a] | 1.9[a] | 2.5[a] |
| | | 1.0[b] | 2.6[b] | 4.3[b] | 1.0[b] | 2.3[b] | 3.9[b] | 1.1[b] | 2.7[b] | 4.4[b] | 1.2[b] | 2.9[b] | 4.8[b] | 1.2[b] | 2.9[b] | 4.8[b] | 1.1[b] | 2.8[b] | 4.7[b] | 1.1[b] | 2.7[b] | 4.5[b] |
| MAM | March | 1.1[a] | 1.8[a] | 2.2[a] | 1.0[a] | 1.7[a] | 2.0[a] | 1.1[a] | 1.9[a] | 2.3[a] | 1.1[a] | 2.0[a] | 2.5[a] | 1.2[a] | 2.0[a] | 2.5[a] | 1.1[a] | 1.9[a] | 2.4[a] | 1.1[a] | 2.0[a] | 2.4[a] |
| | | 1.3[b] | 2.5[b] | 4.2[b] | 1.2[b] | 2.3[b] | 3.9[b] | 1.3[b] | 2.6[b] | 4.3[b] | 1.4[b] | 2.7[b] | 4.7[b] | 1.4[b] | 2.8[b] | 4.7[b] | 1.3[b] | 2.7[b] | 4.5[b] | 1.3[b] | 2.6[b] | 4.5[b] |
| | April | 1.1[a] | 1.8[a] | 2.2[a] | 1.0[a] | 1.5[a] | 1.8[a] | 1.2[a] | 1.8[a] | 2.3[a] | 1.3[a] | 2.0[a] | 2.6[a] | 1.3[a] | 2.0[a] | 2.6[a] | 1.2[a] | 2.0[a] | 2.5[a] | 1.2[a] | 1.9[a] | 2.4[a] |
| | | 1.1[b] | 2.5[b] | 4.2[b] | 0.9[b] | 2.2[b] | 3.7[b] | 1.2[b] | 2.5[b] | 4.3[b] | 1.4[b] | 2.8[b] | 4.7[b] | 1.4[b] | 2.8[b] | 4.7[b] | 1.4[b] | 2.8[b] | 4.7[b] | 1.3[b] | 2.6[b] | 4.4[b] |
| | May | 0.8[a] | 1.6[a] | 2.2[a] | 0.7[a] | 1.4[a] | 1.9[a] | 0.9[a] | 1.6[a] | 2.2[a] | 1.0[a] | 1.7[a] | 2.3[a] | 1.0[a] | 1.7[a] | 2.3[a] | 0.9[a] | 1.7[a] | 2.3[a] | 0.9[a] | 1.6[a] | 2.2[a] |
| | | 0.9[b] | 2.4[b] | 4.0[b] | 0.7[b] | 2.3[b] | 3.7[b] | 0.9 | 2.4[b] | 4.0[b] | 1.1[b] | 2.6[b] | 4.3[b] | 1.1[b] | 2.6[b] | 4.3[b] | 1.1[b] | 2.6[b] | 4.4[b] | 1.0[b] | 2.5[b] | 4.1[b] |
| JJAS | June | 1.0[a] | 1.8[a] | 2.4[a] | 1.0[a] | 1.8[a] | 2.3[a] | 1.0[a] | 1.7[a] | 2.3[a] | 0.9[a] | 1.6[a] | 2.2[a] | 0.9[a] | 1.6[a] | 2.2[a] | 1.0[a] | 1.8[a] | 2.3[a] | 1.0[a] | 1.7[a] | 2.3[a] |
| | | 1.2[b] | 2.8[b] | 4.4[b] | 1.1[b] | 2.7[b] | 4.4[b] | 1.1[b] | 2.7[b] | 4.3[b] | 1.1[b] | 2.6[b] | 4.3[b] | 1.1[b] | 2.6[b] | 4.3[b] | 1.2[b] | 2.7[b] | 4.4[b] | 1.1[b] | 2.7[b] | 4.3[b] |
| | July | 1.2[a] | 2.1[a] | 2.6[a] | 1.2[a] | 2.1[a] | 2.5[a] | 1.2[a] | 2.2[a] | 2.6[a] | 1.3[a] | 2.2[a] | 2.7[a] | 1.3[a] | 2.2[a] | 2.7[a] | 1.3[a] | 2.2[a] | 2.7[a] | 1.2[a] | 2.2[a] | 2.6[a] |
| | | 1.2[b] | 2.9[b] | 4.9[b] | 1.2[b] | 2.8[b] | 4.8[b] | 1.2[b] | 3.0[b] | 5.0[b] | 1.3[b] | 3.0[b] | 5.1[b] | 1.3[b] | 3.0[b] | 5.1[b] | 1.3[b] | 3.0[b] | 5.1[b] | 1.2[b] | 2.9[b] | 5.0[b] |
| | August | 1.5[a] | 2.2[a] | 2.6[a] | 1.3[a] | 2.1[a] | 2.3[a] | 1.5[a] | 2.3[a] | 2.7[a] | 1.4[a] | 2.3[a] | 2.7[a] | 1.4[a] | 2.3[a] | 2.7[a] | 1.4[a] | 2.2[a] | 2.7[a] | 1.5[a] | 2.3[a] | 2.7[a] |
| | | 1.4[b] | 3.1[b] | 4.9[b] | 1.3[b] | 2.8[b] | 4.6[b] | 1.4[b] | 3.2[b] | 4.9[b] | 1.3[b] | 3.2[b] | 5.1[b] | 1.3[b] | 3.2[b] | 5.1[b] | 1.3[b] | 3.1[b] | 5.0[b] | 1.3[b] | 3.2[b] | 5.0[b] |
| | September | 1.1[a] | 2.0[a] | 2.4[a] | 1.0[a] | 1.8[a] | 2.3[a] | 1.2[a] | 2.1[a] | 2.4[a] | 1.2[a] | 2.2[a] | 2.5[a] | 1.2[a] | 2.2[a] | 2.5[a] | 1.3[a] | 2.2[a] | 2.6[a] | 1.2[a] | 2.1[a] | 2.5[a] |
| | | 1.3[b] | 2.7[b] | 4.5[b] | 1.1[b] | 2.5[b] | 4.3[b] | 1.3[b] | 2.8[b] | 4.6[b] | 1.4[b] | 3.0[b] | 4.9[b] | 1.4[b] | 3.0[b] | 4.9[b] | 1.4[b] | 2.9[b] | 4.9[b] | 1.4[b] | 2.9[b] | 4.8[b] |
| OND | October | 1.0[a] | 1.9[a] | 2.3[a] | 1.0[a] | 1.8[a] | 2.1[a] | 1.0[a] | 1.9[a] | 2.3[a] | 1.1[a] | 2.0[a] | 2.4[a] | 1.1[a] | 2.0[a] | 2.4[a] | 1.1[a] | 2.0[a] | 2.4[a] | 1.1[a] | 2.0[a] | 2.4[a] |
| | | 1.3[b] | 2.6[b] | 4.4[b] | 1.1[b] | 2.5[b] | 4.1[b] | 1.3[b] | 2.6[b] | 4.4[b] | 1.4[b] | 2.7[b] | 4.6[b] | 1.4[b] | 2.7[b] | 4.5[b] | 1.4[b] | 2.8[b] | 4.6[b] | 1.4[b] | 2.7[b] | 4.5[b] |
| | November | 1.0[a] | 1.9[a] | 2.3[a] | 0.9[a] | 1.6[a] | 2.0[a] | 1.1[a] | 1.9[a] | 2.3[a] | 1.2[a] | 2.0[a] | 2.4[a] | 1.2[a] | 2.0[a] | 2.4[a] | 1.2[a] | 2.0[a] | 2.4[a] | 1.1[a] | 2.0[a] | 2.3[a] |
| | | 1.2[b] | 2.6[b] | 4.3[b] | 1.0[b] | 2.3[b] | 3.8[b] | 1.3[b] | 2.6[b] | 4.4[b] | 1.4[b] | 2.8[b] | 4.6[b] | 1.4[b] | 2.8[b] | 4.5[b] | 1.4[b] | 2.8[b] | 4.6[b] | 1.3[b] | 2.7[b] | 4.4[b] |
| | December | 1.1[a] | 1.9[a] | 2.4[a] | 1.0[a] | 1.8[a] | 2.2[a] | 1.1[a] | 2.0[a] | 2.5[a] | 1.2[a] | 2.1[a] | 2.5[a] | 1.2[a] | 2.1[a] | 2.5[a] | 1.2[a] | 2.0[a] | 2.5[a] | 1.1[a] | 2.0[a] | 2.4[a] |
| | | 1.2[b] | 2.7[b] | 4.4[b] | 1.1[b] | 2.4[b] | 4.0[b] | 1.3[b] | 2.8[b] | 4.4[b] | 1.3[b] | 2.9[b] | 4.7[b] | 1.4[b] | 2.9[b] | 4.8[b] | 1.3[b] | 2.9[b] | 4.7[b] | 1.2[b] | 2.8[b] | 4.5[b] |

**TABLE 7 |** Projected change in maximum temperature (°C) in the Kagera and Geita regions during the present (2011–2040), mid (2041–2070), and end (2071–2100) century for Representative Concentration Pathway [a](RCP) 4.5 scenario and [b]RCP 8.5 scenario.

| Seasons | Month | Chato | | | Nyang'hwale | | | Biharamulo | | | Karagwe | | | Kyerwa | | | Missenyi | | | Ngara | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 |
| JF | January | 0.7 [a] | 1.3 [a] | 1.6 [a] | 0.7 [a] | 1.3 [a] | 1.7 [a] | 0.7 [a] | 1.4 [a] | 1.7 [a] | 0.7 [a] | 1.2 [a] | 1.6 [a] | 0.7 [a] | 1.2 [a] | 1.6 [a] | 0.7 [a] | 1.3 [a] | 1.7 [a] | 0.7 [a] | 1.3 [a] | 1.6 [a] |
| | | 0.7 [b] | 1.9 [b] | 3.3 [b] | 0.7 [b] | 1.9 [b] | 3.3 [b] | 0.8 [b] | 2.0 [b] | 3.4 [b] | 0.8 [b] | 1.9 [b] | 3.4 [b] | 0.8 [b] | 1.9 [b] | 3.4 [b] | 0.8 [b] | 1.9 [b] | 3.4 [b] | 0.7 [b] | 1.9 [b] | 3.3 [b] |
| | February | 0.8 [a] | 1.4 [a] | 1.8 [a] | 0.8 [a] | 1.4 [a] | 1.8 [a] | 0.8 [a] | 1.4 [a] | 1.8 [a] | 0.8 [a] | 1.3 [a] | 1.8 [a] | 0.8 [a] | 1.3 [a] | 1.8 [a] | 0.8 [a] | 1.4 [a] | 1.8 [a] | 0.8 [a] | 1.4 [a] | 1.8 [a] |
| | | 0.9 [b] | 2.1 [b] | 3.5 [b] | 1.0 [b] | 2.1 [b] | 3.6 [b] | 0.9 [b] | 2.2 [b] | 3.6 [b] | 0.8 [b] | 2.1 [b] | 3.6 [b] | 0.9 [b] | 2.1 [b] | 3.6 [b] | 0.9 [b] | 2.1 [b] | 3.6 [b] | 0.9 [b] | 2.1 [b] | 3.6 [b] |
| MAM | March | 1.1 [a] | 1.8 [a] | 2.1 [a] | 1.1 [a] | 1.7 [a] | 2.1 [a] | 1.1 [a] | 1.9 [a] | 2.2 [a] | 1.1 [a] | 1.9 [a] | 2.2 [a] | 1.2 [a] | 1.9 [a] | 2.2 [a] | 1.1 [a] | 1.8 [a] | 2.1 [a] | 1.1 [a] | 1.9 [a] | 2.1 [a] |
| | | 1.2 [b] | 2.4 [b] | 4.1 [b] | 1.2 [b] | 2.3 [b] | 4.0 [b] | 1.3 [b] | 2.4 [b] | 4.2 [b] | 1.2 [b] | 2.4 [b] | 4.3 [b] | 1.2 [b] | 2.5 [b] | 4.4 [b] | 1.1 [b] | 2.4 [b] | 4.2 [b] | 1.2 [b] | 2.4 [b] | 4.2 [b] |
| | April | 0.9 [a] | 1.6 [a] | 1.9 [a] | 0.8 [a] | 1.4 [a] | 1.7 [a] | 0.9 [a] | 1.6 [a] | 2.0 [a] | 0.9 [a] | 1.8 [a] | 2.2 [a] | 1.0 [a] | 1.8 [a] | 2.2 [a] | 1.0 [a] | 1.8 [a] | 2.2 [a] | 0.9 [a] | 1.6 [a] | 2.0 [a] |
| | | 0.8 [b] | 2.3 [b] | 3.7 [b] | 0.7 [b] | 2.2 [b] | 3.5 [b] | 0.9 [b] | 2.3 [b] | 3.8 [b] | 1.0 [b] | 2.5 [b] | 4.0 [b] | 1.0 [b] | 2.5 [b] | 4.0 [b] | 1.1 [b] | 2.5 [b] | 4.0 [b] | 0.9 [b] | 2.3 [b] | 3.7 [b] |
| | May | 0.7 [a] | 1.6 [a] | 2.0 [a] | 0.7 [a] | 1.5 [a] | 1.9 [a] | 0.8 [a] | 1.6 [a] | 2.0 [a] | 0.8 [a] | 1.5 [a] | 2.0 [a] | 0.8 [a] | 1.6 [a] | 2.0 [a] | 0.8 [a] | 1.6 [a] | 2.0 [a] | 0.8 [a] | 1.6 [a] | 2.0 [a] |
| | | 1.0 [b] | 2.4 [b] | 3.8 [b] | 0.9 [b] | 2.3 [b] | 3.7 [b] | 1.0 [b] | 2.4 [b] | 3.9 [b] | 1.0 [b] | 2.3 [b] | 3.9 [b] | 1.0 [b] | 2.3 [b] | 3.9 [b] | 1.0 [b] | 2.4 [b] | 3.9 [b] | 1.0 [b] | 2.3 [b] | 3.9 [b] |
| JJAS | June | 1.0 [a] | 1.9 [a] | 2.4 [a] | 1.0 [a] | 1.8 [a] | 2.3 [a] | 1.0 [a] | 1.9 [a] | 2.4 [a] | 1.0 [a] | 1.8 [a] | 2.3 [a] | 1.0 [a] | 1.8 [a] | 2.3 [a] | 1.0 [a] | 1.8 [a] | 2.3 [a] | 1.0 [a] | 1.9 [a] | 2.3 [a] |
| | | 1.2 [b] | 2.6 [b] | 4.2 [b] | 1.1 [b] | 2.6 [b] | 4.2 [b] | 1.1 [b] | 2.6 [b] | 4.3 [b] | 1.1 [b] | 2.5 [b] | 4.2 [b] | 1.1 [b] | 2.5 [b] | 4.2 [b] | 1.1 [b] | 2.6 [b] | 4.2 [b] | 1.1 [b] | 2.6 [b] | 4.3 [b] |
| | July | 1.1 [a] | 1.9 [a] | 2.4 [a] | 1.0 [a] | 1.9 [a] | 2.3 [a] | 1.0 [a] | 1.9 [a] | 2.4 [a] | 1.1 [a] | 1.8 [a] | 2.3 [a] | 1.1 [a] | 1.8 [a] | 2.3 [a] | 1.1 [a] | 1.9 [a] | 2.4 [a] | 1.0 [a] | 1.9 [a] | 2.3 [a] |
| | | 1.2 [b] | 2.7 [b] | 4.4 [b] | 1.2 [b] | 2.6 [b] | 4.3 [b] | 1.2 [b] | 2.7 [b] | 4.4 [b] | 1.1 [b] | 2.6 [b] | 4.4 [b] | 1.1 [b] | 2.6 [b] | 4.4 [b] | 1.2 [b] | 2.7 [b] | 4.4 [b] | 1.1 [b] | 2.6 [b] | 4.4 [b] |
| | August | 1.1 [a] | 2.0 [a] | 2.3 [a] | 1.1 [a] | 1.9 [a] | 2.3 [a] | 1.0 [a] | 2.0 [a] | 2.3 [a] | 0.9 [a] | 1.9 [a] | 2.3 [a] | 0.9 [a] | 1.8 [a] | 2.2 [a] | 1.0 [a] | 1.9 [a] | 2.3 [a] | 1.0 [a] | 2.0 [a] | 2.3 [a] |
| | | 1.2 [b] | 2.6 [b] | 4.4 [b] | 1.2 [b] | 2.5 [b] | 4.3 [b] | 1.2 [b] | 2.6 [b] | 4.4 [b] | 1.1 [b] | 2.5 [b] | 4.4 [b] | 1.1 [b] | 2.5 [b] | 4.4 [b] | 1.1 [b] | 2.6 [b] | 4.4 [b] | 1.2 [b] | 2.6 [b] | 4.4 [b] |
| | September | 0.9 [a] | 1.6 [a] | 2.2 [a] | 0.9 [a] | 1.7 [a] | 2.2 [a] | 0.8 [a] | 1.6 [a] | 2.2 [a] | 0.7 [a] | 1.6 [a] | 2.2 [a] | 0.7 [a] | 1.6 [a] | 2.1 [a] | 0.8 [a] | 1.7 [a] | 2.2 [a] | 0.8 [a] | 1.7 [a] | 2.2 [a] |
| | | 1.0 [b] | 2.4 [b] | 4.2 [b] | 1.0 [b] | 2.4 [b] | 4.1 [b] | 1.1 [b] | 2.4 [b] | 4.2 [b] | 1.1 [b] | 2.4 [b] | 4.3 [b] | 1.1 [b] | 2.4 [b] | 4.2 [b] | 1.1 [b] | 2.5 [b] | 4.3 [b] | 1.1 [b] | 2.5 [b] | 4.3 [b] |
| OND | October | 0.8 [a] | 1.6 [a] | 2.0 [a] | 0.8 [a] | 1.6 [a] | 2.0 [a] | 0.8 [a] | 1.6 [a] | 2.0 [a] | 0.9 [a] | 1.5 [a] | 2.0 [a] | 0.8 [a] | 1.5 [a] | 2.0 [a] | 0.9 [a] | 1.6 [a] | 2.0 [a] | 0.8 [a] | 1.5 [a] | 2.0 [a] |
| | | 1.0 [b] | 2.3 [b] | 3.9 [b] | 1.0 [b] | 2.3 [b] | 3.8 [b] | 1.0 [b] | 2.4 [b] | 3.9 [b] | 1.0 [b] | 2.4 [b] | 3.9 [b] | 1.0 [b] | 2.3 [b] | 3.9 [b] | 1.1 [b] | 2.4 [b] | 3.9 [b] | 1.0 [b] | 2.3 [b] | 3.9 [b] |
| | November | 0.6 [a] | 1.2 [a] | 1.6 [a] | 0.6 [a] | 1.2 [a] | 1.6 [a] | 0.6 [a] | 1.2 [a] | 1.6 [a] | 0.6 [a] | 1.3 [a] | 1.7 [a] | 0.6 [a] | 1.3 [a] | 1.7 [a] | 0.7 [a] | 1.3 [a] | 1.7 [a] | 0.5 [a] | 1.2 [a] | 1.6 [a] |
| | | 0.7 [b] | 1.9 [b] | 3.1 [b] | 0.7 [b] | 1.9 [b] | 3.1 [b] | 0.8 [b] | 2.0 [b] | 3.2 [b] | 0.8 [b] | 1.9 [b] | 3.2 [b] | 0.8 [b] | 1.9 [b] | 3.2 [b] | 0.8 [b] | 2.0 [b] | 3.2 [b] | 0.7 [b] | 1.9 [b] | 3.1 [b] |
| | December | 0.7 [a] | 1.3 [a] | 1.7 [a] | 0.7 [a] | 1.4 [a] | 1.7 [a] | 0.7 [a] | 1.4 [a] | 1.8 [a] | 0.6 [a] | 1.3 [a] | 1.7 [a] | 0.7 [a] | 1.3 [a] | 1.7 [a] | 0.7 [a] | 1.3 [a] | 1.7 [a] | 0.6 [a] | 1.3 [a] | 1.7 [a] |
| | | 0.7 [b] | 1.9 [b] | 3.1 [b] | 0.8 [b] | 1.9 [b] | 3.1 [b] | 0.8 [b] | 2.0 [b] | 3.2 [b] | 0.7 [b] | 2.0 [b] | 3.2 [b] | 0.7 [b] | 2.0 [b] | 3.2 [b] | 0.7 [b] | 2.0 [b] | 3.2 [b] | 0.7 [b] | 1.9 [b] | 3.1 [b] |

**TABLE 8 |** Projected percentage changes in rainfall (%) in the Kagera and Geita regions during the present (2011–2040), mid (2041–2070), and end (2071–2100) century for Representative Concentration Pathway [a](RCP) 4.5 scenario and [b]RCP 8.5 scenario.

| Seasons | Month | Chato | | | Nyang'hwale | | | Biharamulo | | | Karagwe | | | Kyerwa | | | Missenyi | | | Ngara | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 |
| JF | January | 16[a] | 29[a] | 37[a] | 9[a] | 20[a] | 21[a] | 16[a] | 23[a] | 23[a] | 22.7[a] | 42[a] | 39[a] | 22.7[a] | 42[a] | 39[a] | 13[a] | 32[a] | 28[a] | 16[a] | 27[a] | 35[a] |
| | | 20[b] | 38[b] | 46[b] | 9[b] | 21[b] | 26[b] | 16[b] | 26[b] | 26[b] | 23.8[b] | 38[b] | 48[b] | 21.3[b] | 36[b] | 46[b] | 20[b] | 33[b] | 37[b] | 18[b] | 27[b] | 38[b] |
| | February | 8[a] | 17[a] | 17[a] | 6[a] | 15[a] | 13[a] | 3[a] | 9[a] | 9.3[a] | 4.1[a] | 17[a] | 13[a] | 2.6[a] | 17[a] | 11.7[a] | 5[a] | 15[a] | 14[a] | 1.9[a] | 9.8[a] | 11.0[a] |
| | | 9[b] | 19[b] | 24[b] | 2[b] | 9[b] | 14[b] | 5[b] | 12[b] | 12[b] | 7.5[b] | 17[b] | 15[b] | 7.2[b] | 16[b] | 13[b] | 7[b] | 17[b] | 17[b] | 7.3[b] | 13[b] | 11[b] |
| MAM | March | −3[a] | −3[a] | −2[a] | −3[a] | 4[a] | 2[a] | −0.4[a] | −2[a] | −2[a] | −2.0[a] | −3[a] | −0.2[a] | −2.3[a] | −2[a] | 0.7[a] | −3.6[a] | −7[a] | −4.8[a] | −1[a] | 0.5[a] | 3.8[a] |
| | | −3[b] | −4[b] | −3[b] | −1[b] | 2[b] | 0.2[b] | −1[b] | −3[b] | −3[b] | 1.1[b] | −2[b] | −6[b] | 1.9[b] | −1[b] | −6[b] | −1.5[b] | −6[b] | −11[b] | −1[b] | 0.6[b] | −0.1[b] |
| | April | 7[a] | 6[a] | 4[a] | 6[a] | 9[a] | 13[a] | 5[a] | 4[a] | 3.7[a] | 2.8[a] | 2[a] | 2.8[a] | 4.5[a] | 3.4[a] | 4[a] | −1.2[a] | −4[a] | −3.6[a] | 4[a] | 5.8[a] | 7.1[a] |
| | | 11[b] | 2[b] | 6[b] | 13[b] | 7[b] | 17[b] | 9[b] | 1[b] | 1.2[b] | 5.7[b] | 1[b] | 5[b] | 7.2[b] | 3.3[b] | 7[b] | 0.9[b] | −6[b] | −4[b] | 11[b] | 3.0[b] | 10.3[b] |
| | May | 10[a] | 9[a] | 7[a] | 11[a] | 10[a] | 7[a] | 9[a] | 7.4[a] | 7.4[a] | 2.6[a] | 6[a] | 8[a] | 4.2[a] | 8.8[a] | 10[a] | −4.7[a] | −3[a] | −1.6[a] | 10[a] | 7.8[a] | 12.7[a] |
| | | 3[b] | 3[b] | 23[b] | 7[b] | 2[b] | 21[b] | 7[b] | 7.[b] | 7.2[b] | 0.8[b] | 5[b] | 13[b] | 2.1[b] | 8.0[b] | 15[b] | −6.3[b] | −6[b] | −2[b] | 9[b] | 8.5[b] | 15[b] |
| JJAS | June | −19[a] | 6[a] | −20[a] | −2[a] | 15[a] | −19[a] | −5[a] | −9[a] | −8.5[a] | −18.7[a] | 7[a] | 5[a] | −17[a] | 11[a] | 7.7[a] | −28.1[a] | −13[a] | −9.6[a] | −20[a] | −14[a] | −37[a] |
| | | −10[b] | 6[b] | 50[b] | −3[b] | 4[b] | 52[b] | −15[b] | −7[b] | −7.0[b] | 20.5[b] | 19[b] | 43[b] | 23[b] | 23[b] | 47[b] | 0.3[b] | −7[b] | 6.71[b] | −10[b] | −9[b] | 13[b] |
| | July | −78[a] | −32[a] | −42[a] | −61[a] | 37[a] | −2[a] | −71[a] | −32[a] | −32.2[a] | −41.3[a] | −2[a] | −8[a] | −33[a] | 11[a] | 2.6[a] | −48.8[a] | −29[a] | −40[a] | −62[a] | −38[a] | −30[a] |
| | | −63[b] | −19[b] | −19[b] | −19[b] | 10[b] | 33[b] | −42[b] | 11[b] | 10.6[b] | −44.1[b] | 0.2[b] | −7[b] | −37[b] | 12[b] | 10[b] | −53.3[b] | −38[b] | −42[b] | −50[b] | 12[b] | −39[b] |
| | August | 11[a] | −3[a] | 16[a] | −6[a] | 5[a] | 19[a] | 34[a] | −1[a] | −0.5[a] | 28.8[a] | 9[a] | 13[a] | 29.1[a] | 10[a] | 15[a] | 19[a] | −3[a] | −2.1[a] | 39[a] | −4[a] | 46.8[a] |
| | | 4[b] | 22[b] | 27[b] | 2[b] | 32[b] | 39[b] | 8.9[b] | 14[b] | 14.4[b] | 5.6[b] | 6[b] | 11[b] | 6.3[b] | 10[b] | 13[b] | 1[b] | −10[b] | −6[b] | −1[b] | 5[b] | 12[b] |
| | September | 10[a] | 13[a] | −1[a] | 9[a] | 14[a] | 1[a] | 15[a] | 16[a] | 15.9[a] | 18.6[a] | 17[a] | 11[a] | 18.3[a] | 18[a] | 13[a] | 16.5[a] | 9[a] | 0.6[a] | 15.6[a] | 13[a] | 5[a] |
| | | 4[b] | 4[b] | 4[b] | 6[b] | 4[b] | 11[b] | 7.8[b] | 9[b] | 8.5[b] | 8.9[b] | 9[b] | 5[b] | 9.1[b] | 10[b] | 8[b] | 3.6[b] | 0.2[b] | −7[b] | 5.6[b] | 6[b] | 1[b] |
| OND | October | 5[a] | 8[a] | 7[a] | 9[a] | 7[a] | 7[a] | 6.3[a] | 10[a] | 10.3[a] | 6.3[a] | 10[a] | 10[a] | 7.5[a] | 10[a] | 11[a] | 3.3[a] | 6[a] | 5.7[a] | 7.8[a] | 10[a] | 7.1[a] |
| | | 6[b] | 5[b] | 8[b] | 6[b] | 5[b] | 11[b] | 9.0[b] | 6[b] | 6.3[b] | 7.6[b] | 9[b] | 15[b] | 8.2[b] | 10[b] | 16[b] | 3.4[b] | 3[b] | 5.97[b] | 9.5[b] | 7[b] | 15[b] |
| | November | 13[a] | 17[a] | 18[a] | 8[a] | 13[a] | 14[a] | 13[a] | 15[a] | 15.3[a] | 9.4[a] | 12[a] | 15[a] | 10.1[a] | 12[a] | 15[a] | 7.2[a] | 7[a] | 12.7[a] | 13.7[a] | 14.9[a] | 17[a] |
| | | 11[b] | 15[b] | 29[b] | 6[b] | 11[b] | 25[b] | 8.8[b] | 13[b] | 13.0[b] | 9.7[b] | 15[b] | 30[b] | 10.7[b] | 16[b] | 29[b] | 5.9[b] | 9[b] | 22[b] | 9.8[b] | 14.2[b] | 31[b] |
| | December | 9[a] | 13[a] | 14[a] | 7[a] | 9[a] | 9[a] | 5.9[a] | 6.6[a] | 6.6[a] | 13.0[a] | 14[a] | 17[a] | 12.7[a] | 16[a] | 18.6[a] | 10.2[a] | 9[a] | 12.4[a] | 8.1[a] | 9.2[a] | 15[a] |
| | | 14[b] | 22[b] | 37[b] | 10[b] | 15[b] | 24[b] | 12[b] | 15[b] | 15.7[b] | 12.6[b] | 19[b] | 37[b] | 13.5[b] | 19[b] | 39[b] | 10.7[b] | 13[b] | 24[b] | 13.1[b] | 17[b] | 35[b] |

**TABLE 9** | Projected extreme climate indices related to intensity in the Kagera and Geita regions during the present (2011–2040), mid (2041–2070) and end. (2071–2100) centuries under Representative Concentration Pathway [a](RCP) 4.5 scenario and [b]RCP 8.5 scenario.

| Districts | TXx | | | TXn | | | TNx | | | TNn | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 |
| Chato | 0.02[a] (**) | 0.03[a] (**) | 0.01[a] | 0.02[a] | 0.02[a] (+) | 0.02[a] (+) | 0.03[a] (**) | 0.01[a] | −0.02[a] | 0.02[a] (**) | 0.02[a] (**) | −0.01[a] |
| | 0.034[b] (***) | 0.050[b] (***) | 0.054[b] (***) | 0.006[b] | 0.046[b] (**) | 0.033[b] (*) | 0.038[b] (**) | 0.059[b] (***) | 0.075[b] (***) | 0.035[b] (***) | 0.063[b] (***) | 0.075[b] (***) |
| Nyang'hwale | 0.02[a] (**) | 0.04[a] (***) | 0.01[a] | 0.01[a] | 0.02[a] | 0.01[a] | 0.03[a] (**) | 0.02[a] (**) | 0.02[a] | 0.02[a] (*) | 0.02[a] (**) | 0.01[a] (+) |
| | 0.034[b] (***) | 0.058[b] (***) | 0.038[b] (***) | 0.003[b] | 0.046[b] (***) | 0.046[b] (**) | 0.038[b] (*) | 0.059[b] (***) | 0.057[b] (***) | 0.038[b] (***) | 0.058[b] (***) | 0.067[b] (***) |
| Biharamulo | 0.02[a] (***) | 0.03[a] (**) | 0.01[a] | 0.02[a] | 0.02[a] (+) | 0.02[a] | 0.03[a] (**) | 0.02[a] | −0.03[a] (*) | 0.01[a] | 0.03[a] (**) | −0.01[a] |
| | 0.039[b] (***) | 0.054[b] (***) | 0.057[b] (***) | 0.003[b] | 0.043[b] (***) | 0.039[b] (**) | 0.050[b] (***) | 0.050[b] (***) | 0.069[b] (***) | 0.039[b] (***) | 0.067[b] (***) | 0.071[b] (***) |
| Karagwe | 0.02[a] (***) | 0.01[a] (+) | 0.01[a] (*) | 0.03[a] (*) | 0.02[a] (+) | 0.00[a] | 0.03[a] (*) | 0.03[a] (+) | 0.00[a] | 0.02[a] (***) | 0.02[a] (+) | 0.00[a] |
| | 0.023[b] (**) | 0.064[b] (***) | 0.06[b] (***) | 0.017[b] (+) | 0.054[b] (**) | 0.034[b] (*) | 0.033[b] (***) | 0.071[b] (***) | 0.069[b] (***) | 0.037[b] (***) | 0.075[b] (***) | 0.080[b] (***) |
| Kyerwa | 0.02[a] (**) | 0.01[a] | 0.01[a] (*) | 0.03[a] (**) | 0.02[a] (*) | 0.00[a] | 0.03[a] | 0.02[a] | 0.01[a] | 0.02[a] (***) | 0.02[a] (*) | 0.00[a] |
| | 0.022[b] (**) | 0.066[b] (***) | 0.058[b] (***) | 0.023[b] (+) | 0.055[b] (**) | 0.031[b] (*) | 0.033[b] (**) | 0.065[b] (***) | 0.07[b] (***) | 0.033[b] (***) | 0.071[b] (***) | 0.075[b] (***) |
| Missenyi | 0.02[a] (**) | 0.01[a] | 0.01[a] | 0.02[a] (*) | 0.01[a] | 0.01[a] | 0.03[a] (***) | 0.03[a] (***) | 0.01[a] | 0.02[a] (**) | 0.02[a] (*) | 0.00[a] |
| | 0.024[b] (**) | 0.069[b] (***) | 0.05[b] (***) | 0.012[b] | 0.057[b] (***) | 0.033[b] (**) | 0.035[b] (***) | 0.067[b] (***) | 0.067[b] (***) | 0.038[b] (***) | 0.071[b] (***) | 0.077[b] (***) |
| Ngara | 0.02[a] (***) | 0.02[a] (*) | 0.01[a] | 0.03[a] | 0.03[a] (**) | 0.01[a] | 0.03[a] (+) | 0.02[a] (*) | −0.01[a] | 0.01[a] | 0.02[a] (**) | −0.01[a] |
| | 0.038[b] (***) | 0.054[b] (***) | 0.061[b] (***) | 0.020[b] (*) | 0.04[b] (***) | 0.037[b] (*) | 0.047[b] (***) | 0.057[b] (***) | 0.063[b] (***) | 0.027[b] (**) | 0.062[b] (***) | 0.076[b] (***) |

*(***) trend significant at $\alpha = 0.001$, (**) trend significant at $\alpha = 0.01$, (*) trend significant at $\alpha = 0.05$, and (+) trend significant at $\alpha = 0.1$.*
*TXx, maximum daily maximum temperature; TNx, maximum daily minimum temperature; TXn, the minimum daily maximum temperature; TNn, minimum daily minimum temperature.*

extreme temperature indices as the response rates of warmer temperatures indices for adaption scenario (RCP 4.5) are lower than those of business-as-usual scenario (RCP 8.5). The cold indices TXn and TNn during the present century under RCP 4.5 scenario are likely to increase in the range of 0.01–0.03°C/year and 0.01–0.02°C/year, respectively, while under RCP 8.5 scenario, the cold indices would increase in the range of 0.003–0.023°C/year for TXn and from 0.027–0.039°C/year for TNn.

The warmest day (TXx) during the mid-century (2041–2070) would increase in the range of 0.01–0.04°C/year and 0.05–0.069°C/year under RCP 4.5 and RCP 8.5 scenarios, respectively, while the warmest night (TNx) is likely to increase in the range of 0.01–0.03°C/year and 0.05–0.071°C/year under RCP 4.5 and RCP 8.5 scenarios, respectively (**Table 9**). On the other hand, the coldest day (TXn) during the mid-century would increase in the range of 0.01–0.03°C/year and 0.04–0.057°C/year under RCP 4.5 and RCP 8.5 scenarios, respectively. While the coldest night (TNn) is likely to increase in the range of 0.01–0.02°C/year and 0.027–0.039°C/year under RCP 4.5 and RCP 8.5 scenarios, respectively (**Table 9**).

In the end century (2071–2100), the warmest day (TXx) would increase at 0.01°C/year under RCP 4.5 scenario and in the range of 0.038–0.061°C/year under RCP 8.5 scenario. While the coldest day (TXn) is likely to increase in the range of 0–0.02°C/year and 0.031–0.046°C/year under RCP 4.5 and RCP 8.5 scenarios, respectively (**Table 9**).

The analysis of rainfall extreme indices reveals that during the present century (2011–2040) under RCP 4.5 scenario, four districts (Chato, Biharamulo, Karagwe, and Ngara) would experience a statistically significant increasing trend in the maximum 1-day precipitation of 0.1, 0.1, 0.01, and 0.08 mm/year, respectively (**Table 10**). On the other hand, during the present century, Misenyi is likely to experience a statistically decreasing trend in maximum 1-day precipitation by−0.056 mm/year. At the end century (2071–2100) under RCP 8.5 scenario, Karagwe and Kyerwa would experience a statistically significant increasing trend in maximum 1-day precipitation of 0.126 and 0.120 mm/year, respectively.

During the present century (2011–2040) under RCP 4.5 scenario, the maximum 5-day precipitation shows a non-statistically increasing trend across all districts. However, in the mid-century (2041–2070), Kyerwa and Missenyi would experience a statistically significant increase in maximum 5-days precipitation of 0.11 mm/year for RCP 4.5 scenario and 0.202 mm/year for RCP 8.5 scenario, respectively (**Table 10**). In the end century (2071–2100), Nyang'hwale, Karagwe, and Missenyi are likely to experience a statistically significant increasing trend in maximum 5-days precipitation of 0.28, 0.18, and 0.26 mm/year, respectively, for RCP 4.5 scenario (**Table 10**).

## CONCLUSION AND RECOMMENDATION

In this study, the analysis of climate change and extreme climatic events in the Kagera and Geita regions has been carried out using the outputs from the CORDEX-RCMs. Daily simulated climate

**TABLE 10 |** Projected extreme climate indices related to intensity in the Kagera and Geita regions during the present (2011–2040), mid (2041–2070) and end. (2071–2100) centuries under Representative Concentration Pathway [a](RCP) 4.5 scenario and [b]RCP 8.5 scenario.

| Districts | RX1day | | | RX5day | | |
|---|---|---|---|---|---|---|
| | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 |
| Chato | 0.10[a] (*) | 0.03[a] | 0.06[a] | 0.13[a] | 0.01[a] | 0.15[a] |
| | −0.025[b] | −0.025[b] | −0.077[b] | −0.136[b] | 0.019[b] | −0.106[b] |
| Nyang'hwale | −0.01[a] | 0.00[a] | 0.05[a] | 0.00[a] | 0.22[a] | 0.28[a] (*) |
| | −0.012[b] | 0.002[b] | 0.046[b] | 0.004[b] | −0.097[b] | 0.032[b] |
| Biharamulo | 0.10[a] (*) | −0.02[a] | 0.03[a] | 0.09[a] | −0.06[a] | 0.06[a] |
| | 0.009[b] | −0.012[b] | −0.077[b] | −0.076[b] | 0.014[b] | −0.068[b] |
| Karagwe | 0.08[a] (*) | 0.04[a] | 0.04[a] | −0.04[a] | 0.08[a] | 0.18[a] (*) |
| | −0.032[b] | 0.030[b] | 0.126[b] (*) | 0.046[b] | 0.142[b] | 0.092[b] |
| Kyerwa | 0.05[a] | 0.07[a] | 0.04[a] | −0.06[a] | 0.11[a] (+) | 0.12[a] |
| | −0.017[b] | 0.037[b] | 0.120[b] (*) | 0.040[b] | 0.108[b] | 0.047[b] |
| Missenyi | −0.01[a] | 0.00[a] | −0.02[a] | −0.12[a] | −0.02[a] | 0.26[a] (*) |
| | −0.056[b] (**) | 0.059[b] | 0.085[b] | −0.072[b] | 0.202[b] (+) | −0.103[b] |
| Ngara | 0.08[a] (*) | −0.0[a] | 0.00[a] | 0.01[a] | 0.10[a] | 0.04[a] |
| | −0.002[b] | 0.028[b] | 0.036[b] | −0.024 | −0.010[b] | 0.047[b] |

*(**) trend significant at $\alpha = 0.01$, (*) trend significant at $\alpha = 0.05$, and (+) trend significant at $\alpha = 0.1$.*
*RX1day, maximum 1-day precipitation amount; RX5day, maximum 5-days precipitation amount.*

variables (rainfall and minimum and maximum temperatures) from the CORDEX-RCMs were used as input into the RClimDex software for computation of extreme climate events during historical (1971–2000) climate condition and future climate projection (2011–2100) under two RCP (RCP 4.5 and RCP 8.5) emission scenarios. The existence, magnitude, and statistical significance of potential trends in climate data time series were estimated using the Mann–Kendall (MK) nonparametric test and Theil-SEN slope estimator methods.

Results from the analysis revealed that there has been a significant increase in temperature in all districts in the Kagera and Geita regions. This has been observed in historical (1971–2000) and projected climate condition during the present (2011–2040), mid (2041–2070), and end (2071–2100) centuries under both RCP 4.5 and RCP 8.5 emission scenarios. Moreover, rainfall has decreased in the historical climate, while in future climate, it is predicted to increase especially during October, November, December season. In the long rainy season (MAM, rainfall is projected to decline especially in March (the beginning of the long rainfall season). These results support the previous studies (Nicholson, 2017; Wainwright et al., 2019; Borhara et al., 2020; Ogega et al., 2020) that indicated a decline in long rainy season (MAM) and an increase in short rainy (OND) season. It is especially important to note here that the analysis revealed a significant increase in extreme climate events. The number of warm nights and warm days is projected to increase significantly, cold days and cold nights are projected to decline significantly, and the number of extreme wet days is projected to increase significantly is some districts. In general, the intensity, duration, and frequency of extreme climate events in Kagera and Geita are likely to increase significantly. These results agree with what was reported by Ogega et al. (2020) that extreme climate indices related to rainfall are projected to increase in the East African region. This will present a serious challenge to many sectors; in particular, the agriculture sector will be at the highest risk (Velásquez et al., 2018). Therefore, there is an urgent need to plan and develop adaptation options on climate-related threats. There is an urgent need to develop adaptation strategies to withstand the projected significant increase in minimum temperatures. As it is well-known that higher minimum temperatures affect the respiration process of many crops. This process tends to increase with the increase in minimum temperature. On the other hand, photosynthesis is affected by moisture availability and carbon dioxide concentration. The length of the growing season is severely affected by the increase in temperatures (Luhunga et al., 2016). The projected increase in extreme wet days in the Kagera and Geita regions is likely to present a significant challenge to the agriculture sector (Velásquez et al., 2018). Therefore, actionable adaptation options must be put in place to reduce the impacts of climate change to the agriculture sector.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

The data search and analysis was done by PL. The validation of the model data was done by AS. Results analysis and manuscript writing was done by both authors. All authors contributed to the designing, analyzing, and writing of the manuscript.

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# Co-designing Indices for Tailored Seasonal Climate Forecasts in Malawi

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In central and southern Malawi, climate variability significantly impacts agricultural production and food availability owing to a high dependence on rain-fed maize production. Seasonal climate forecast information has the potential to inform farmers' agricultural planning, thereby improving preparedness to extreme events. In this paper we describe and evaluate an approach to co-designing and testing agro-climatic indices for use in seasonal forecasts that are tailored to farmer-defined decision-making needs in three districts of central and southern Malawi. Specifically, we aim to (a) identify critical maize specific agro-climatic indices by engaging key stakeholders and farmers; (b) compare and triangulate these indices with the historical climate record in study districts; and (c) analyze empirical relationships between seasonal total rainfall and maize specific indices in order to assess the potential for forecasting them at appropriate seasonal timescales. The identified agro-climatic indices include critical temperature/rainfall thresholds that are directly associated with phenological stages of maize growth with direct implications for maize yield and quality. While there are statistically significant relationships between observed wet season rainfall totals and several agro-climatic indices (e.g., heavy rainfall days and dry spell), the forecast skill of the UK Met Office's coupled initialized global seasonal forecasting system (GloSea5) over Malawi is currently low to provide confident predictions of total wet season rainfall and the agro-climatic indices correlated with it. We reflect on some of the opportunities and challenges associated with integrating farmers' information needs into a seasonal forecast process, through the use of agro-climatic indices.

**Keywords: agro-climatic indices, Africa, maize, farmers, decision making**

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## INTRODUCTION

In central and southern Malawi, climate variability significantly impacts agricultural production and food availability owing to a high dependence on rain-fed maize production (Fisher and Lewin, 2013). A large majority of maize growing farmers are involved in semi-subsistence farming and are vulnerable to frequent exposure to climate extremes (Stevens and Madani, 2016). Investment in the development and improvement of seasonal climate forecasts (SCF) is seen as a potential means to improving the preparedness and resilience of agriculture in this context (Ziervogel and Opere, 2010; Kalanda-Joshua et al., 2011; Hansen et al., 2019). However, forecasting climate extremes and agricultural impacts in central and southern Malawi is challenging for a variety of technical reasons, including the relative lack of forecast model skill over Malawi, as the country lies in the transition zone of the dipole pattern for the ENSO-rainfall teleconnection (Jury et al., 1992; Diro, 2016), and there is limited availability of observational data to evaluate forecast skill or calibrate models at small spatial scales (Dinku et al., 2014).

There is also a significant knowledge gap around the use of SCF and how it interacts with farmers' information needs for on-farm decision making processes (Simelton et al., 2013; Coulibaly et al., 2015; Vincent et al., 2017; Clarkson et al., 2019; Tembo-Nhlema et al., 2019). The design and delivery of SCFs is rarely informed by a clear understanding of the timelines around agricultural and livelihood decision making (Ingram et al., 2002; Hansen et al., 2019), or the impacts of weather on crop-specific growth and development stages (Cairns et al., 2013). This limits the potential for translating forecasts into locally relevant and crop-specific indices that can inform farm-level decision making (Klopper et al., 2006; Hansen et al., 2019). Hewitt et al. (2012) argue that an effective climate service must have a credible scientific basis, and appropriately engage and meet the needs of users. There is a growing recognition amongst the climate services community (Vaughan et al., 2018; Bruno Soares and Buontempo, 2019; Hansen et al., 2019), that participation of the users of climate information across the design and delivery of climate service tools can help in both addressing technical knowledge gaps (Kniveton et al., 2015; Meadow et al., 2015) and improving the contextual relevance and uptake of information (Roncoli et al., 2008; Vincent et al., 2018).

There is evidence that suggests that observed crop responses to weather and climate can be explained using a relatively simple set of agro-climatic indices (Tadross et al., 2009; Trnka et al., 2011; Mathieu and Aires, 2018). In essence, this reduces the complexity of climate–crop impacts to a few key relationships and thresholds (Lobell and Field, 2007). Conventionally, indices are developed in a techno-scientific way, derived and validated through combinations of complex crop models and controlled experimental observation data (Tadross et al., 2009; Mathieu and Aires, 2018). However, in this study we start from the premise that such indices hold potential as a means for bringing together alternative knowledges, in order to tailor SCF information to the specific locations and needs of maize farmers in Malawi. We aim to contribute toward ongoing efforts in co-producing weather and climate services by implementing and evaluating a participatory approach to the development of agro-climatic indices for SCF, which starts from the experiences and decision-making processes of farmers themselves. We describe and evaluate a participatory research study in three Districts of southern and central Malawi as a means to identifying relevant and useful agro-climatic indices that add value to existing seasonal forecast services.

We calculate these farmer-derived indices using weather station observations to understand the recorded frequency and intensity of identified indices and analyze historical relationships between these indices and variables commonly described in seasonal forecast outputs, such as total seasonal rainfall. We also evaluate the skill of the UK Met Office's coupled initialized global seasonal forecasting system (GloSea5) over Malawi. Specifically, we

(a) identify critical maize specific agro-climatic indices that influence crop management practices in three districts of central and southern Malawi by engaging key stakeholders and farmers;
(b) compare and triangulate these indices with the historical climate record in these districts;
(c) analyze the statistical characteristics of maize specific agro-climatic indices, and quantify their correlations with wet season rainfall totals.

## RAIN-FED MAIZE AGRICULTURE AND SEASONAL CLIMATE FORECASTS IN MALAWI

In Malawi, small-scale, semi-subsistence rain-fed agriculture contributes to about 70% of total agricultural production. This is dominated by maize which covers about 50% of the total cultivated land and is grown by 97% of farmers (African Development Bank, 2018). Recent weather events including flooding due to cyclone *Idai* in March 2019, and rainfall extremes associated with the 2015–16 El Niño event, directly impacted agricultural production and affected millions of livelihoods (African Development Bank, 2018). Altered rainfall distributions and reduced rainfall quantities interact with farm-level decision-making (for example decisions related to the choice of planting dates) to either exacerbate or mitigate impacts in terms of crop losses, labor burdens, input costs, and more (Jew et al., 2020). This close connection between maize production and weather and climate suggests that actionable SCF play an important role in farmers' decision-making throughout the maize growing season.

In Malawi, seasonal forecasts are produced by the Department for Climate Change and Meteorological Services (DCCMS). In September the forecast is communicated to the Department of Agricultural Extension Service (DAES). Information is passed down from DAES to Agricultural Extension Development Officers (AEDOs) through District Agricultural Development Officer (DADO) in each Agricultural Development Districts (ADD) before reaching the lead farmers and other farmers in advance of the main growing season. These forecasts, at both National and District levels, are expressed as the probabilities for three tercile categories of predicted seasonal total rainfall: below-normal (dry conditions), normal (around the average), and above-normal (wet conditions). A probability is assigned to each category, indicating the chance of the category occurring during the target season at district level. As such, the forecast probabilities indicate both the direction of the forecast, as well as the amount of confidence in the forecast, accounting for the broad range of uncertainties that are inherent in forecasting (e.g., uncertainty in key physical processes, incomplete observations, etc.). However, these tercile forecasts are not updated frequently throughout the growing season (Venäläinen et al., 2016; Tembo-Nhlema et al., 2019), and lack targeted information for the agricultural sector, such as risk of dry spells occurrence during key maize growth stages (Simelton et al., 2013), making forecasts less useful for farmers evolving information needs.

## RESEARCH METHODS

### Choice of Pilot Districts

The study focuses on three pilot districts in central and southern Malawi: Salima, Mangochi, and Zomba. These districts were selected on the basis of area under rainfed maize cultivation, drought, flood, and food security risk assessments (World Bank, 2009), and the presence of ongoing activity associated with the uptake and use of seasonal climate forecasts through both the Malawi Red Cross Society (MRCS) and the Participatory Integrated Climate Services for Agriculture training (PICSA) programme (**Table 1**). MRCS is involved building community resilience and scaling up nutrition through various projects on disaster risk reduction and preparedness such as on. MRCS is also involved in forecast-based financing across Malawi, whereby triggers are being developed to initiate early action and to release funding before the occurrence of floods or droughts event. PICSA with support from the World Food Programme (WFP) has trained ∼20,000 lead farmers and 200,000 farmers across 10 districts in Malawi to use both historical climate information and seasonal forecast to make informed decisions at individual farm level such as choice of relevant crop variety, livestock, and livelihood options (UNDP, 2020).

The process of identifying study districts also involved consulting a wide range of stakeholders to understand the current landscape of agricultural climate services in Malawi. This consultation took place in in November 2018 and involved meeting representatives from the Department of Agricultural Extension Service (DAES), National Smallholder Farmers' Association of Malawi (NASFAM), Farm Radio Trust, United Nations Development Programme (UNDP), World Food Programme (WFP), Food and Agriculture Organization (FAO), and the Department for Climate Change and Meteorological Services (DCCMS). The consultations with these organizations helped to: (i) align our research with existing in-country on-going research and application; (ii) avoid duplication of efforts in terms of location and research foci; (iii) add value to existing or planned agricultural climate services activity.

### Focus Group Discussions

We carried out focus group discussions (FGDs) in specific Extension Planning Areas (EPAs) within each district. The EPAs are sub-district administrative units for which agricultural extension service delivery, an important mechanism for the dissemination of forecast information, is carried out. The selected EPAs have PICSA and MRCS ongoing projects focusing on early warning early action and farmer engagement in weather services delivery and have at least one weather station with a long-term observational record. The chosen EPAs also provided scope for understanding spatial resolution and heterogeneity (if exists) in agro-climatic indices by allowing for intra-district (across three EPAs in Mangochi; Nankumba, Mbwadzulu, and Maiwa) and inter-district (one EPA each in Salima; Khombedza and Zomba; Mpokwa) comparison (**Figure 1**).

FGDs were used to identify the maize-specific agro-climate indices that are important determinants of crop management practices. FGDs were selected as the preferred method to engage with farmers and Agricultural Extension Development Officers (AEDOs) across the three districts as it allows the discussion and interaction of a specific group in relation to a particular topic of interest (Bryman, 2016). We conducted 15 FGDs between April and May 2019 across five EPAs; 10 FGDs with farmers and 5 FGDs with Agricultural Extension Development Officers (AEDOs). The AEDOs are farm advisors who work closely with farmers and farming households in communicating seasonal forecast information and providing relevant farm, crop, and livestock management advice. The farmers involved in the FGD were selected by the AEDOs and included both male and female farmers (and amongst which one or more than one was the lead farmer i.e., farmer representative). In total, 70 female farmers and 48 male farmers, and 21 AEDOs participated in the FGDs. The age of male farmer and female farmer participants ranged from 28–58 to 20–54, respectively. The FGDs were conducted in the local language Chichewa, facilitated by a local research assistant who audio recorded, translated and transcribed the discussions. The FGDs were conducted with the support of the MRCS and its district offices in Salima, Mangochi, and Zomba. The MRCS and their district officies have developed trusted relationships with AEDOs and farmers in the selected EPAs through their preparedness and relief work during flood and drought events.

We followed a protocol to conduct the FGD (outlined in full in **Appendix 1**) by which farmers collectively constructed a seasonal calendar, chronologically describing key farm level activities and decisions throughout the year. Decision calendars can be used as tools for identifying and organizing information about the timing of decisions of specific users and thus provide useful entry-points for understanding climate information needs and how to best tailor existing climate services products (Bert et al., 2006; Ray and Webb, 2016). The discussion focused on identifying crucial farm activities and describing how they depended upon or are affected by weather conditions, crop and field conditions during normal and extreme years, and non-climatic factors affecting farm decisions under normal and extreme weather conditions in different months. We used information on how extreme weather conditions negatively affect crop growth and farm decisions to identify crucial months for maize growing farmers, critical weather conditions affecting maize growth in the region.

From the collected qualitative data, we coded and organized climate and farm decision-making information according to month of the maize growing season. We also extracted farmer responses regarding specific seasonal climatic phenomenon or event which led to adverse impacts on crops, or affected crop management decisions and their timing, so that we could derive a cause-effect relationship. Where possible, we identified thresholds above or below which the particular phenomenon/event had adverse implications on maize yields, so that this could be distilled into a combination of agro-climatic indices and their threshold values. We found it difficult to

**TABLE 1 |** Criteria for selecting the pilot districts.

| Districts | Area under rainfed maize 2017[a] | Drought prone category[b] | Flood prone category[c] | Food security risk[d] | PICSA | MRCS |
|---|---|---|---|---|---|---|
| Salima | 38,212 (31%) | High | High | Medium | | ✓ |
| Mangochi | 90,267 (30%) | High | High | Medium | ✓ | ✓ |
| Zomba | 79,865 (48%) | Medium | High | High | ✓ | ✓ |

[a]*Malawi food security outlook 2017–18, FEWS NET in (hectares and percentage of total district agricultural area).*
[b]*Risk assessment based on drought return period (RP) for the period 1968–2007—Low (RP >10 year); Medium (RP 4–10 year); High (RP 2–4 year).*
[c]*Risk assessment based on number of households affected during 2000–2010.*
[d]*Based on 10-year (2005–2014) data collection by Malawi Vulnerability Assessment Committee (MVAC).*

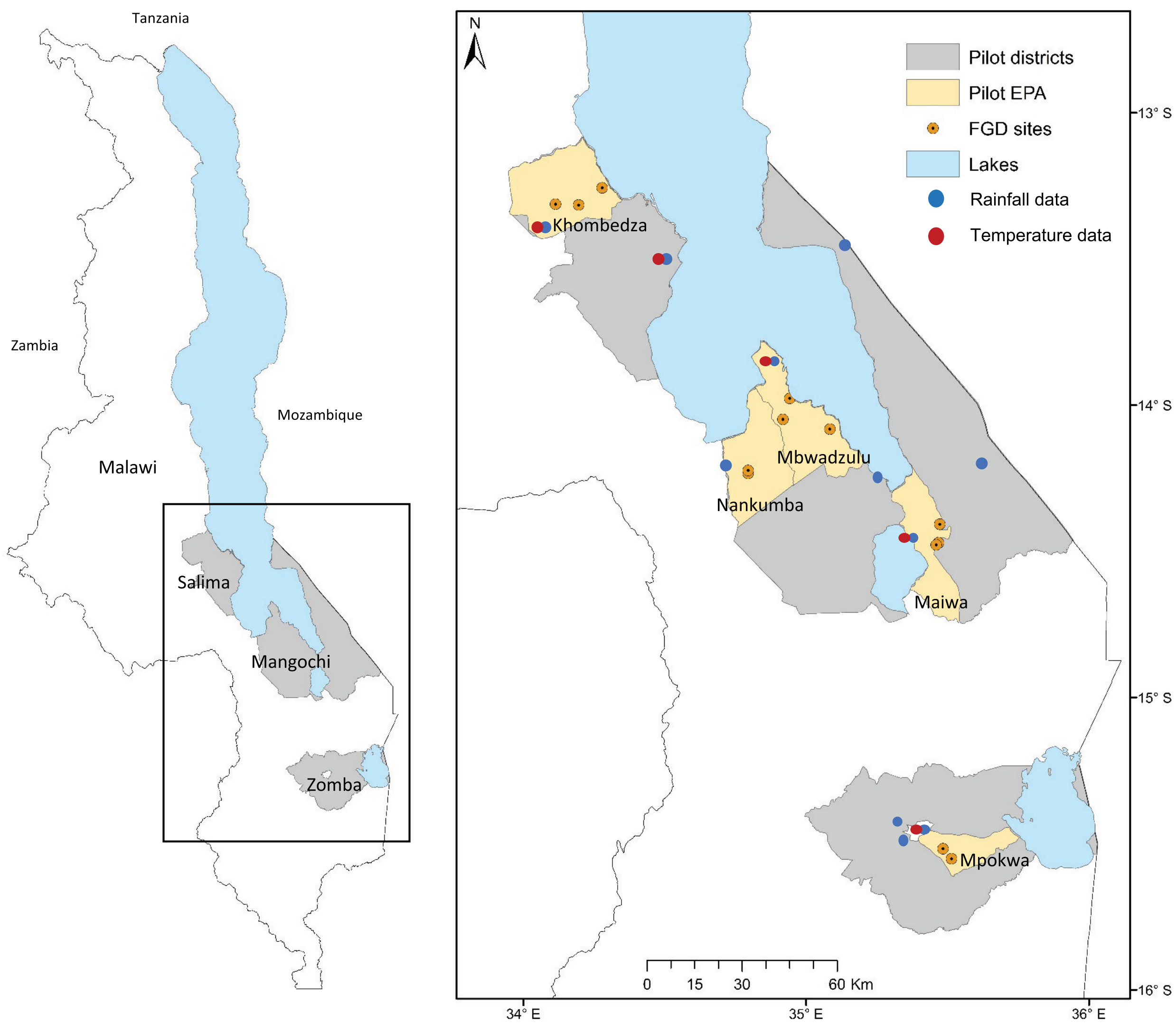


**FIGURE 1 |** Location of Salima, Mangochi, and Zomba districts in central and southern Malawi (left), highlighting selected Extension Planning Areas (EPA), focus group discussion (FGD) locations, and the availability of rainfall and temperature observational data within these districts (right).

identify specific thresholds for these indices from FGDs. The farmers and AEDOs provided the qualitative descriptions of the indices in form of impact of extreme weather events on maize growth, their farm decisions and livelihoods but not in terms of the amount of rainfall or temperature threshold that affected the maize yield or growth. Therefore, we followed an iterative process of engaging the meteorologists from the DCCMS while identifying, testing, and validating the thresholds drawn from the peer-reviewed literature.

## Station Data

The identified agro-climatic indices (**Table 2** results section) were calculated from long-term observations of daily temperature and rainfall. The 12 weather stations used for this analysis are all located within the Lakeshore Area and Shire Highlands climatic forecasting zones, as designated by DCCMS. Salima and Mangochi districts are part of Lakeshore area, and Zomba district is part of Shire Highlands (**Figure 1**). Missing data were handled on a case-by-case basis, depending on the implications for the subsequent calculations. Because wet season rainfall totals and agroclimatic indices were calculated on an annual basis only, any years which contained substantial gaps in the daily data (e.g., missing a block of at least 30 days, as defined by DCCMS) were removed from the analysis. The rainfall data at these stations span 39–119 years with a mean length of 58 years, while the temperature data span 25–55 years with a mean length of 39 years. All rainfall datasets, and 10 out of 12 temperature datasets, extend for more than 30 years. None of the datasets are shorter than 15 years, which is a minimum duration over which climate variability can be evaluated (Dunning et al., 2016). As such, the data provides an informative sample of Malawi's climate for the two zones from which these observations are drawn, as well as the study districts.

## Defining the Wet Season and Computing Correlations Between Wet Season Rainfall and Agro-Climatic Indices

For each of the identified agro-climatic index, we calculate the annual frequency of agro-climatic event occurrence for the time windows identified as agriculturally relevant in the elicitation process. For all indices except "delayed onset of rains" and "high temperature and dryness" we explore correlations between the annual frequency of the event occurrence, during the months relevant to that index, and the corresponding total wet season rainfall that year. Since some of the agro-climatic events are relatively rare within individual months, we predominantly calculate the correlations across the entire wet season to maximize the likelihood of identifying robust statistical relationships. The aim is to provide information on both the climatological properties of the indices, and also to assess whether skillful seasonal forecasts of total wet season rainfall could indirectly provide information about important agro-climatic indices. Since the annual frequency is a discrete count, we use Poisson regression to quantify its association with total wet season rainfall total, which is continuous We use McFadden's pseudo-$R^2$ statistic (Heinzl and Mittlböck, 2003) to quantify the goodness of fit of the relationship between the agro-climatic indices and total wet season rainfall. Pseduo-$R^2$ is calculated as 1-(deviance/null deviance) of the fitted relationship, where the deviance quantifies how well the model predicts the observed values, and null deviance is the same expression but under the null hypothesis that the agro-climatic index is independent of total wet season rainfall. Smaller deviance values indicate a better model fit, meaning that pseudo-$R^2$ values closer to 1 suggest that the fitted model is better at predicting the agro-climatic index than the null model. All analysis was carried out using R.

To calculate total wet season rainfall for each location, it is first necessary to estimate onset and cessation dates for each wet season, and then calculate the total precipitation between these dates. Malawi's wet season is driven by the seasonal progression of the Intertropical Convergence Zone (ITCZ). This zonal band of convective and precipitative maxima migrates south in the austral spring (September–November), bringing the first rains and heralding the onset of the wet season, while its equatorward return during the austral autumn (March–May) is associated with the wet season's cessation. Our approach to total wet season rainfall calculation follows the method outlined in Liebmann and Marengo (2001), adapted to calculate the onset and cessation dates for each year and station. See Liebmann and Marengo (2001) and Dunning et al. (2016) for further details.

## Frequency Analysis for "High Temperature and Dryness" and "Delayed Onset of Rains"

Since it is determined by both temperature and precipitation, the "high temperature and dryness" index cannot be straightforwardly correlated with total wet season rainfall. Instead, we focus on exploring the climatological properties of this index. Since these events are rare in the observational record, we use the mean number of events per year at each station as the rate parameter ($\lambda$) of the Poisson distribution, which gives a better estimate of the annual probability that several events will occur in a year. We repeat this approach for three duration thresholds, i.e., identifying "high temperature and dryness" conditions which occur for $\geq$ 14 consecutive days, $\geq$10 consecutive days and $\geq$7 consecutive days (see **Supplementary Table 3**). We explored changing the duration thresholds identified during the FGDs because some events were extremely infrequent in the observational station record. The threshold for these indices were adjusted through iterative discussions between project scientists and meteorologists at the DCCMS during the indices identification stage and climate analysis stages.

Similarly, the "delayed onset of rains" index is assessed by estimating the likelihood of "true" and "false" wet season onsets using the following definition: "onset occurs when $\geq$25 mm rainfall accumulated in 3 consecutive days, which should not be followed by 10 consecutive dry days (CDD; rainfall <2 mm) in the following 20 days" (Kniveton et al., 2009; Tadross et al., 2009), based on iterative discussions with the DCCMS. According to this definition, the occurrence of <10 CDD within the 20 days following the $\geq$25 mm "event" will be considered a "true" onset. This definition is used to categorize potential wet season onset dates throughout November and December as true or false. Then, comparing the number of false onsets to the total number of onsets gives the proportion of "true" to "false" onsets.

**TABLE 2 |** Details of identified maize specific agro-climatic indices, and corresponding critical months, thresholds, empirical relationship with total wet season rainfall.

| | Identified agro-climatic indices | Critical months | Thresholds | Relationship between index and total seasonal rainfall (frequency analysis of historical records for 5 and 6) across all stations |
|---|---|---|---|---|
| 1. | Heavy rainfall | Nov–Jan | Daily rainfall ≥30 mm (flood management, remove ground cover which obstructs the flow) | $r = 0.42$–$0.70$. Mean $r = 0.58$, significant at 1% level |
| 2. | Dry spell | Nov–March | 10 consecutive dry days (daily rainfall <2 mm) | $r = -0.22$ to $-0.56$. Mean $r = -0.41$, significant at 10% level |
| 3. | Prolonged dry spell | Feb–mid-April | 14-day drought (daily rainfall <2 mm) | Weakly negative ($r \approx -0.1$ to $-0.6$) correlation with total seasonal rainfall statistically significant at 15% level for any station. |
| 4. | Consecutive 10-day rainfall | March–April | Daily rainfall ≥10 mm | Frequency analysis of observations shows that the combination of threshold-duration does not occur at any station used in this analysis. Observations show events of up to 4 consecutive rainy days with ≥10 mm daily rainfall. |
| 5. | High temperature and dryness | Jan–March | Tmax. >30°C represents heat stress to maize during it reaches ripening phase (Steward et al., 2019). This index (hot-dry days) is for ≥14 consecutive days with daily rainfall <2 mm. | Frequency analysis at stations with temperature and rainfall data shows that annual probability of one or more such events occurring is highest at Monkey Bay station (17.5%), followed by Mangochi station (10.5%). The annual probability increases when the threshold duration is reduced. |
| 6. | Delayed onset of rains | Nov–Dec | 25 mm of accumulated rainfall in over 3 consecutive days without 10 consecutive dry days (rainfall <2 mm) occurring in the next 20 days (Tadross et al., 2009, DCCMS) | Mean probability of a false wet season onset in November and December is ∼18% overall (all occurrences) and ∼16% per year. |

## Seasonal Forecast Model

To assess the potential to improving seasonal rainfall forecasts in Malawi, we evaluate the skill of the UK Met Office's Global Seasonal Forecast System 5 (GloSea5; MacLachlan et al., 2015; Walker et al., 2019) at predicting total wet season rainfall, which show higher skill than Greater Horn of Africa Climate Outlook Forum (GHACOF) consensus-based forecasts (Walker et al., 2019). To do this, retrospective seasonal forecast model runs were initialized on September 1st and October 1st over the period 1993–2015, and then run for 210 days to give forecasts of October–March and November-April rainfall. We quantify the skill of GloSea5 seasonal hindcasts of rainfall for Malawi, relative to the WATCH Forcing Data applied to ERA-Interim (WFDEI) reanalysis precipitation dataset (Weedon et al., 2014). For each initialization, early (OND/NDJ), late (JFM/FMA), and full wet season (ONDJFM/NDJFMA) hindcast skill across the entire country is evaluated using tercile Relative Operating Characteristic (ROC) curves and rainfall anomaly timeseries comparisons. Although skill varies regionally across Malawi, we present results only for the domain average (8–18° S, 32–36° E) to test if GloSea5 is generally skillful in the region. The horizontal resolution of the model (∼50 km) is not high enough to provide reliable information at the district level.

# RESULTS AND ANALYSIS

## Identification of Maize Specific Climate Indices and Their Thresholds

Across five EPAs in three districts, agro-climatic indices that impact maize growth during particular phenological phases were identified. These are (i) delayed onset of rains during the establishment phase; (ii) heavy rainfall events during vegetative and flowering phase; (iii) dry spells and prolonged dry spells during the entire maize growth phase; (iv) hot and dry incidences during flowering and yield formation phase; and (v) consecutive rain days during the yield formation and ripening phase. **Figure 2** summaries the linkages between maize growth phases/stages and farm practices as well as the implications weather related events can have on these during the main maize growing season from November to April. Despite subtle differences in their farm activities during each calendar month across the five EPAs, famers' SCF information needs during the crucial months of maize growth and production remains the same. These farm practices are strongly dependent upon the amount and timing of rainfall during November-April season.

> "We plant maize soon after the first rains, they start between 15th and 30th November, we have rainfall once a week followed by sunny weather" (male farmer, Mpokwa EPA).

Similar information on the onset of rains was echoed by farmers across all EPAs. Farmers in different EPAs recall different years as extreme/bad years. Mpokwa farmers gave an example of 2012–13 event, when in January 2013, they planted maize for the 6th time before consistent rains began which resulted in a shorter growing period and delayed harvest. Information about the onset of rains during September–October months was considered as most useful potential agro-climatic indicator by participants as a reliable forecast of this can help with preparing land in time,

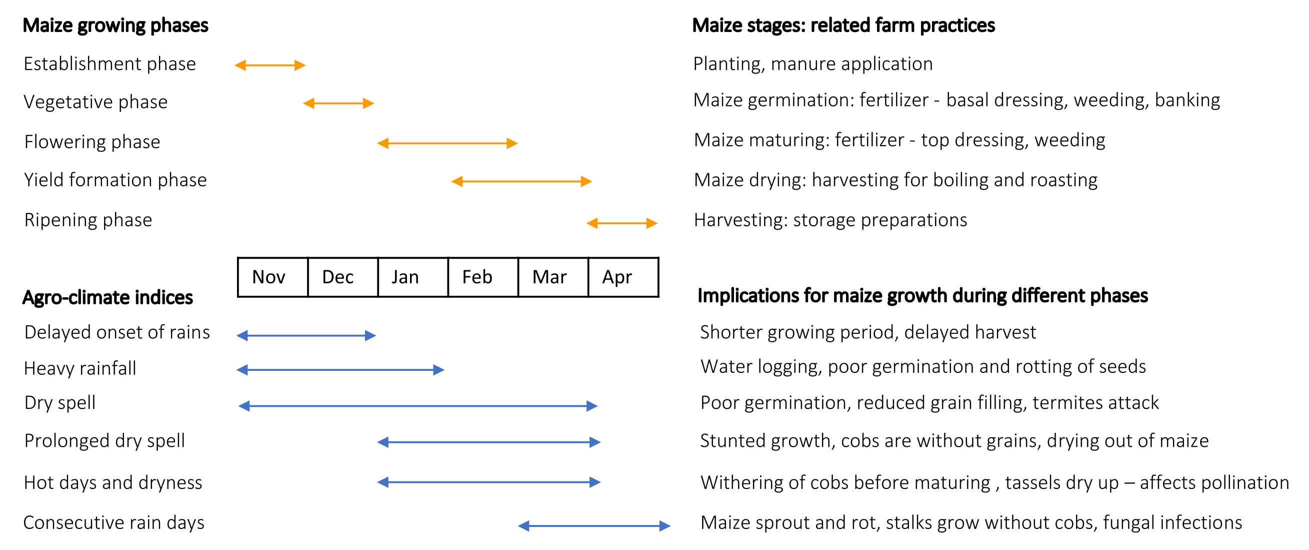


**FIGURE 2 |** Linkages between different phenological stages of maize growth and farm practices during November to April rainy season, and identified maize-specific agro-climate indices and their implications on maize growth and yield.

buying the right seed variety and other necessary inputs such as fertilizers, and budgeting for the season.

Similarly, heavy rainfall events early in the season necessitated weeding before planting began, while their occurrence after planting led to poor germination and rotting of seeds, washing away of fertilizer causing plant wilting, worm infestation, and loss of precious resources (seeds and fertilizer).

> "Due to heavy rains after planting, it takes many days for the maize seeds to germinate. And when we go check, we find that some seeds have rotten. We end up replanting and the same thing happens. In some planting stations, the seeds have not germinated. In the end, there is no uniformity in the growth of the maize plants. And that gives us no hope for a good harvest" (male farmer, Maiwa EPA).

Farmers suggested that excessive multi-day rainfall relatively early into the season caused soil leaching as well waterlogging and flooding of fields. Conversely, such an event later into the season can cause either the maize stalks to only grow tall without developing cobs because of Witch weed (*Kaufiti*) infestation, or it can delay harvesting.

Dry spells cause a myriad of issues from lack of water availability to disease infestation. Dry spells in 2017–18 (Nankumba), 2015–16 and 2017–18 (Khombedza) caused crop withering as well as crops suffering from fall armyworms and termite attacks. Information about dry spells especially during the rainy season could help farmers to decide which varieties of maize they can plant.

> "We plant early maturing maize varieties when we are informed that there will be few rains in our area in January, so that our crops are already matured by then" (male farmer, Khombedza EPA).

Prolonged dry spells lasting a month in December affects seed germination, but their occurrence in January and February causes withering away of crops. In 2010–11, Mpokwa farmers experienced permanent wilting and stunted crop with many cobs without grains because of a long February dry spell, while a 5-week spell in 2017–18 in Khombedza caused scarcity of water for irrigation and fall army worm disease. Since prolonged dry spell affect the maize maturing and its drying, it results in reduced yield and limits the chances of early harvest of maize for household consumption.

We observe a propensity of farmers to elicit a need for rainfall-related weather and climate information compared to temperature, as others also have (Haigh et al., 2015; Klemm and McPherson, 2018). However, we also find that a combined understanding of weather related events and their impacts on the maize growth stags reveals a complex climate information need during maize maturing and drying stages from January to March i.e., temperature-rainfall climate index—an index of high temperature and dryness (see **Table 2** for details).

A combination of prolonged high temperature and dry weather during the rainy season, such as the 2000–01 drought in Mbwadzulu, severely affected the crop predominantly through pest infestation and plant/crop wilting. Farmers and AEDOs use the terms *masiku otentha* meaning hot days, *masimu otentha kwambiri* meaning very hot days, and *nyengo yothentha* meaning it's hot; interchangeably to discuss high temperature days.

> "We often have dry spells in January and our crops wither, turn yellow and are attacked by diseases. This is also because of high temperatures when the tassels are dry, there is no pollination. It normally lasts a week but if the dry spell lasts two to three weeks, we are greatly affected" (female farmer 1, Mbwadzulu EPA).

> "With the high temperatures, we delay with fertilizer application and it is too late to do the application after the maize plants have developed cobs" (female farmer 2, Mbwadzulu EPA).

Since these hot and dry events affects the crop at a relatively advanced stage, it is vital to understand how likely it is to occur, because as the season progresses, the farmer gets progressively locked-in to the agricultural management practice adopted for the season. Participants expressed that information about high temperature and dryness could be very valuable in helping farmers to (or not to) plan re-planting activities, in case first planting fails, as high temperature and dryness lead to drying of soil resulting in withering of crops and loss of yield.

We observe that farmer responses about experiences of climatic extremes do not just reflect perceptions about weather phenomena but also have implications for crops. This connects well with observations that such participatory process not only capture farmer perceptions of rainfall or rainfall changes but also exposure, sensitivity, and impacts on the farming system (Simelton et al., 2013). This can explain some of the discrepancy between farmer recall of events and historical climate observation records. Farmers place more emphasis on certain events if these had more impact on their crop yield.

## Statistical Analysis of Identified Agro-Climatic Indices

We explore the relationship between agro-climatic indices and wet season rainfall totals for four of the six indices listed in **Table 2**; these are: "heavy rainfall," "dry spell," "prolonged dry spell," and "consecutive 10-day rainfall." Using the same weather station data, we also analyze the probability of delayed onset of rains (%), probability of delayed onset per year (%), and the frequency of combined "high temperature and dryness" conditions lasting at least 14, 10, and 7 days. Correlations between the agro-climatic indices and wet season rainfall totals were calculated at each weather station and are listed in **Supplementary Table 1a**. To gain a better understanding of spatial patterns evident in the data, the correlation analysis results were aggregated at the district and regional (central and southern Malawi) levels (also **Supplementary Table 1a**). Aggregate Pearson correlation coefficients are provided as ranges, while the joint statistical significance (referred to as "field significance") of these multiple correlations is estimated using the Walker test (e.g., Wilks, 2006). This approach is robust even when the individual hypothesis tests are non-independent, as in this case due to similarities in meteorological conditions across the weather stations. The correlations for each station, district, and regional level informs the findings presented below.

### Heavy Rainfall, November–January

We find positive correlations ($r \approx 0.4$–$0.7$) between "heavy rainfall" events and total wet season rainfall (**Figure 3**) which are statistically significant at the 1% level for all the stations across the three districts considered here. Using the Walker test, these correlations are found to be collectively significant at the 1% level, when grouped by district, and for the whole region. The interpretation, therefore, is that that heavy rainfall events will tend to be more frequent during wet seasons with higher total rainfall. Despite being highly statistically significant, these relationships show considerable scatter, and caution is needed in interpreting and applying these relationships in decision-making processes (**Supplementary Figure 1**).

### Dry Spell, November–March

We observe negative correlations ($r \approx -0.2$ to $-0.6$) between "dry spell 1–2 weeks" and total wet season rainfall (**Figure 3**). For the stations, all but four of the correlations are significant at the 5% level. Collectively, the correlations are field significant at the 1% level for each district, and the whole region. This relationship suggests that the frequency of 10-day dry spells in November to March tends to be lower when wet season rainfall totals are higher. However, the modest confidence of the station level correlations reported here, in addition to the limited sample size for the conclusions drawn at the district level, must be considered if these relationships are to be used to infer dry spell frequency from skillful wet season rainfall forecasts (**Supplementary Figure 2**).

### Prolonged Dry Spell, February–April

We find weakly negative correlations ($r \approx -0.1$ to $-0.6$) between "prolonged dry spells" of $\geq$14 consecutive days for February–mid-April and total wet season rainfall (**Figure 3**). These correlations are locally significant at the 5% level for six of the stations considered, and not significant at the other six (see **Supplementary Table 1a**). However, these correlations are field significant regionally, indicating that the collection of locally significant station correlations is not a "false discovery" (Wilks, 2006). Nevertheless, there is considerable uncertainty in these relationships (**Supplementary Figure 3b**), meaning they are not robust enough to form the basis of a forecast.

### Consecutive 10-Day Rainfall, March–April

Within the available observations, we identified only one occurrence of $\geq$10 mm daily rainfall sustained over $\geq$10 consecutive days, which was recorded at Salima. As such, there is no evidence for a relationship with total wet season rainfall (**Figure 3**). Testing showed there were very few occurrences of consecutive rainfall events lasting longer than 4 days (**Supplementary Figure 4**). This highlights a potential discrepancy between the occurrence of historic weather events and farmers' perception of them; this is explored further in the discussion.

### High Temperature and Dryness Lasting $\geq$14 Consecutive Days, January–March

Analysis of "high temperature and dryness" events is restricted to the six of the 12 weather stations which provide overlapping data for precipitation and temperature (see **Supplementary Figure 5**). We find that "high temperature and dryness" events which last for at least 14 consecutive days are extremely rare within the available observational records, with no recorded occurrences at Chanco, Chitala and Makoka stations (**Supplementary Table 2**). Monkey Bay in Mangochi district has the highest observed rate ($\sim$0.19 events per year), which gives an estimated 17.5% annual chance

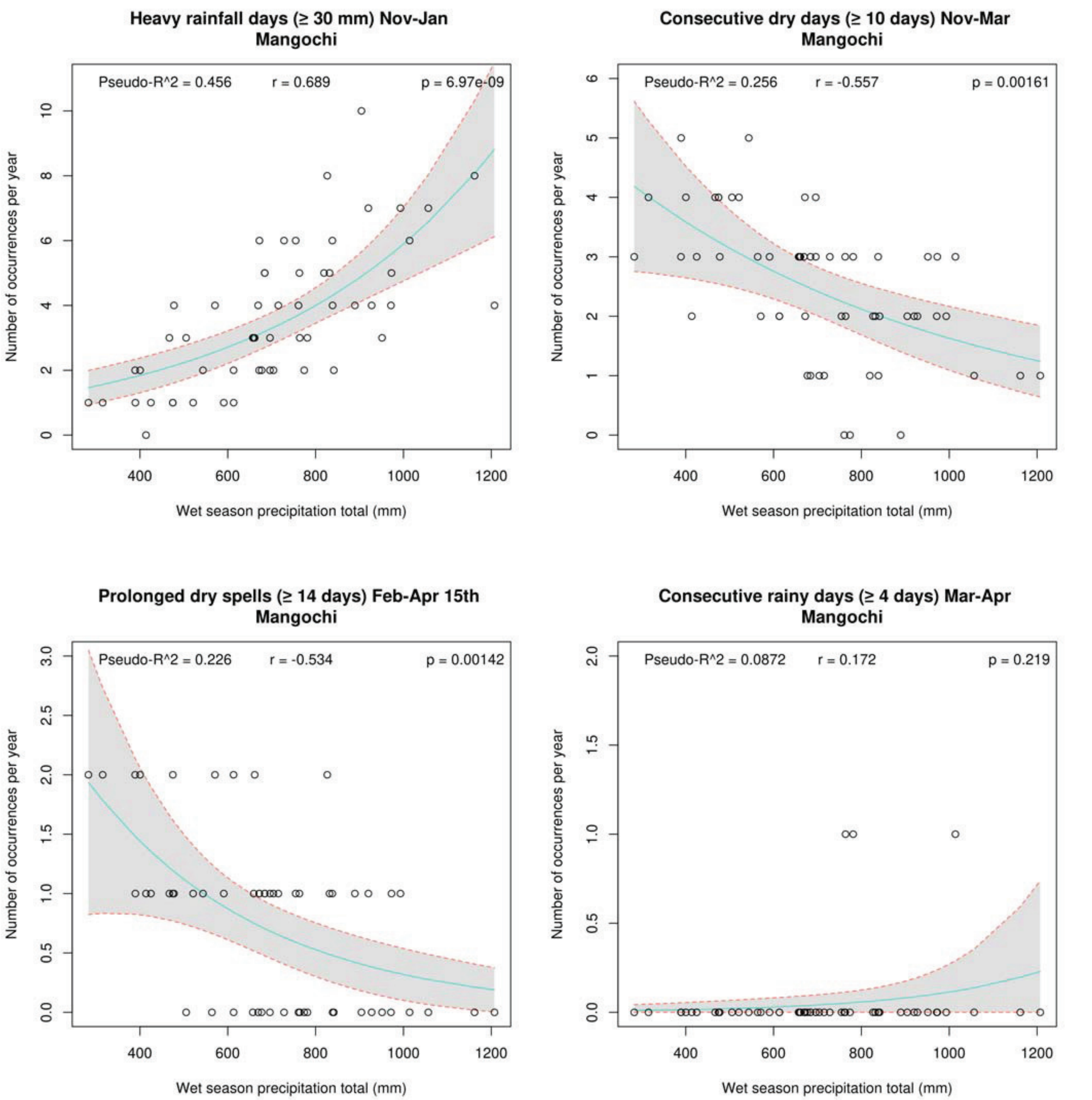


**FIGURE 3 |** Results of correlation analysis between the agro-climatic indices developed through the iterative process and wet season precipitation totals for Mangochi station, Mangochi district. Clockwise from top left: "heavy rainfall" events November–January, "dry spell 1–2 weeks" November–March, "consecutive 4-day rainfall" March–April, and "prolonged dry spells" February–April 15th.

that one or more "high temperature and dryness" event will occur in a given year (see **Supplementary Table 2**).

Due to the rarity of hot-dry events lasting at least 14 days, we also explored the characteristics of shorter duration events lasting at least 10 and 7 days (see **Supplementary Table 2**). However, even for these shorter thresholds we find no recorded events in the available data for Chanco and Chitala stations (**Supplementary Figure 5**). For the 7-day threshold, we calculate an annual chance of roughly 70% that Monkey Bay will experience at least one hot-dry event per year. More generally, we find that no more than three hot-dry events occur in any given year or location (**Supplementary Figure 5**) for any of the three thresholds explored here. Consequently, the estimated annual chance of more than three events per year, estimated using the

Poisson distribution, is negligible for all stations except Monkey Bay, where there is an estimated 3.6% chance per year. We note that these probabilities are long-term averages based on available historical observations and will be influenced by both natural climate variations and climate change over that period.

### Delayed Onset of Rains, November–December

Analysis of the weather station observations show a roughly 84% probability (averaged across the 12 stations) that the traditional onset threshold marks the beginning of the wet season for any given year. The corollary is that the mean probability of a false wet season onset in November and December is ∼16% per year (**Supplementary Table 3**). As such, there is a substantial risk, each year, that maize planted after early rains will experience adverse growing conditions.

## Seasonal Forecast Skill of GloSea5

We find that for the October to March period, GloSea5 seasonal precipitation forecasts offer limited skill across Malawi (**Supplementary Figure 6**), and there will be little to be gained from downscaling the seasonal forecast to individual sites, districts, and regions. For different sub-season periods Relative Operating Characteristic (ROC) scores indicate marginal improvements for above normal and below normal forecasts of precipitation during January–March compared to October–December. Comparing GloSea5 and reanalysis data for the 1993–2015 period indicates a statistically insignificant correlation ($r = 0.21$) for January–March and no obvious correlation for October–November, suggesting limited predictability of the 6-month rainfall forecast for Malawi (**Supplementary Figure 7**). We find greater skill for northern and southern Malawi, but lower skill in the central region. A potentially important reason for the relatively low skill of the model in this region is that Malawi is a point of transition between ENSO precipitation teleconnections, whereby the warm phase of ENSO is associated with wetting in the north and drying in the south (Mason and Chidzambwa, 2008). So, while GloSea5 seasonal prediction system has been shown to exhibit greater skill than GHACOF consensus-based forecasts for East Africa (Walker et al., 2019), the model currently lacks skill in and around Malawi. This may be because Malawi covers a relatively small area, meaning that even slight biases in the location of key weather patterns and teleconnections can result in forecasts with low skill.

# DISCUSSION

Analysis reveals challenges and opportunities in identifying agro-climatic indices and understanding the climatological characteristics of the indices. These important components are analyzed and tested in the Malawian context for an important subsistence crop; maize, but it provides an opportunity to explore crucial aspects in the effort toward developing agricultural climate services in Malawi. We discuss the key issues in this section.

## Identifying Agro-Climatic Indices

We sought to identify agro-climatic indices that affect farm-level decision making with the objective of explicitly linking climate forecasts with on-farm decisions. Our participatory approach contrasts with the more common techno-scientific approaches (Tadross et al., 2009; Mathieu and Aires, 2018), which led to different challenges. Key challenges we faced included; contextualizing local terms and knowledge, and identifying indices that could be developed into forecast information given limited availability of long-term climate data.

There are challenges in contextualizing words and phrases used in the local language. For example, *masiku otentha* (hot days), *masimu otentha kwambiri* (very hot days) and *nyengo yothentha* (it's hot) were used interchangeably during FGDs but they have different meaning and are used/understood in specific contexts. We also found that the process of deriving specific thresholds values, and to ascertain their appropriateness for inclusion in SCF, requires further iterative evaluation and refinement through engagement of meteorologists and agriculture experts. Moreover, we should not assume that there exists a knowledge of agro-climatic indices and thresholds among the users that will emerge from this process in every context (Simelton et al., 2013; Nkiaka et al., 2019; Dorward et al., 2020). Some of the discrepancies between farmers, AEDOs and meteorologists defined indices and thresholds, indices available in literature, and the frequency of their occurrence in station observations indicates the challenges of both identifying and developing indices that should simultaneously meet multiple criteria. These include identifying indices and thresholds, that significantly impact crop productivity, that are understandable for farming communities, that help farmers make informed farm-level decisions, and that are associated with sufficient forecast model skill.

Identifying an appropriate threshold for sectors that rely on anticipatory action such as forecast-based financing, crop insurance etc., is important. Moreover, in a region that faces natural disasters anticipatory action or early warning early action requires developing triggers that have a sufficiently long lead time to initiate and implement early actions before the imminent hazard materializes in a disaster. Slow onset disasters such as drought rely mostly on seasonal to subseasonal forecasts (as opposed to sudden onset disasters such as floods that rely on short term forecasts) (Bazo et al., 2019). The agro-climatic indices as developed in our research could also be used to determine the timing of cash-based transfers to support the most vulnerable and poor farmers in taking early action themselves (Nobre et al., 2019).

The agro-climatic indices identified and developed through this work are limited to temperature and rainfall indices mainly due to the need to validate indices using long-term station observational data. The choice of EPAs with each district was significantly affected by the availability of long-term temperature and rainfall observations, which meant that identification and validation of agro-climatic indices could not be carried out across all EPAs within the district. While temperature and rainfall are the key climate variables affecting the maize yield and quality according to the farmers and AEDOs, there are also other factors that affect maize yield, such as soil condition, type, and availability of farm inputs etc. While information on these non-climatic factors is currently limited the development of crop-specific agro-climatic indices could be supplemented by additional research on the impact of non-climatic factors on farmers' decision making, cropping calendar and crop yield.

### Climatological Characteristics of Agro-Climatic Indices

The second component aims to understand the climatological characteristics of the indices. Here, we evaluated the skill of the GloSea5 model in simulating total wet season rainfall; alongside this, we also analyzed relationships in the observations between rainfall-based agro-climatic indices and total wet season rainfall, the probability of delayed onset of rains, and the frequency of high temperature and dryness events.

This work highlights the challenge of providing a skillful seasonal rainfall forecast for a relatively small country with complex meteorology. In particular, our results show that current models are not able to provide reliable forecasts of wet season rainfall totals—further work is needed to understand why this is the case, and where improvements can be made. Despite the lack of seasonal forecast skill, this work highlights the value of information about the average annual frequency and year-to-year variability of the selected agro-climatic indices, which will be useful to farmers, agricultural planners and policy makers by giving a better understanding of the climatological risk. In addition, our analysis suggests there is potential for adding value to seasonal forecasts, provided they are sufficiently skillful. For example, based on the available observations, we find two agro-climatic indices that exhibit a moderate correlation with total wet season rainfall ("heavy rainfall" and "dry spells") which are regionally significant at the 1% level. In principle, these relatively strong relationships mean that a skillful forecast of total wet season rainfall would indirectly provide information about the likely number of heavy rainfall events and dry spells at sites of interest. However, doing so would require careful assessment of uncertainties in both the seasonal rainfall forecast and the local relationship with the agro-climatic indices. In contrast, "prolonged dry spell" and "consecutive 10-day rainfall" events are rare in the observational record, and there is no evidence for significant relationships with total wet season rainfall. More generally, improved understanding of historical events will complement existing efforts to engage and train farmers to better understand and use historical information for farming decisions in Malawi (Clarkson et al., 2019; Dorward et al., 2020). Further work is needed to understand how maize yield responds to variations in the agro-climatic indices explored in this work, using both field measurements and appropriate crop models.

## SUMMARY AND CONCLUSIONS

The study explores two important components; identification of agro-climatic indices and understanding the climatological characteristics of the indices; that could enable the tailoring of seasonal forecast for the agricultural sector in Malawi. Our approach also reveals challenges in identifying and co-designing indices and thresholds, which is a crucial step in addressing the on-going challenge of including farmer-focused information in seasonal forecasts in Malawi. While we find that total seasonal rainfall could be useful entry point for including information about crop-specific agro-climatic indices, the choice of thresholds for agro-climatic indices requires careful validation. Continuous engagement between agriculture stakeholders and DCCMS to validate the indices will help identify the thresholds that could be used by the DCCMS to develop targeted forecasts. These forecasts could be then tailored over time to address feedback regarding usefulness and usability from a range of water, agriculture, and humanitarian sector stakeholders.

## DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The dataset used for analysis was made available by the Department of Climate Change and Meteorological Services, Malawi on request. Requests to access these datasets should be directed to Department of Climate Change and Meteorological Services, Malawi.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics approval was granted for the research by the ESSL, Environment and LUBS (AREA) Faculty Research Ethics Committee University of Leeds, reference 18-081. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

NM, SW, MB, and EP designed the study. NM and JB conducted the analysis. NM, SW, and EP wrote the manuscript. All authors contributed ideas and edited the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2020.578553/full#supplementary-material

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# Farmer Preparedness for Building Resilient Agri-Food Systems: Lessons From the 2015/2016 El Niño Drought in Malawi

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Across sub-Saharan Africa, climate change is leading to increasingly erratic weather patterns that challenge farming practices, particularly for smallholder farmers. Preparing farmers for these changes and increasing their resilience to extreme weather events is critical for food security in areas where populations are increasing. The El Niño event of 2015/16 led to drought conditions in Malawi which are expected to become more normal in the future. This resulted in widespread crop failure and the need for external food aid. The experiences of Malawian farmers during this time creates an opportunity to identify areas where adaptations in land management practices as part of resilience building initiatives can prepare farmers for future climates. This paper presents results of household surveys and interviews of 201 farmers from a case study in southern Malawi. Half of the farmers surveyed practice Conservation Agriculture (CA), a Climate Smart Agriculture technology that increased resilience to this drought event. The majority of households relied on agriculture for all their livelihood streams, indicating that diversification away from sole dependence on agriculture would increase resilience. Our study shows that poorer, female farmers are less likely to practice CA than wealthier male farmers. Results also illustrate that while farmers had access to seasonal weather forecasts, a key tool to guide land preparation and planting, they remained reluctant to believe them or to amend cropping or land management practices. Agricultural extension services within Malawi can play a vital role in preparing farmers for future extreme weather events and ensuring forecast communication link to predicted agricultural impacts and land management actions for building resilience into agricultural systems. Extension services need to focus on supporting poorer female farmers to adopt CA practices and providing farmers with the tools and knowledge to respond effectively to seasonal and sub-seasonal climate information.

**Keywords: climate services, conservation agriculture (CA), sub-Saharan Africa, climate adaptation, disaster preparedness, climate smart agriculture**

## INTRODUCTION

Climate change and weather variability are key factors affecting food systems in most parts of sub-Saharan Africa (Kotir, 2011), especially among rural subsistence farming communities (Shisanya and Mafongoya, 2016). This has been seen recently in Malawi, where agriculture is predominantly rain-fed and practiced by 76% of Malawi's population (National Statistics Office, 2017). The agricultural sector contributes 30% to GDP, which fell 3.2% from 2014 to 2016 (Botha et al., 2018), affecting the delivery of other essential sectors such as health and education. Flooding in 2014/15, followed by droughts in 2015/16, led to a 30.2% year-on-year drop in maize production (World Bank, 2019), which is grown on 90% of cultivated land (Mutegi et al., 2015). This was due to the El Niño event of 2015/16, one of the strongest on record (NOAA, 2015; Whitfield et al., 2019). Not only are El Niño events predicted to become more extreme (Wang et al., 2019), but these types of conditions (erratic rainfall, droughts and flooding) are expected to become more normal according to predicted future climate change scenarios (Niang et al., 2014; Mittal et al., 2017; Hart et al., 2018).

The decrease in maize yields in 2016 led to 6.5 million people within Malawi requiring food aid (USAID, 2016). Increasing farmers' preparedness and resilience to extreme weather events is critical to ensuring food security and continued development within the country. Strategies to achieve this include the Farm Input Subsidy Programme (FISP), widespread promotion of Climate Smart Agriculture, Sustainable Intensification and increased use of irrigation. This culminated in the release of the National Climate Change Management Policy and the National Agricultural Policy in 2016 (Chinsinga and Chasukwa, 2018).

Conservation Agriculture (CA) is a Climate Smart Agriculture technology, designed to increase resilience to climate change through three pillars of soil and crop management: reduced tillage, intercropping or crop rotation and permanent soil cover (FAO, 2008). It is generally conceptualized to be an agriculture system encompassing several technologies. CA has been shown to increase resilience to dry spells and heat stress (e.g., Ngwira et al., 2012; Steward et al., 2018, 2019; Boillat et al., 2019) but has limited uptake among farmers, and increasing evidence of disadoption, where farmers return to their previous practices once the intervention in place to promote CA ceases (Pedzisa et al., 2015; Ward et al., 2016; Chinseu et al., 2019; Bouwman et al., 2021). Reasons for this have been discussed widely (see Hermans et al., 2020), with possible reasons varying from constraints at household level such as poor health, labor and capital availability (Jew et al., 2020), a lack of technical support (Chinseu et al., 2019) and practical limitations, such as a lack of equipment (Habanyati et al., 2018) or land (Bouwman et al., 2021). Given the promising yield results shown from previous studies, understanding how promotion of CA can be improved will enhance farmer preparedness and resilience to erratic climate events.

A further consideration is that of the provision of climate and weather information to farmers, and how they access, interpret, and make decisions based on this information. Appropriate and timely information is expected to improve the capacity of farmers to manage the risks associated with climate variability and change (Vaughan et al., 2019). The use of weather information allows farmers to identify crops and plan for the season (Roudier et al., 2014), and use of climate information can enable national policies to be developed to support farmers in decision making over varying timescales (Vincent et al., 2017; Nkiaka et al., 2019).

As the climate alters and conditions become less suitable for agricultural production (particularly that of the main food crop maize) in the medium to long term future (Stevens and Madani, 2016), greater diversity in livelihoods may also improve agricultural system resilience and preparedness. Currently within Malawi only 23% of households in rural areas are engaged in non-farm enterprises (National Statistics Office, 2017). Previous studies have illustrated the dependency on agricultural livelihoods in many households (Chidanti-Malunga, 2011).

Resilience and preparedness to extreme climate events requires a multifaceted approach (Whitfield et al., 2019), and it is important to understand the extent to which farmers in Malawi have the capacity to prepare and adapt to climate change. Using a case study from southern Malawi, we conducted a survey of farmers who practiced CA and of those who did not during the 2015–16 El Niño drought event. In order to understand the extent of their preparedness and resilience to this, and future extreme weather events, we asked the following research questions: (1) Who are CA farmers, and are there opportunities to increase participation in CA farming?; (2) How do farmers (CA and non-CA) access weather information, and how do they utilize this information in guiding their cropping and land management decisions?; (3) To what extent are farmers' livelihoods resilient to extreme weather and are there opportunities for diversification?

## METHODOLOGY

### Study Area and Context

Malawi has a sub-tropical climate with one crop growing season that runs from December to April (Mutegi et al., 2015). Malawi has one of the highest population densities in Africa, with ∼150 people per square kilometer in the southern regions and over 50% of rural households occupying <1 ha of land (National Statistical Office, 2015; FAOSTAT, 2017). Poverty affects 59.5% of the rural population (National Statistics Office, 2017) and high dependence on low-productivity small scale farming is considered the greatest barrier to reducing rural poverty (UNDP, 2016).

Since 2005, key investments in the agriculture sector have been hybrid seed (especially maize) and mineral fertilizer which have been supported through the Government's Farm Input Subsidy Programme (FISP) (Chirwa and Dorward, 2013a), which in 2020 has been extended through an Affordable Inputs Programme (AIP). The AIP targets 4.2 million smallholder farming households, each accessing two bags of fertilizer weighing 50 kg each at a cost of US$ 5.8 per bag and 5 kg certified maize seed at US$ 2.60 per pack. The budget of AIP is a staggering Malawian Kwacha (MK) 160 billion (∼ US $208 million) of the MK 245 billion (∼US$ 318 million) allocated to the Ministry of Agriculture, representing a 78% increase from the MK 36 billion (∼US$ 47 million) allocation to the final edition of FISP. Unlike FISP, which included legumes in the package, AIP is focusing entirely on maize as Malawi's dominant staple grain (GoM, 2020).

The participation of the private sector has also increased within the seed and fertilizer industry due to market availability (Chirwa and Dorward, 2013b) since the programme is funded by the Government of Malawi.

Research took place in southern Malawi, within the districts of Machinga and Balaka during August and September 2016 (**Figure 1**). These districts were selected according to the criteria of having experienced some, but not complete, crop loss in the 2015/16 season with CA practiced by some farmers for at least 3 years. Populations within Balaka and Machinga have been rated as highly vulnerable to climate-related risk and shocks within Malawi (Government of Malawi, 2018). Within each District we followed government extension structures which comprise of District Agriculture Development Offices (DADO). The DADO is divided into Extension Planning Areas (EPAs). These are geographically demarcated areas composed of several villages. EPAs are managed by an Agricultural Extension Development Officer (AEDO). Each EPA is then divided into Sections that have a smaller number of villages and act as a unit for local level field demonstration. In this study, an Extension Planning Area (EPA) was selected where both CA and non-CA was practiced, and within each EPA two Sections were selected where farmers had access to agricultural extension advice through the presence of an Agricultural Extension Development Officer (AEDO). Lead farmers who demonstrate CA practices to their fellow farmers are also present in all Sections. These selection criteria enabled comparisons between CA and non-CA farmers. Four Sections were selected in total.

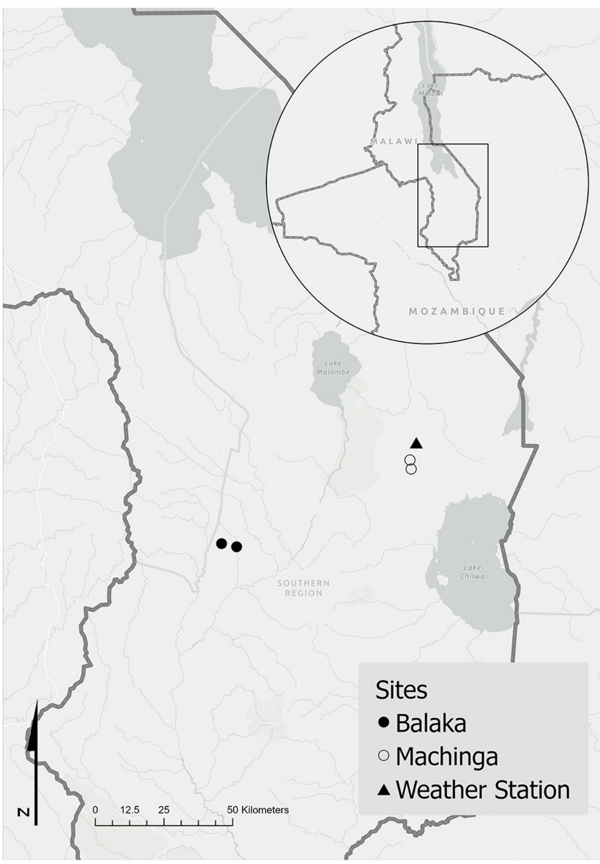


**FIGURE 1 |** Study sites within Malawi.

Prior to the start of the research, interviews were conducted with agricultural extension officers to gain an understanding of the study sites. Within the two sections studied in Machinga, CA was promoted by Total Land Care (a local NGO) from 2013 to 2017, and had been adopted by approximately 1.5% of the 2,600 households within the Sections. Maize is the dominant crop grown, with limited livestock keeping. Fishing in nearby Lake Chilwa is an important source of income for many households. In Balaka, CA was introduced in 2007 by the Food and Agriculture Organization of the United Nations (FAO) as part of a 5-year programme. Since then, CA has been promoted by other organizations including World Food Programme, ActionAid, and World Vision, this has led to a higher adoption rates of 5.5% of the 2,967 households within the two sections. There are few other income generating activities within the area other than agriculture and other resource-based livelihoods such as selling of charcoal, firewood and brick molding.

## Methods

Household surveys consisting of open and closed questions (see survey in **Supplementary Material A**) were conducted within each Section. The survey gathered details of agricultural practices, yields and access to information and support during the 2015–16 farming season. Surveys were completed by farmers who did not practice any CA methods (non-CA) and farmers who self-identified as practicing CA in at least one of their plots of land. This was verified by checking their descriptions of their farming practices. CA was considered to be practice of at least one of the three pillars of CA including intercropping or crop rotation, minimum or zero tillage and permanent organic soil cover, such as mulching or use of a cover crop. Sampling for CA farmers was exhaustive, initially using those registered in Section records, on village lists and then through identification by lead farmers. Non-CA farmer sampling was conducted through random selection of names from village household lists. The household survey was initially written in English and then translated into Chichewa by five research assistants, who checked for different local words to ensure understanding. This was conducted through an iterative process over intensive piloting for 1 week prior to the research period.

This resulted in a total of 201 complete questionnaires, 104 from CA farmers, and 97 non-CA farmers (**Table 1**).

Descriptive and inferential statistics were performed on quantitative data referring to demographics and crop yields in R 3.3.2 (The R Foundation for Statistical Computing, 2016). Qualitative data referring to weather information and subsequent practices was coded in NVivo 10 (QSR International, 2012).

# RESULTS

## Who Are CA Farmers?

The average age of respondents (both CA and non-CA) was 43.5 ± 15.3 (mean ± SD, $n = 200$). The average age of CA farmers was

47.4 ± 13.8 ($n$ = 103), and the average age of non-CA farmers was 39.3±15.8 ($n$ = 97). This is a significant difference in the ages of farmers between the two types of farming systems (MW, $p < 0.0005$), illustrated in **Figure 2**. There are also differences in gender between the two groups. Of the 201 respondents there were 116 women, and 85 men. More women ($n$ = 68, 58.6%) cultivated non-CA than men ($n$ = 29, 34.15%), and more men ($n$ = 56, 65.9%) practiced CA compared to women ($n$ = 48, 41.4%). This relationship between gender and agriculture system is significant ($\chi^2$ (1, $n$ = 201) = 10.83, $p < 0.005$). Results show that differences between gender and wealth are also significant, with women more likely to be poorer (Fisher's exact test, $p < 0.05$, **Supplementary Figure 1**).

There was some evidence of an association between wealth and the type of cultivation (Fisher's exact test, $p = 0.058$) (**Figure 3**). When assessing the association between gender and wealth within the farming types there was a significant association between wealth and gender for CA farmers (Fisher's exact test, $p < 0.05$), with male farmers wealthier than female farmers (**Figure 3**).

**TABLE 1 |** Distribution of non-CA and CA farmers participating in the household survey.

| District | Section | Non-CA | CA | CA LF | Non-CA LF | Total |
|---|---|---|---|---|---|---|
| Balaka | 1 | 24 | 20 | 8 | 0 | 52 |
| | 2 | 23 | 17 | 3 | 1 | 44 |
| Machinga | 1 | 25 | 21 | 5 | 0 | 51 |
| | 2 | 24 | 22 | 8 | 0 | 54 |
| Total | | 96 | 80 | 24 | 1 | 201 |

*LF = Lead farmer.*

## Seasonal Weather Forecast Information

The seasonal forecast is provided by the Government of Malawi's Department of Climate Change and Meteorological Services (DCCMS) and for 2015/2016 the prediction was communicated as normal to above normal rainfall for the whole country (GoM, 2015), despite the regional prediction of drought as associated with the strong El Niño Southern Oscillation conditions (Blamey et al., 2018). Below average rainfall amounts were expected from October to December 2015, while average rainfall amounts were predicted to occur from January to March 2016 with January 2016 expected to be the wettest month. Finally, prolonged dry spells were expected between February and March 2016 (GoM, 2015).

Agriculture, weather, and weather information in the study area was communicated by the Farm Radio Trust, an NGO supporting extension and advisory services through radio and mobile phone. In addition, the DCCMS disseminated the weather information through newspapers, radio and TV communications.

### Accessing Weather Information

Results from the household surveys show that the majority of farmers (166, 82.6%) got their information about the weather from the radio. Other sources of information included extension services and other phone services (**Table 2**). Extension service information was accessed by 22.1% of CA farmers compared to 11.3% of non-CA farmers. Few farmers (3.5%) obtained no information about the weather at all.

### Response to Weather Information

When farmers were asked whether they were aware that the rainfall for the 2015/16 season would be erratic, 77.6% said that they had not known. Of the 82.6% of farmers who received their weather information from the radio, 76.5% (127) did not know that rainfall would be erratic. Qualitative data indicated that

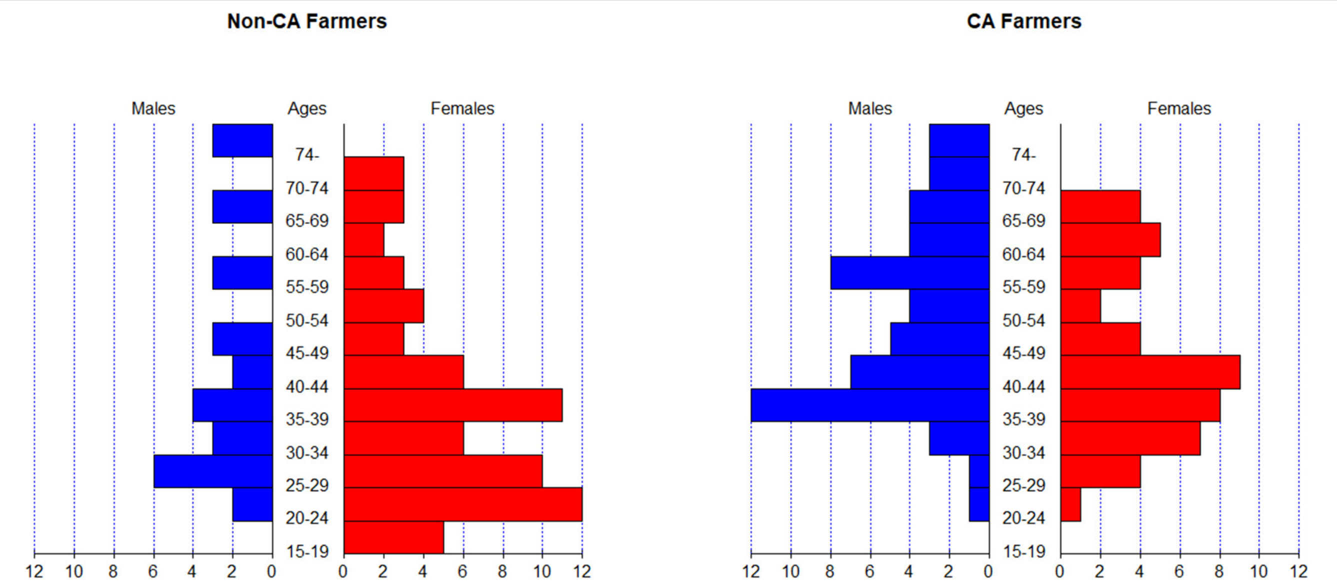


**FIGURE 2 |** Distribution of ages by respondents for CA and non-CA farmers (Household survey, $n$ = 201).

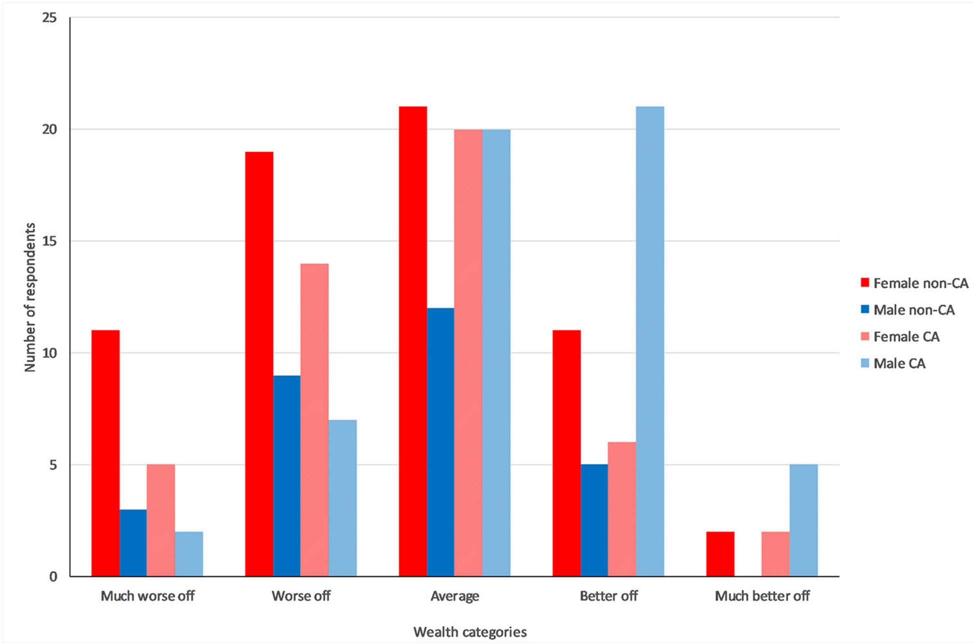


**FIGURE 3 |** Wealth and gender by farming type (Household survey, $n = 201$).

**TABLE 2 |** Sources of weather information [multiple answers accepted (Household survey $n = 201$)].

| Method | CA farmers ($n = 104$) | Non-CA famers ($n = 97$) | Male ($n = 85$) | Female ($n = 116$) | Total ($n = 201$) |
|---|---|---|---|---|---|
| Radio | 85 (81.7%) | 81 (83.5%) | 77 (90.6%) | 89 (76.7%) | 166 (82.6%) |
| Extension services | 23 (22.1%) | 11 (11.3%) | 17 (20%) | 17 (14.7%) | 34 (16.9%) |
| SMS/phone services | 5 (2.9%) | 1 (1%) | 5 (5.9%) | 1 (0.9%) | 6 (3%) |
| From friends | 6 (3.8%) | 10 (10.3%) | 2 (2.4%) | 2 (1.7%) | 16 (8%) |
| Personal observations | 3 (2.9%) | 1 (1%) | 3 (3.5%) | 13 (11.2%) | 4 (2%) |
| Newspaper | 2 (2.1%) | 0 | 1 (1.2%) | 1 (0.7%) | 2 (1%) |
| None | 4 (3.8%) | 3 (3.1%) | 1 (1.2%) | 6 (5.2%) | 7 (3.5%) |

within this group there was a mistrust of radio weather forecasts, with 10 respondents saying that the weather forecast on the radio had been for good or higher rainfall, 11 saying that the weather experts are not accurate and 5 saying that they do not believe the radio. One respondent said "*I did not know… The weather experts through the radio lied to us... I won't trust them again*" (female CA farmer, Machinga, household survey 2016).

Of the 34 (22.9%) who both listened to the radio weather forecasts and knew that the rainfall would be erratic, qualitative data indicated that four respondents based their knowledge on their own observations of change in wind, and the remaining respondents had heard it on the radio, however three of these said that they had not believed the forecast. Two respondents said that initially the forecasts had said that the rainfall would be good, but that the forecast changed just before the rains were due to start.

There was no evidence of differences between crop yields of farmers who had been aware that the weather would be erratic in 2015/16 compared to those who were not aware (**Table 3**).

There was some discrepancy between gender and engagement with weather forecasting. Of the 116 female farmers, 99 (85.3%) did not know that the rainfall would be erratic, compared to 67.1% of men (57 of 85). With regards to radio access, 89 women (76.7%) got their weather forecast from the radio, and 76 of these women (85.4%) did not know that the rainfall would be erratic. In comparison, 77 male farmers (90.6%) got their weather forecast from the radio, and 51 (66.2%) did not know that the rainfall would be erratic.

## Future Weather Predictions for 2016/17

Respondents were asked what they thought the weather would be like for the coming growing season (November 2016–April 2017). Half (100) of respondents stated that they did not know what the rains would be like. Qualitatively, 10 respondents said that the weather had become unpredictable, and others said that it was "God's plan" or that they were "resigned to fate." Of the remaining half of respondents, 95% said that

**TABLE 3 |** Crop yields for farmers who were aware of erratic rainfall and those who were not.

| Crop | Yield knowledge of weather | Yield - no knowledge | Mann Whitney *U* Test |
|---|---|---|---|
| Hybrid maize | 658.2 ± 578.7 ($n = 45$) | 602.2 ± 651.4 ($n = 169$) | $p = 0.1531$ |
| Failed harvest | 9 (16.7%) | 25 (12.9%) | |
| Local maize | 357.6 ± 251.1 ($n = 19$) | 301.2 ± 246.6 ($n = 54$) | $p = 0.2478$ |
| Failed harvest | 4 (17.4%) | 12 (18.2%) | |
| Groundnuts | 489.5 ± 524.9 ($n = 27$) | 314 ± 314 ($n = 66$) | $p = 0.3014$ |
| Failed harvest | 5 (15.6%) | 18 (21.4%) | |
| Pigeonpeas | 186.9 ± 215.7 ($n = 29$) | 127.2 ±160.7 ($n = 87$) | $p = 0.1669$ |
| Failed harvest | 15 (34.1%) | 43 (33.1%) | |
| Cowpeas | 196 ± 157.5 ($n = 12$) | 149.9 ± 195.2 ($n = 47$) | $p = 0.1176$ |
| Failed harvest | 9 (42.9%) | 36 (43.4%) | |
| Cassava | 169.9 ± 21.8 ($n = 2$) | 227.1 ± 198.9 ($n = 12$) | $p = 1$ |
| Failed harvest | 3 (60%) | 4 (25%) | |

*Household survey 2016 [n = 200, Weather awareness =NA (n = 9)].*

they thought the rains would be "good" or "early." Reasons for this were largely based on indigenous local knowledge (environmental observations), with respondents citing current weather conditions such as "hot and windy" or "northerly winds." Other reasons included the use of indigenous local knowledge, including that the mango trees had flowered well, there were many ants and termites, or that it smelt like rain. Other responses were largely based on fate, with respondents believing that there would be good rains because it would be compensation for last season's poor rains, that God would be merciful, or that good rains followed bad ones.

### Preparation for 2016/17

Respondents were asked if they would take any action to protect their crops from extreme weather such as drought or flooding in the 2016/17 season. CA farmers seemed to be happy with the impact that their methods had on reducing the impact of dry spells in the previous season, with 75 farmers (72%) saying that they would continue with CA methods. Hybrid maize yields for CA farmers were double those of non-CA farmers (Jew et al., 2020). These methods included mulching and using planting basins. There was some emphasis on the management of box ridges to enable moisture to be retained or released through adding drains. Other methods included growing a wider variety of crops with some drought tolerant varieties and planting early. The remaining CA respondents ($n = 26$, 25%) did not know what they would do. Reasons for this included it being hard to prepare because they did not know what the rains would be like, and that they did not know what to do to help them to protect the crops.

The responses of non-CA farmers were similar. Evidence from neighbors farming CA encouraged some farmers to begin CA practice, with 43.3% of farmers indicating that they would like to either undertake full CA in the following season or to adapt practices applied through CA, such as box ridges or mulching. Other methods included using drought tolerant crops, planting a diverse range of crops, practicing irrigation and using mineral fertilizer. Five farmers said that they would seek extension officers' advice on what to do. Again, 29 farmers (30%) did not know what they could do to protect their crops from extreme weather conditions, with some farmers explaining that it is difficult to plan when they do not know what the weather will do, and others saying that they would have to accept what happens, with one respondent suggesting that he would look for alternative income sources to continue to support his livelihood.

## Other Routes to Resilience

### Resilience - Crop Diversity

Households grow a range of crops for both subsistence and for sale (**Table 4**). All households grew either a hybrid maize (modified seeds for drought tolerance or early maturing) or local maize seed (grown from seeds local varieties of crops mostly kept from the previous harvest). The results show that most of the farmers grew hybrid maize followed by pigeonpeas. The majority of households grew at least three different crops (**Figure 4**).

**Table 5** illustrates that both CA farmers and non-CA farmers experienced similar perceived decreases in yields from their expected to harvested yields. The exception is cowpeas, where CA farmers perceived a lower decrease in yield than non-CA farmers.

### Resilience - Livestock

Respondents were asked to list the type and number of animals that they kept (**Table 6**). The most commonly kept animals are goats and chickens, which are kept for subsistence and also for sale. Almost twice as many households engaged in CA kept chickens than those who did not practice CA (70.2 vs. 40.2%). Of those households who did keep chickens, CA farmers kept more on average than non-CA farmers (9.3 ± 8.3 (mean ± SD) chickens compared to 5.6 ± 4.2 chickens); this was a statistically significant difference (MW, $p < 0.01$). More CA farmers also kept goats than non-CA farmers (51 vs. 32%), but the difference between the average number of goats kept (4.8 ± 4.4 vs. 3.2 ± 2.2) was not significant (MW, $P = 0.09$). Doves, ducks, turkeys, guineafowl, pigs, rabbits and sheep were also kept for their meat, both for subsistence and sale by a limited number of households. Very few households kept cattle, and of those that did they kept them to sell, with only one household listing transport as a reason for keeping cattle. When converted into Tropical Livestock Units (TLU) non-CA households had an average total of 1.776 TLU, and CA households 2.473 TLU (**Table 6**).

Keeping livestock as assets or diversifying into livestock keeping as another income stream does come with risks from a range of sources. Disease resulting in loss was reported by 60.7% of households who kept chickens. The main disease named was Newcastle Disease. Respondents reported limited losses from wild animals, including the loss of four goats from two separate households to hyenas, and one reported loss of guineafowl. This predation was not assessed if it was linked to drought. There were 38 reports of loss of chickens, reasons for this included predation by wild birds (e.g., hawks and eagles, cited by 19 respondents) and feral dogs (12 respondents).

Climate hazards were reported as a threat to livestock by a limited number of respondents, with singular reports of loss of doves, goats and pigs due to lack of food caused by drought.

**TABLE 4 |** Crops grown by both CA and non-CA farmers by household.

| Crop | CA households | Non-CA households | Crop | CA households | Non-CA households |
|---|---|---|---|---|---|
| Hybrid maize | 102 (99%) | 78 (80.4%) | Pumpkins | 6 (5.8%) | 1 (1%) |
| Pigeonpeas | 78 (75.7%) | 59 (60.8%) | Velvet bean | 6 (5.8%) | 0 |
| Groundnuts | 59 (57.3%) | 55 (56.7%) | Beans | 3 (2.9%) | 2 (2.1%) |
| Cowpeas | 51 (49.5%) | 42 (43.3%) | Vegetables | 3 (2.9%) | 2 (2.1%) |
| Local maize | 37 (35.9%) | 43 (44.3%) | Sorghum | 0 | 4 (4.1%) |
| Millet | 34 (33%) | 33 (34%) | Tomatoes | 1 (1%) | 3 (3.1%) |
| *Cotton | 27 (26.2%) | 19 (19.6%) | Sugarcane | 2 (1.9%) | 0 |
| Cassava | 13 (12.6%) | 11 (11.3%) | Banana | 0 | 1 (1%) |
| Sweet potato | 6 (5.8%) | 4 (4.1%) | Hyacinth beans | 1 (1%) | 0 |
| Soybean | 7 (6.8%) | 2 (2.1%) | Mustard | 0 | 1 (1%) |
| Rice | 6 (5.8%) | 2 (2.1%) | Sesame | 0 | 1 (1%) |
| *Tobacco | 6 (5.8%) | 2 (2.1%) | | | |

*All crops are grown for both household consumption and for sale, apart from those marked with *, which are cash crops only (Household survey 2016, n = 200, CA n = 103, non-CA n = 97).*

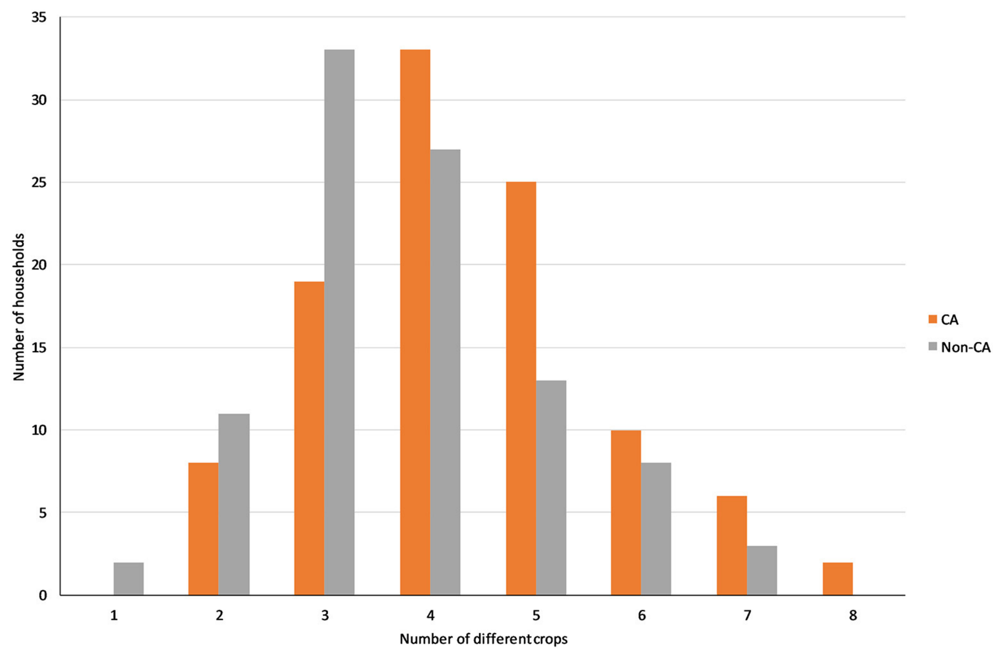


**FIGURE 4 |** Number of different crops grown per household (Household survey, $n = 200$).

There were 10 reports of loss of chickens due to temperature fluctuations and lack of food.

## Off-Farm Livelihoods

The majority of respondents classified farming as their main livelihood activity (**Table 7**). However, most respondents had more than one livelihood activity: 54.2% respondents with two livelihood activities, 22.9% with three, 2.5% with four, and 20.4% having no further livelihood activity.

Examples of businesses include selling produce such as tomatoes, mandazi (a dough bun), and fish. A full list of livelihood activities is in **Supplementary Table 2**. In total 408 livelihood activities were undertaken, of which 245 (60%) involved farming. A further 48 were listed as labor or piecework, which is likely to be farm based.

# DISCUSSION

Smallholder farmer preparedness for extreme weather events in Malawi involves long term changes to farming practices and livelihoods, which need to be facilitated through policies and extension programmes that better support farmers' needs. This study identified three areas where improvements are needed to increase preparedness for smallholder farmers: gender equality

**TABLE 5 |** Crop yields under CA and non-CA in 2015/16 and the yields that are normally expected.

| Crop | Number of plots | Total crop fail (%) | Average 2015/16 yield (kg ha$^{-1}$) | SD (kg ha$^{-1}$) | Expected yield (kg ha$^{-1}$) | SD (kg ha$^{-1}$) | Percentage decrease of yield |
|---|---|---|---|---|---|---|---|
| **CA** | | | | | | | |
| Hybrid maize | 107 | 9 (8.4%) | 899.6 | 741.5 | 2882.7 | 2154 | 68.8% |
| Local maize | 5 | 1 (20 %) | 211.5 | 174.4 | 1899.1 | 956 | 88.9% |
| Cassava | 2 | 1 (50%) | 247.1 | - | 1853.3 | - | 86.7% |
| Pigeonpeas | 46 | 8 (17.4%) | 147.3 | 159.6 | 588.7 | 517.1 | 75.0% |
| Cowpeas | 27 | 9 (33.3%) | 173.7 | 222.7 | 325.2 | 401.3 | 46.6% |
| Groundnuts | 14 | 3 (21.4%) | 237.2 | 201.4 | 1241.8 | 959.2 | 80.9% |
| **Non-CA** | | | | | | | |
| Hybrid maize | 149 | 25 (17.3%) | 392.2 | 395.0 | 1876.1 | 1415.1 | 79.1% |
| Local maize | 85 | 15 (17.4%) | 324.5 | 247.4 | 1866.9 | 1183.5 | 82.6% |
| Cassava | 20 | 6 (30%) | 324.9 | 428.1 | 1084.5 | 527.1 | 70.0% |
| Pigeonpeas | 130 | 51 (39.2%) | 145.4 | 187.4 | 599.0 | 745.3 | 75.7% |
| Cowpeas | 78 | 37 (47.4%) | 160.9 | 175.3 | 612.1 | 777.7 | 73.7% |
| Groundnuts | 104 | 20 (19.2%) | 382.5 | 409.4 | 1503.7 | 1490 | 74.6% |

*Average yield calculated using harvested crops (Household survey 2016, n = 200). For statistical comparison between CA and non-CA yields for 2015/16 see* ***Supplementary Table 1***.

**TABLE 6 |** Livestock kept by households (Household survey, *n* = 201).

| Animal | Number of households (*n* = 104) | Total number of animals | Average number of animals per household | Average TLU per household | Number of households (*n* = 97) | Total number of animals | Average number of animals per household | Average TLU per household |
|---|---|---|---|---|---|---|---|---|
| Cat | 8 (7.7%) | 13 | 1.6 | | 5 (5.2%) | 6 | 1.2 | |
| Cattle | 2 (1.9%) | 2 | 2.0 | 1.4 | 2 (2.1%) | 4 | 2.0 | 1.4 |
| Chickens | 73 (70.2%) | 640 | 9.3 | 0.093 | 39 (40.2%) | 209 | 5.6 | 0.056 |
| Dog | 7 (6.7%) | 9 | 1.3 | | 1 (1%) | 1 | 1.0 | |
| Doves | 12 (11.5%) | 68 | 6.8 | | 5 (5.2%) | 44 | 11.0 | |
| Duck | 11 (10.6%) | 32 | 2.9 | | 3 (3.1%) | 6 | 2.0 | |
| Goats | 53 (51%) | 252 | 4.8 | 0.48 | 31 (32%) | 100 | 3.2 | 0.32 |
| Guineafowl | 2 (1.9%) | 11 | 5.5 | | | | | |
| Pigs | 4 (3.8%) | 15 | 3.8 | | | | | |
| Rabbits | 2 (1.9%) | 6 | 3.0 | | | | | |
| Sheep | 2 (1.9%) | 10 | 5.0 | 0.5 | | | | |
| Turkey | | | | | 1 (1%) | 2 | 2.0 | |
| None | 16 (15.4%) | | | | 43 (44.3%) | | | |

*TLU = Tropical livestock unit.*

in promotion of CA: trust in, and capacity to utilize seasonal weather forecast information; and diversification in livelihood streams that are independent from farming.

## Gender Biases in CA

Evidence from this study illustrates that it is wealthier, male farmers who are more likely to practice CA, which is promoted through NGOs, extension services and in government policy. This gender gap in relation to the adoption of CA is well-documented across sub-Saharan Africa (Wekesah et al., 2019). Reasons for this are varied, including the role of women within the household, where they retain responsibility for caring duties and household tasks (Farnworth et al., 2016) in addition to their farming activities, resulting in limited time to invest in learning new agricultural techniques. Male farmers are more likely to be connected to village political systems, and have time to attend training meetings. Integrated and inclusive planning of household tasks in line with agriculture interventions within a season is lacking, thereby weakening the resilience of food systems. While reduced tillage may decrease initial labor demands in comparison with ridge making, labor demands are increased for tasks such as weeding (Andersson and D'Souza, 2014), and this increased labor disproportionally falls on women (Montt and Luu, 2020). Women often have limited access to capital, basic tools and transport (Murray et al., 2016) constraining their ability to participate.

This gender bias in agricultural training is known, with policy interventions aiming to increase female participation in

**TABLE 7 |** Respondent's main occupation (Household survey, $n = 201$).

| Farming type | Farmer | Laborer | Business | Teacher | Grand Total |
|---|---|---|---|---|---|
| CA | 97 (93%) | 3 (2.9%) | 3 (2.9%) | 1 (0.9%) | 104 |
| Non-CA | 80 (82.5%) | 10 (10.3%) | 7 (7.2%) | | 97 |
| **Total** | **177 (88.1%)** | **13 (6.5%)** | **10 (5%)** | **1 (0.5%)** | **201** |

agricultural training, yet there is little evidence to suggest that this has been implemented across sub-Saharan Africa (Quisumbing and Pandolfelli, 2010). A study by Mudege et al. (2017) in Malawi found that barriers to women accessing training and information often stem from negative stereotypical perceptions of women held by husbands and extension workers, which are exacerbated by institutional biases within extension systems that reinforce these gender norms. Preparedness for resilience food systems will require specific interventions targeting women farmers including provision of tailored seasonal extension services.

Given that women's participation within CA can increase their income and household food security (Wekesah et al., 2019) this bias against the involvement of female farmers in new technologies such as CA should be addressed as a priority and would also help to address problems of CA disadoption (Chinseu et al., 2019). Targeting interventions at female farmers, and particularly those who are poorer, would address the current imbalance, thereby increasing their future capacity to invest in further agricultural interventions. Interventions should not increase their workload and there is need to promote labor saving technologies. There is need to have a pre-season household assessment by extension service providers to understand critical factors that will affect attainment of resilience food systems during the agricultural season. This will include understanding assets, sources and quality of labor, income, and alternative food sources that are available to increase preparedness as a buffer against poor yields.

It is also important that interventions take a holistic approach to promoting agricultural technologies alongside investment in health and education services locally. There is evidence not only that factors at household level such as poor health constrain women's ability to participate (Jew et al., 2020), but that successful farming strategies can put women at risk of being dispossessed of land by men (Wekesah et al., 2019). The complexity of gender relations illustrates that changes are needed at policy level and require nuanced development, in addition to greater attention to a research agenda focussing on gender within CA to guide these developments (Farnworth et al., 2016; Murray et al., 2016; Wekesah et al., 2019). Easy and quick "wins" include using female extension officers to increase female participation, which has been successful agricultural innovation across the border in Mozambique (Kondylis et al., 2016). In this case, trainings should be gender sensitive and targeted in its duration, distance to training and language of instruction to encourage women's participation, especially younger women with small children.

In addition, introduction of new technologies among poor smallholder farmers should not advocate for free inputs as they are also disincentives to adoption of such technologies when such support is withdrawn at the end of the project, as poorer farmers lack the capacity to take personal or household risks to invest in inputs. Wealthier farmers are able to take greater risks and invest in new methods, as should they fail they have additional income sources through which to support their households. Additional income sources include diversified crops or livestock, as illustrated in this case study, where CA farmers grow more different types of crops and have higher numbers of livestock than non-CA farmers. New technologies and provision of agricultural inputs and extension advice should be introduced after a detailed analysis of a household including tasks that are taken by women before, during and after the crop growing season. Agricultural extension and advisory services should be designed to support sustainability of new technologies and project-based intervention needs to complement government efforts that seem to be sustainable in nature. As such, testing and validation of technologies should be showcased through community demonstration blocks rather than on household farm sites as this has an implication of special capital and support to new interventions.

## Access, Trust, and Response to Weather Predictions

Most farmers in this study had some access to weather information, with the majority of them getting this from the radio. Radio broadcast agricultural extension advice predates 2007 (Chapota et al., 2014), providing a familiar outlet for farmers to receive agricultural advice. Despite this widely accepted and accessed source of information, only 21.4% of respondents were aware that the weather would be erratic, despite the majority of farmers receiving weather reports—only 3.5% of respondents said that they did not get weather information. Instead, farmers rely more on indigenous and local knowledge, personal experience and traditional cropping calendars than on climate information for their decision making (Coulibaly et al., 2015). Understanding why farmers access weather information but do not comprehend its significance is critical. This appears to be due in part to a lack of trust in the information provided, but also to poor communication of weather forecasting, which needs to be delivered by a farmer-friendly method that ensures farmers can understand the messages. Should this communications barrier remain, it will be problematic in the future as the climate changes and the traditional signs become less reliable and as computer-based forecasting becomes more skilful and reliable.

In addition to farmer-friendly forecasting, associated preparedness actions should be included in radio messages. This will allow farmers to put in place interventions that will allow them to address anticipated gaps in rainfall in advance. Limited or lack of access to farmer friendly weather forecasts has several implications to preparedness for building resilient agri-food systems. For example, without it farmers will not be able to make investment decisions on the appropriate type of crops or livestock. They will have no information as to when the rains will start or end, thereby affecting their decision on planting dates. Preparedness programming should include providing relevant information using pathways that will be accessible by resource-constrained farmers. Allowing pre-season farmer learning centers to discuss the weather forecast and understand implications associated with such information will add value to preparedness for resilient agri-food systems.

Despite a push to increase the amount of information communicated via mobile phones (Steinfield et al., 2015), only 3% of farmers accessed weather information through mobile phone services. For example in 2016, mobile phone subscriptions were ∼41.72 per 100 inhabitants, which has stagnated in recent years—estimations for 2018 were 39.01 subscriptions per 100 people, meaning that ∼51.7% households had access to a mobile phone (ITU, 2020). Even though number of mobile subscribers is increasing, agriculture change agents have not embraced their use to support farmer preparedness for resilient food systems.

The results have shown that some farmers showed fatalist attitudes toward rainfall variability. This has several implications on preparedness. Firstly, farmers tend to continue ignoring the notion that farming is business and as such it requires proper planning and forecasting. Failing to understand the main inputs of any business will result in producing services or products that will result in losses. Secondly, by not trusting forecasted weather including rainfall variability shows that farmers invest in decisions that are always affected by weather related risks, including prolonged dry spells. Thirdly, credibility of weather forecast is of paramount importance as previous weather information has been contrary to actual season weather. This has led to most farmers failing to trust the information, and therefore improving local and regional forecasting is of paramount importance.

Access to information is associated with more extension officers working with NGOs because of the available logistical support, including field allowances, which are not readily available in the traditional extension system supported by the government. Having a strong government-led extension service framework that will support and coordinate delivery of advisory services will allow inclusion of tasks that can strengthen farmer preparedness in case of any seasonal risks. Even though there are interventions supporting site specific weather information generation with the involvement of users such as smallholder farmers (Dorward et al., 2015) these are mostly project-based interventions that fail to consider agricultural extension providers. For farmers to start trusting weather information, there is need to engage more players, including religious and traditional leaders, teachers, local volunteers and community radio stations which are often pivotal in addressing local needs (Simelton et al., 2013). Designing targeted capacity building programmes on generation and application of weather information and the relation of this information to the agricultural calendar will be an important step in building greater resilience of African food systems.

## Future Farming Planning

A further barrier to acting upon weather information was a lack of knowledge about how to respond to the forecast and make appropriate agricultural changes in advance of the agricultural season. This led to farmers making reactive responses to the erratic rainfall—maize seeds were replanted up to three times by some farmers, which drained their limited capital and had repercussions on their ability to purchase food after these crops had failed. Constraints such as a lack of capital significantly impact farmers' capacity to make either proactive or reactive responses to changing weather patterns. Furthermore, there is no deliberate effort at EPA level to analyse the forecast so that local farmers can understand the implications and then take decisions to create resilient food systems. This is evident in the lack of a significant difference in yields between farmers who were aware of the erratic weather and those who were not (**Table 3**), whereas there were significant differences between the hybrid maize yields of CA farmers and non-CA farmers (Boillat et al., 2019; **Table 5** and **Supplementary Table 1**, for more details see Jew et al., 2020). As illustrated in **Table 5**, farmers perceived a significant decrease in yields from what they would have expected across all crops. However, there are large standard deviations for expected yields per hectare for all crops. This illustrates that farmers have differing expectations from yields. This could be due to differences in fertilizer, pesticide and herbicide application, the type of soil and the amount of effort put into cultivating the crop. While this illustrates that collecting field data of crop yields would be preferable to farmer reporting of yields, it also demonstrates that farmers have high expectations of crops yields, and are likely to be disappointed even when their crop has performed well. For example, hybrid maize yields cultivated under CA were 2.3 times better than hybrid maize crop yields cultivated non-CA conditions, yet CA farmers were still disappointed with their yields, as they were 68.8% lower than they expected. CA farmers expected their yields to be 1.5 times better than those expected by farmers cultivating hybrid maize through non-CA methods, and this was surpassed, however not with the high yields expected (**Table 5**). A lack of evidence of increased yields is thought to be a reason for disadoption of CA (Chinseu et al., 2019), and this illustrates the importance of not "overselling" the benefits of CA to potential adopters, particularly as shown here, CA cultivation of hybrid maize does outperform non-CA cultivation during erratic rainfall conditions. The influence of the different components of CA cultivation on maize performance on this dataset is examined in detail in Boillat et al. (2019).

There was evidence that farmers wanted to continue, or to start, CA farming in the following year. These responses highlight the continued need for effective and available extension advice. The Malawi agricultural extension services are constrained by both a lack of funding and staff capacity (Brown et al., 2018; Jew et al., 2020) illustrating that there is both a need to invest in these services but also that there is a role for NGO support, as long as the messages are consistent (Brown et al., 2017). This weakness can also directly be linked to farmer preparedness as the majority of farmers do not have access to extension workers.

Responses surrounding knowledge about weather information for the coming growing season have shown that there is a need to provide detailed analysis of predicted weather. This will call for DCCMs to invest more in equipment and human resources to support provision of credible weather information. Provision of this information should also be associated with information that will strengthen farmer preparedness for resilient food systems. Understanding both short- and long-term future weather can also allow policy makers to design tailor made agricultural support systems including review of Affordable Input Programme (AIP) and revised extension messages through the agricultural year.

## Diversification

Diversification within livelihoods as well as in cropping is critical in addressing food systems resilience (Pelletier et al., 2016). Within this study most farmers grow more than three crops in a cropping season, with CA farmers more likely to grow more (**Figure 4**). The decision to grow more crops was not linked to a deliberate preparedness framework, but taken as a normal risk aversion strategy. Maize remains the staple crop for Malawian subsistence farmers, however, by the end of the twenty-first century it is likely that large losses in productivity will occur across southern Africa regardless of the management strategies put in place (Rurinda et al., 2015). While agricultural technologies such as CA can provide some resilience in the short to medium term it is clear that farmers will need to plant more resilient crops in future. Decision processes will be improved if proper preparedness interventions are included in national programmes, including crop and livestock research programmes, designing of academic programmes and reviewing the agriculture extension and advisory services. This agricultural transformation will require advancement of new technologies that will not only utilize available water, but address other challenges such as shortage of land, pests, and diseases and new feeding habits by the youthful population.

Encouraging farmers to diversify to different crops and promotion of well-planned livestock management initiatives are therefore also desirable and should be included in the preparedness programming. Suitable crops such as sweet potato (Motsa et al., 2015), sorghum (Hadebe et al., 2017), and cassava (Brown et al., 2016) have been suggested, along with legumes such as pigeonpea for their ability to improve soil quality through nitrogen fixing (Waldman et al., 2017), and are therefore suitable for intercropping. However, due to limited programming, such opportunities are not given the required attention, especially during preseason planning.

Beyond encouraging farmers to grow a more diversified range of crops there are also political, social and economic issues to be considered (Tendall et al., 2015). Farmers cultivating more crops does not immediately translate into greater dietary diversity (Rajendran et al., 2017). Instead, greater access to markets and increased purchasing power which enables households to purchase diverse foodstuffs is important (Koppmair et al., 2017). Therefore, ensuring that there are viable markets for crops beyond maize remains a critical contribution to resilience. During agricultural planning both at national, district and section level, there is need for a holistic assessment to address such gaps before the cropping season. The assessment should also look at available markets for both on-farm and off-farm interventions, crop-livestock integration and social protection interventions.

Given the importance of markets and income to increase food security and to lift households out of poverty (Wiggins and Keats, 2013), livelihood overexposure to one sector increases vulnerability. Deliberate promoting of other off-farm activities, especially during the preseason, can be a better practice to support resilience of agri-food systems as farmers will have more income to support agriculture activities. Although most famers had an additional livelihood, most of these were associated with agriculture, particularly through labor on other farms. This means that extreme weather events that affect agriculture will also have negative impacts on the second income stream. Roughly half of households kept goats and chickens, with limited other livestock kept. Goat husbandry has been shown to contribute significantly to household incomes (Kaumbata et al., 2020) and there is opportunity to promote crop-livestock systems. However, this should be done with care, given that livestock and CA can compete for maize residue for feed and mulching, leading to opportunity costs despite potential benefits from the use of manure (Giller et al., 2009; Valbuena et al., 2012). A holistic preparedness assessment before the cropping season will allow to understand available opportunities to support food systems. Livestock systems are also vulnerable to climatic changes and extreme weather events, suggesting that livelihood diversification away from all types of farming would lead to greater resilience. However, opportunities for this in rural Malawi are scarce, demonstrating opportunities for policy interventions to stimulate markets for off-farm income (Berre et al., 2017), with roles for NGOs and external donors.

# CONCLUSION

Results from this case study demonstrate that hybrid maize cultivated under CA performed better than under traditional tillage during the El Niño event of 2015/16, which resulted in prolonged dry periods. Despite higher numbers of women being engaged in subsistence farming, it was wealthier, male farmers who were more likely to participate in CA. Participation in CA can help to increase food security and preparedness for extreme weather events, and this bias against the involvement of female farmers in CA should be addressed as a priority.

This study illustrated that the use of climate information to support resilience building in agri-food systems has been largely neglected by extension services and NGOs. Despite increased efforts by government and development partners to release daily and seasonal forecast weather services, many farmers do not trust this information. This has resulted in the continued use of agricultural techniques that do not provide resilience to the forecast weather conditions. Our findings suggest that supporting resilient food systems will require deliberate effort by extension and advisory service providers to invest in building the capacity of farmers to practice interventions based on forecast information. This should include assistance with planning and making decisions on the type of investments needed to achieve resilient agri-food systems. This calls for a holistic approach to preparedness—accessible accurate weather forecasts, coupled with advice on how to respond to seasonal weather forecasts, building capacity for farmers to act on the advice—particularly around access to inputs. There is need for long term adjustments to livelihood activities and cropping decisions that increase diversity both at crop and livelihood level.

An integrated and intensive programme that takes agriculture as a business will require proper planning, utilization of available information and support of crop-livestock systems among all groups, but with a particular focus on women due to their lack of participation in agricultural technologies. This will also require joint implementation of programmes between NGOs and government extension workers to support the improved communication of action-based weather and climate information as a key element in a package of measure aimed at building more resilient food systems.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors upon request, without undue reservation.

## ETHICS STATEMENT

The studies the involving human participants were reviewed and approved by Faculty of Environment Research Ethics Committee, University of Leeds. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

DM: wrote the manuscript, provided expert assistance in-country EJ: wrote the manuscript, collected, and analyzed the data. AD: edited the manuscript, project leader.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2020.584245/full#supplementary-material

**Supplementary Figure 1 |** Wealth comparison between men and women (Household survey 2016, $n = 201$). Y axis- number of people. Statistically women are more likely to be poorer than men [Fisher's exact test ($p > 0.005$)].

**Supplementary Table 1 |** Yield comparison between crops cultivated under CA and non-CA in 2015/16 (Household survey, 2016).

**Supplementary Table 2 |** Alternative incomes (Household survey, 2016).

**Supplementary Material A |** The Household Survey.

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# Exploring the Adaptive Capacity of Sugarcane Contract Farming Schemes in the Face of Extreme Events

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Adaptive capacity determines the extent to which exposure to natural hazards and extreme events translates into impacts. This study traces the effectiveness of adaptive capacity of two different sugarcane contract farming schemes (so-called outgrower schemes)—Phata and Kasinthula—in Chikwawa district in southern Malawi which, due to their proximity, are similarly exposed to extreme events, but have shown different impacts in terms of sugarcane production. We develop a framework to explore and compare the adaptive capacity at scheme management level, and relate the findings to the historical changes in yield, the occurrence of extreme events in the district and the lived experiences of the scheme management over the last ten years (2010–2019) using qualitative data from interviews with scheme managers. The total level and components of adaptive capacity differ in several aspects. Phata had much better prerequisites to mitigate the impacts of the extreme events (i.e., maintain production), particularly related to the Asset base, Knowledge and information, Innovation, and Forward-looking decision-making. Kasinthula on the other hand, was impacted by compound events whilst having low financial capacity, weak governance and reduced human capacity. Kasinthula had limited capacity to recover from the severe 2015 floods, the adaptive capacity thus drawn upon and were not restored when next event occurred (drought). This novel, comparative approach to assessing adaptive capacity, linking to past events, has been shown useful in order to determine the components that are missing and need to be built in order to reduce risk from extreme events and climate change. These findings are important to ensure future adaptation of sugarcane outgrowers, and relevant also to other contract farming arrangements or similar kinds of agricultural organizations.

**Keywords: Malawi, adaptation, floods, droughts, cyclones, outgrowers**

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## INTRODUCTION

Extreme events cause significant economic losses and numerous deaths in Sub-Saharan Africa annually (World Bank, 2016). The extent and frequency of these events are expected to increase in the future. Droughts have caused most weather and climate related deaths, while floods and storms have caused most economic losses [World Meteorological Organization (WMO), 2014]. Malawi is one of the most vulnerable countries to climate change and increasingly affected by extreme events, with major floods (in 2015) and a drought (in 2016) in recent years. The total costs of damages and losses of these two events were estimated at USD 335 million, and USD 366 million respectively (Government of Malawi, 2015b, 2016). The majority of the population is dependent on smallholder agriculture, which becomes increasingly challenging with climate variability, change and extreme events.

Rain fed agriculture is particularly vulnerable to climate change and variability, and irrigation, including small-scale, rainwater harvesting or large-scale interventions, has been promoted as an adaptation strategy in Malawi (Government of Malawi, 2015a). Sugarcane production in Malawi is among the most important export earnings in the country, and an important source of employment in the sugar producing areas (Chinsinga, 2017), requires irrigation due to a single rainy season, and increasingly also due to more frequent and prolonged dry spells. Through contract farming agreements, so called outgrower schemes, smallholder farmers comprise part of the sugar industry. The outgrower schemes are built up as block farm arrangements with joint irrigation systems, which thus facilitate large-scale production of sugarcane on smallholder community land. The success of these outgrower schemes varies (Herrman and Grote, 2015; Dubb et al., 2017; Adams et al., 2019), and there is limited knowledge about how these outgrower schemes are affected by extreme events, as well as how well they adapt to climatic challenges (Zhao and Li, 2015). Assessing the adaptive capacity of such organizations would thus provide a useful measure of how the schemes are prepared and can recover from events such as droughts, floods and cyclones.

## LITERATURE REVIEW

Adaptive capacity is "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, take advantage of opportunities, or to cope with the consequences" (IPCC, 2007, p. 869). It is a stock of latent assets that can be drawn upon to enable adaptation. Thus, adaptive capacity is a critical component of risk, and determines the extent to which exposure and vulnerability to extreme events translates into negative effects (IPCC, 2007, p. 869). Factors that contribute to the adaptive capacity of a system involve social, political, economic, technological and institutional aspects that depend on scale and context (Vincent, 2007). For almost two decades, there has been a rapid growth in research on adaptive capacity (Mortreux and Barnett, 2017).

Multiple approaches and frameworks have been developed in order to assess, quantify and anticipate adaptive capacities of various systems at a range of scales. These include national to local and household level assessment (Vincent, 2007; Jones et al., 2017; Matewos, 2020), and most relevant for this study—various kinds of institutions, such as resource governance regimes (Pahl-Wostl, 2009), community-based natural resource management (Armitage, 2005), or private sector business entities and networks (Parsons et al., 2018; Canevari-Luzardo et al., 2020). The literature that covers the adaptive capacity of institutions is rapidly evolving and the various dimensions of an institution's governance and management that contribute to its adaptive capacity are well-covered (Gupta et al., 2010; Engle, 2011). Jones et al. (2017) identify five characteristics of local adaptive capacity that are applicable to the scale of organization in focus in this study: Asset base, Institutions and entitlements, Knowledge and information, Innovation, and Forward-looking decision-making. These characteristics are outlined below.

Adaptive capacity was earlier commonly attributed predominantly to the presence of the five capitals, or assets, i.e., natural, physical, financial, social, and human capacity (Vincent, 2007; Jones et al., 2017; Mortreux and Barnett, 2017). Availability of a diverse range (abundant and redundant) of assets are critical for an organization to be able to respond to emerging circumstances (Ospina and Heeks, 2010). However, as the theory and conceptualization of adaptive capacity has advanced, it has been recognized that the focus on capitals, or assets, alone is not sufficient to understand the complete and multifaceted dimensions that either support or inhibit the capacities (Mortreux and Barnett, 2017). In order for the various capacities to be used, or activated, other factors have to be considered, e.g., those that enable mobilization of capabilities (Jones et al., 2017; Mortreux et al., 2020). These include psycho-social factors linked to behavior, such as risk attitudes (e.g., Jain et al., 2015), personal experiences (e.g., Hertwig et al., 2004; Olsson et al., 2004, and Parsons et al., 2018) and trust (e.g., Pelling and High, 2005).

Interconnectivity, i.e., being part of networks and have connections with a wide variety of institutions, is likely to positively affect the adaptive capacity of an institution at any scale, such as national to household (Adger, 2003; Vincent, 2007), and context, such as resource management and governance (Armitage, 2005; Pahl-Wostl, 2009), or private sector (Parsons et al., 2018; Canevari-Luzardo et al., 2020). The ability of an institution to manage social relations (e.g., those who form part of the network) at multiple scales is seen as a factor that is likely to support adaptive capacity (Jones et al., 2017). Where there may be power imbalances and dynamics within these social relations, and fair governance that considers equity social differentiation of entitlement to assets, is likely to promote adaptive capacity (Gupta et al., 2010; Cohen et al., 2016; Jones et al., 2017).

Knowledge and information are well recognized factors that contribute to the ability to adapt to climatic challenges and thus promote adaptive capacity (Olsson et al., 2004; Pahl-Wostl, 2009; Jones et al., 2017). Sufficient skills within the institution prevent maladaptive practices, i.e., decisions that are made for short-term gains as opposed to ensuring long-term stability and sustainability (Jones et al., 2017). Learning from past experience and mobilizing such knowledge and skills to preparedness has been highlighted as important in building and maintaining adaptive capacity (Olsson et al., 2004, Armitage, 2005; Parsons et al., 2018). Learning from past experience is particularly important when the climate hazards are not only slow changes such as gradual shifts in temperature and rainfall patterns, but also sudden and abrupt changes such as extreme events. Much of the research on adaptive capacity has focused on gradual climate change and less attention has been given adaptive capacity in the context of climate extremes (Thonicke et al., 2020). During an extreme event, adaptive capacity is drawn upon and this depletes the asset base, or stock, for a time until it has been restored. In hazard-exposed areas where extreme events are severe, and occur at an increasing frequency (such as Malawi; Botha et al., 2018), it may be that stock of adaptive capacity is unable to replenish after one event before the next one occurs. This eroding capacity in light of existing exposure would lead to increase risk of negative impacts; and this is compounded when combined to increasing frequency of hazard exposure. Assessing riskalso requires consideration of the nature of hazard exposure, which comes from the availability, use and dissemination of weather and climate information, including early warnings.

Climate and weather are not the only elements of uncertainty that influence the management and governance of an institution. Population growth, socio-economic trends, global and local market fluctuations, resource access, politics, and legislations are factors that directly or indirectly affect outcomes of any decision. An organization that face such complex challenges, require a management structure to foster innovation and take advantage of opportunities (Cohen et al., 2016; Jones et al., 2017). Rigidity in management practices, rules and aversion toward experimentation may thus hamper adaptive capacity. Forward-looking decision-making approaches with appropriate timeframes in management, and consideration of a range of uncertainties, projections and predictive modeling are highlighted as contributors to an institution's adaptive capacity (Armitage, 2005; Vermeulen et al., 2013).

In this paper, we take an innovative approach to adaptive capacity, unpacking its multiple components and historically assessing the extent to which it was successful in enabling adaptation to climate change in the face of exposure to extreme events. This approach—assessing the extent to which adaptive capacity existed through retrospectively analyzing how it mediated impacts of extreme event exposure has rarely been applied (Duncan et al., 2017), and contrasts with the more typical approaches which determine adaptive capacity as a latent capacity that will be activated in the case of current or future exposure [e.g., Vincent (2007) and Mortreux and Barnett (2017)]. We do this by assessing adaptive capacity in two closely-located outgrower schemes in the Chikwawa district in southern Malawi which have been exposed to the same extreme events. However, the Kasinthula Sugarcane Outgrower scheme and the Phata Sugar Cooperative have had largely different outcomes of their management and governance, in terms of sugarcane production (as an indicator of the success of adaptive capacity in enabling adaptation in the face of exposure to extreme events). The two schemes' disparate outcomes thus provide a unique opportunity to identify the nature of adaptive capacity that is important in order to reduce negative impacts of exposure to such extreme events and ensure future adaptation.

Since adaptive capacity is a latent stock, or potential that will be drawn upon in the future, usually the only way to assess its effectiveness in enabling adaptation is through modeling studies or by waiting for future exposure to occur (Engle, 2011). Here, we develop a framework to assess and compare the potential adaptive capacity of two sugarcane outgrower schemes looking into the past and use sugarcane production as a proxy for positive outcomes of adaptive capacity in the context of lessened impacts of extreme events. Through in-depth interviews with outgrower scheme managers we obtain information about the schemes' current features and characteristics of adaptive capacity and the lived experience of extreme events according to the scheme management. The comparative adaptive capacity assessment is then presented qualitatively and we relate the findings to their success in enabling adaptation, defined by the sugarcane yield in the light of the occurrence of extreme events in the Chikwawa district of the last 10 years (2010–2019). This approach contributes to providing better knowledge about the causes of poor adaptive capacity and the contributors when stocks were high. This is particularly so when using two contrasting examples of schemes that have been similarly exposed to, but differently affected by, extreme events.

## METHODS

### Developing a Framework to Assess Adaptive Capacity of Sugarcane Outgrower Schemes

An organization, such as a sugarcane outgrower scheme in focus in this paper, can be seen as a kind of institution, being formed by patterns of rules and decision making (Gupta et al., 2010). An outgrower scheme is a large-scale agricultural entity that is run as a business, managed by experts with technical skills in agriculture and entrepreneurship, but with the aim to benefit smallholder farmers that constitute the members of the scheme. Given the scale-specificity of adaptive capacity, assessing it at the level of the outgrower schemes requires modification of existing frameworks accordingly. Informed by the theoretical drivers of adaptive capacity discussed in the previous section we developed a framework that considers features and characteristics of the scale and kind of organization in focus that are likely to support adaptive capacity (**Table 1**). We adapted the Local Adaptive Capacity (LAC) framework by Jones et al. (2017) by adjusting the framework to local organization level, rather than household and community. Similar to the adaptive capacity wheel developed by Gupta et al. (2010) we further included sub-categories to be assessed. Other frameworks for assessing various scales, contexts and aspects of adaptive capacity were used to adapt the LAC framework to be relevant for the context of sugarcane outgrower schemes (i.e., Vincent, 2007; Gupta et al., 2010; Canevari-Luzardo et al., 2020, **Table 1**). The framework includes the main characteristics of an institution as follows: Asset base, Institutions and entitlements, Knowledge and information, Innovation, and Forward-looking decision-making (Jones et al., 2017; see **Table 1** for descriptions of the characteristics and sub-characteristics).

### Case Study Context

Chikwawa is amongst the districts in Malawi most exposed to climate related shocks (Coulibaly et al., 2015; Mwale et al.,

**TABLE 1 |** Our adaptive capacity framework, adapted from Jones et al. (2017) to correspond to the context and scale of the management level of sugarcane outgrower schemes.

| Characteristic[a] | Summary[a] | Sub-characteristic (adapted to an outgrower scheme context) |
|---|---|---|
| Asset base | The availability of a diverse range of key assets that allow the organization to respond to evolving circumstances | Wide range of assets[a]: Asset diversity that can substitute each other.<br>Financial: Stability[b], absence of loans, absence of dependency on donors.<br>The crop(s): Diversity. Vulnerability to climate extremes and pests<br>Human: Managers, staff, farmers (beneficiaries) (availability of expertise, knowledge, and human labor)[c] |
| Institutions and entitlements | The existence of an appropriate and evolving institutional environment that allows for access and entitlement to key assets and capitals | Institutional interconnectivity[b], business partnerships and networks[d]<br>Equity and fairness[a] (Fair governance[c]) |
| Knowledge and information | The ability the organization have to generate, receive, assess, and disseminate knowledge and information in support of appropriate adaptation options | Institutional memory[c], learning from past experience[c], knowledge about adaptation options[a]<br>Knowledge and use of climate information and early warnings[a]<br>Communication of risk with the farmers and how is capacity building and training with farmers carried out[a]. Alternative livelihood strategies for the farmers.<br>Maladaptive practices (i.e., actions or processes that may deliver short-term gains but ultimately increase vulnerability in the longer term)[a] |
| Innovation | The presence of an enabling environment to foster innovation, experimentation, and learning in order to take advantage of new opportunities | Rigidity/Flexibility in management practices (e.g., Irrigation infrastructure)[a]<br>Rigidity/Flexibility in decision making around innovation[a,c] |
| Forward-looking decision-making | The ability to anticipate, incorporate and respond to changes with regard to governance, structure and future planning | Time-frame of management[a]<br>Consideration of future uncertainties and projections[c] |

*Various elements are also inspired by Vincent (2007), Gupta et al. (2010), and Canevari-Luzardo et al. (2020).*
[a] *Jones et al. (2017).*
[b] *Vincent (2007).*
[c] *Gupta et al. (2010).*
[d] *Canevari-Luzardo et al. (2020).*

2015). Due to the location of the Illovo Sugar Limited estate and mill in the area there are opportunities also for smallholder farmers to partake in the sugar industry by the formation of contract farming agreements. Two outgrower schemes supply the Illovo mill with sugarcane according to supply agreements: The Kasinthula Cane Growers' Association (hereafter Kasinthula) was established in 1997, and Phata Sugarcane Outgrowers Cooperative (hereafter Phata) in 2011. Kasinthula consists of an association of almost 800 farmers and Phata of 1,100. The two schemes' governance models are similar; the land under sugarcane production is administered through a land trust that was formed during the establishment of the scheme in order to lease individual plots of land by the farmers. The agricultural operations are run by management companies, who manage the supply agreements with Illovo. The farmers are members of the scheme, and perform specific agricultural tasks in the fields. Farmers may also be employed by the management company for other agricultural operations that require certain skills. The management companies are the levels of organization in focus in this study, as these are where the decisions regarding financial, agricultural and human resource matters take place, which the farmers in the scheme then follow. Both schemes have their executive managers contracted from AgriCane, an agricultural management consultancy. AgriCane was part of the establishment of Kasinthula, and again, was contracted early 2019 to take over the management and turn the scheme around from a near bankruptcy. AgriCane has managed Phata since the onset.

## Extreme Events in Chikwawa

Through history, there have been several extreme events occurring in Malawi, with their frequency and intensity increasing over time (Botha et al., 2018). A large number of these events have affected the Chikwawa district (Government of Malawi, 2015b, 2016, 2019; USAID, 2019; Zuzani et al., 2019) (see **Figure 1**). These events include droughts, storms, cyclones and floods, which have affected the district on a large scale including damages to buildings and infrastructure, injuries, and lost lives (Government of Malawi, 2015b, 2016, 2019; USAID, 2019; Zuzani et al., 2019). The agricultural sector has been mostly affected and this issue continues to be a great concern in the country (Government of Malawi, 2016; World Bank, 2019). The three most severe events during the last decade, in terms of costs of damages and losses, in Malawi and Chikwawa, were floods in January 2015, droughts in the 2015/2016 and 2016/2017 seasons, and tropical cyclones, including floods in January-March 2019.

The rainfall in January 2015 was the highest recorded (Government of Malawi, 2015b), and the Southern Region, received 400% higher rains than usual, compared with the long term mean (Reliefweb, 2020). The floods that resulted from these rains caused vast costs in damages and losses (Government of Malawi, 2015b; Hendriks and Boersma, 2019). The agricultural sector incurred great losses in Chikwawa due to a large amount of crops and livestock being lost or damaged, as well as damages to irrigation systems. The costs of damages on irrigation infrastructure reached 623 million Malawian Kwacha in the Chikwawa District, which was highest in the country.

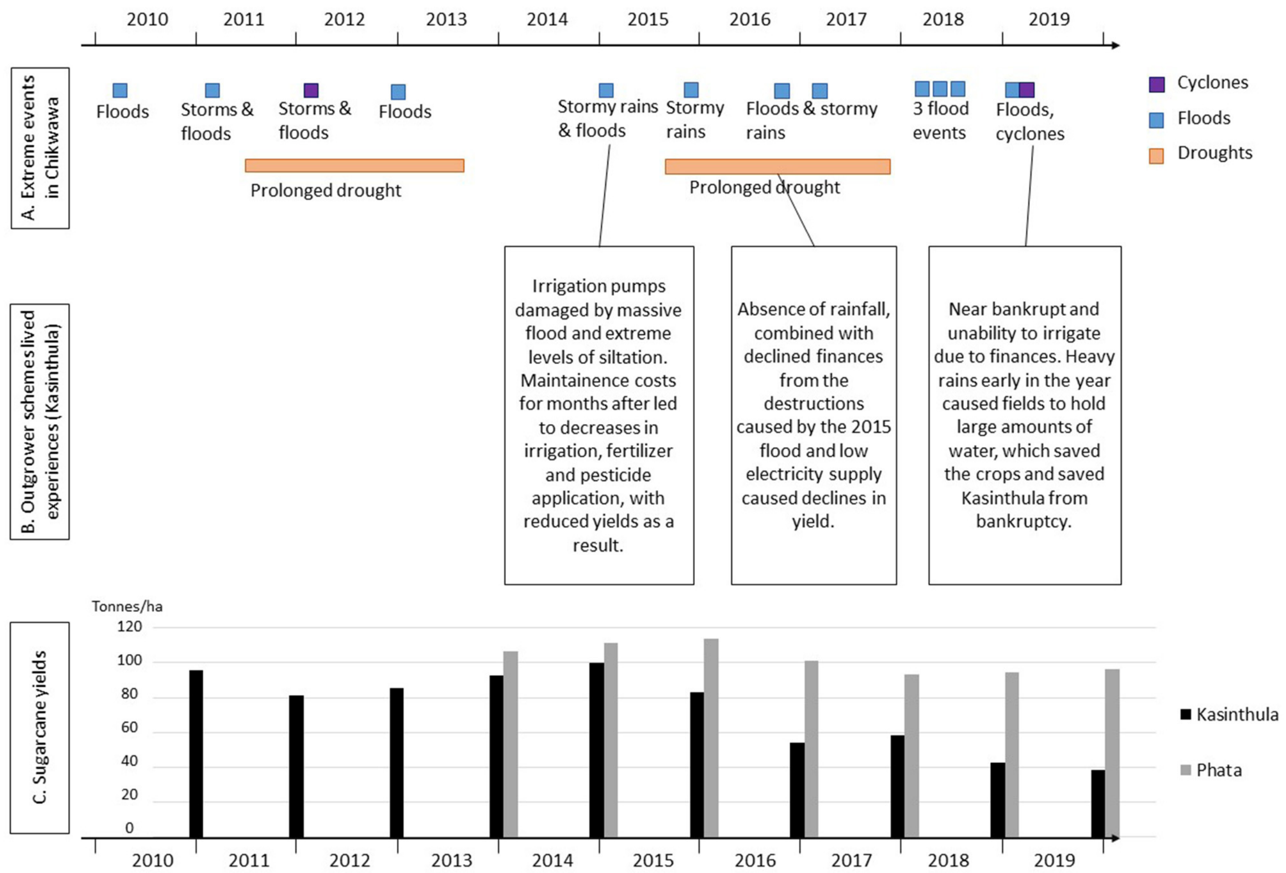


**FIGURE 1 |** Timeline over **(A)** the occurrence of extreme events (droughts, cyclones, storms, and floods) during 2010–2019 in the Chikwawa District (sources: ReliefWeb, PreventionWeb, EM-DAT, Government of Malawi, 2015b, 2016, 2019), **(B)** The lived experiences of the effects of extreme events by Kasinthula managers (Phata managers stated there were no, or marginal effects) (source: interviews), **(C)** Sugarcane yields, Phata, and Kasinthula schemes (obtained from scheme managers).

While still recovering from this devastating flood event, Malawi experienced a major drought period (Government of Malawi, 2016). Prolonged dry spells during the 2015/2016 season were particularly affecting the southern Malawi, resulting in crop failure and subsequent food shortage (Government of Malawi, 2016). During October to December 2015, Malawi received 32.8 percent less than average rainfall (Government of Malawi, 2016). This worsened from January to March 2016, which is the most critical period for sugarcane production. Chikwawa, along with six other districts, received significantly below average rainfall over the same six months period (Government of Malawi, 2016). Chikwawa was reported to have lost 90% of their crops caused by the drought, while still recovering from the losses caused by the 2015 floods (Government of Malawi, 2016). The drought continued across the following season, 2016/2017 which further exacerbated food insecurity and loss of livelihoods (Government of Malawi, 2017; Mazvimavi et al., 2017).

The beginning of 2019 saw several tropical cyclones affecting southern Africa. Malawi was first severely affected by the continuous and extensive rainfalls caused by the Tropical Cyclone Desmond during end January 2019. Severe flooding occurred in southern Malawi, affecting almost 16,000 people Chikwawa (International Federation of Red Cross Red Crescent Societies [IFRC], 2019). In early March another severe weather system caused heavy rains in Malawi, which intensified into Cyclone Idai (Government of Malawi, 2019). Chikwawa suffered the highest agricultural losses, and lost 11% of the maize harvest, an irrigation infrastructure for the value of 3.74 million USD (Government of Malawi, 2019).

## Methods—Data Collection and Analysis

We applied a case-study approach to explore nuances to the contexts under which the adaptive capacity of two sugarcane schemes have played out historically over the past decade, in the face of extreme events (Crowe et al., 2011; Parsons et al., 2018). The information from various sources were collated to provide a nuanced description of the contexts at study, including literature, interview data, field observations and yield data. In order to gain insights into the various characteristics and sub-characteristics of the adaptive capacity framework (Section Developing a Framework to Assess Adaptive Capacity of Sugarcane Outgrower Schemes, **Table 1**), we conducted seven

**TABLE 2** | Interview schedule.

| Date | Interview method | Interviewee number | Role of Interviewee |
|---|---|---|---|
| June 2017 | semi-structured in-depth interview—individual | 1 | Agricultural manager, Kasinthula |
| | | 2 | Human resource manager, Kasinthula |
| | | 3 | Land trust manager, Kasinthula |
| November 2017 | semi-structured in-depth interview—individual | 1 | Agricultural manager, Kasinthula |
| | | 3 | Land trust manager, Kasinthula |
| March 2020 | Informal interview—individual | 4 | General manager, Kasinthula (newly appointed) |
| March 2020 | Semi-structured in-depth—group | 5 | General manager, Phata |
| | | 6 | Financial manager, Phata |
| | | 7 | Safety and health environment officer, Phata |
| March 2020 | semi-structured in-depth interview—individual | 1 | Agricultural manager, Kasinthula (previously acting general and financial manager) |
| | | 8 | Manager with responsibility of outgrower relations, Illovo |

individual interviews and one group interview with totally seven managers and senior staff members of the two sugarcane outgrower schemes Kasinthula and Phata (June 2017, November 2017 and March 2020, one of whom was interviewed twice; **Table 2**). The interviews further assessed the changes in yield as well as broader effects and lived experiences (at scheme management level) of the extreme events over the last decade. Data on sugarcane yield (tons per hectare) were provided by the managers of Kasinthula (years 2010–2019) and Phata (2013–2019—Phata's first harvest took place in 2013). The scale of institution (relatively small organizations) and scope of information required (management level insights), the number of available respondents from the two schemes were low. However, in order to triangulate and provide additional context, a ninth interview was held with a manager at Illovo who is managing the contact and relationship with the outgrower schemes, in March 2020. Field observations and informal conversations with farmers and other stakeholders were conducted parallel to the interviews during the three field visits, and although not formally captured, information gained confirmed the information provided through the interviews.

The responses from the in-depth interviews were transcribed, hand-coded, and qualitatively analyzed using inductive thematic content analysis (Neuendorf, 2019). Key words from the characteristics and sub-characteristics in the framework (**Table 1**) guided the choice of codes, and was adapted as new themes emerged during the transcription and coding. After familiarization with the responses, the coded information was condensed and sorted according to characteristics and sub-characteristics and summarized to provide an overview of the various aspects of adaptive capacity (see **Table 3**).

In order to assess the occurrence of extreme events at district level over the last 10 years (2010-2019) we reviewed academic and gray literature. Gray literature included local and international reputable sources, including Post Disaster Needs Assessment Reports, a disaster related dataset obtained from the Malawian Department of Disaster Management Affairs (DoDMA) which included reports of disaster events at district or village level, ReliefWeb, PreventionWeb, EM-DAT (International Disaster Database) and the Dartmouth Flood Observatory. Academic literature was searched using Google and Google Scholar with search terms including "extreme events," "extreme weather events," "natural hazards," "weather shocks," "floods," "droughts," and/or "cyclones," and "Malawi" and/or "Chikwawa." The information from the literature review was consolidated into a spreadsheet, where each event was dated and described according to the available information from the various sources. The events that occurred in Chikwawa during 2010-2019 were plotted in a timeline according to time and nature of event (i.e., floods, cyclones or droughts) (see **Figure 1**).

# RESULTS

## Effects of the Extreme Events on Smallholder Sugarcane Production–Lived Experiences and Yields

A number of extreme events have been documented in Chikwawa over the last ten years (2010–2019) (**Figure 1**). The exposure to these events has arguably been the same for the two schemes, considering they are located only a few kilometers apart (the distance between the fields of the two respective schemes ranges between 1 and 12 km). The intake points for the irrigation pumps in the Shire River are ∼7 km apart between the two schemes. Despite similar exposure, the two schemes have been affected differently. The differences in effects, and the lived experiences, of the extreme events, are noteworthy as they reflect different levels of adaptive capacity. Phata managers, on one hand, reported that the scheme was not affected by the 2016 drought, nor the major floods in 2015 and 2019, other than that the events caused "*minor inconveniences*." The slight decline in yield in 2016 and 2017 for Phata (**Figure 1**) is according to the Phata managers within an acceptable range, and caused by disturbances in the national electricity supply which affects the irrigation. Phata could maintain yields despite the electricity shortage due to investing in a generator. Thus, their adaptive capacity was sufficient to be drawn on and enable adaptation, such that the impacts were minimal.

The managers of Kasinthula, on the other hand, explained how the onset of the extreme flood in 2015 was the beginning of a series of cascading and drastic events that had severe consequences to the scheme—its finances, management and yields (**Figure 1**). Unlike Phata, which was not yet established, the Kasinthula scheme also experienced the floods, storms and drought events that occurred between 2010 and 2013 (see **Figure 1**), but the impacts on yield of these events were negligible, according to the interviewed managers. The 2015 floods caused

**TABLE 3 |** A summary of the mechanisms and features of two sugarcane outgrower schemes (Phata and Kasinthula) corresponding to various aspects of adaptive capacity, obtained through in-depth interviews with scheme managers.

| Characteristic/sub-characteristic | Summary—Phata | Summary—Kasinthula |
|---|---|---|
| **Asset base** | | |
| Wide range of assets: Asset diversity that can substitute each other. | · Sugarcane only income source for the scheme. | · Sugarcane only income source for the scheme. |
| Financial: Stability, absence of loans, absence of dependency on donors. | · All loans paid off.<br>· Stable income due to stable production.<br>· Savings in place. | · Large debts.<br>· Reduced income from declining crops.<br>· Dependent on donations and new loans. |
| The crop(s): Diversity. Vulnerability to climate extremes and pests | · Monoculture | · Monoculture |
| Human: Managers, staff, farmers (beneficiaries) (availability of expertise, knowledge, and human labor) | · Managers have high expertise and knowledge<br>· Management positions filled.<br>· Access to human labor.<br>· Functioning boards (appointed by members of the scheme)<br>· Capacity building in many topics and skill training high among all farmers (compulsory attendance, courses repeated). | · In-sufficiently skilled managers.<br>· Under-staffed management (many positions vacated and not replaced)<br>· Human labor unmotivated due to staff not being paid during some periods<br>· Boards not appointed (supposed to be appointed by Government).<br>· Low capacity building among farmers, low attendance, and reduced human labor. |
| **Institutions and entitlements** | | |
| Institutional interconnectivity, business partnerships and networks | · Connections and agreements with Illovo Sugar, Sugarcane Growers association of Malawi (SUGAM), Fairtrade, NGOs (Concern Universal, Solidaridad, BonSucro), EU, AgriCane, AgDevCo.<br>· Appreciation from Government. | · Connections and agreements with Illovo Sugar, Sugarcane Growers association of Malawi (SUGAM), Fairtrade, Divine Chocolate, NGOs (Concern Universal, Solidaridad, BonSucro), Only last year connections with AgriCane, AgDevCo.<br>· No support from Government. |
| Equity and fairness (Fair governance) | · Farmers associations represented in boards and decision-making.<br>· Fairtrade committee.<br>· 43% women members (farmers)<br>· 30% women in committees.<br>· Gender based violence committee. | · Farmers association represented in boards and decision-making.<br>· Fairtrade committee.<br>· 32% women members (farmers)<br>· 22% women in committees (on quota). |
| **Knowledge and information** | | |
| Institutional memory, learning from past experience, knowledge about adaptation options | · Barely affected by extreme events the past decade. Acknowledges that climate change may come with risk in future. Recalls 1992 drought followed by 1993 droughts. 30,000 ha cane was lost, yield reduced from 110 to 11 tons/ha.<br>· Management and infrastructure set up with climate risk in mind from the onset of the scheme. | · Severely affected by 2015 flood and 2016 drought. Slight damages from 2019 cyclone, but mostly was what kept the cane growing (saved the season's harvest).<br>· Management and infrastructure maintenance changed (drainage systems, dike), agricultural practices changed (soil conservation, new cane varieties). |
| Knowledge and use of climate information and early warnings | · Monthly government weather bulletins.<br>· Illovo climate data.<br>· Illovo's CanePro data for day to day irrigation scheduling. | · Official channels.<br>· Illovo climate data.<br>· Early warning from Illovo. |
| Communication of risk with the farmers and how is capacity building and training with farmers carried out. Alternative livelihood strategies for the farmers. | · Farmers trained to improve their livelihood strategies.<br>· Tree planting, food crops, beehives for added benefits.<br>· No climate information dissemination. | · Training has been scattered over the years, and reached only few. Some initiatives only started with the onset of new management.<br>· Tree planting, food crops, beehives being introduced this year.<br>· No climate information dissemination. |
| Maladaptive practices | Set up to avoid maladaptive practices as follows:<br>· Boards dominated by skilled professionals, with presence from farmer representatives who gives feedback to farmers.<br>· Farmers trained in dividend policy, business understanding, entrepreneurship, sugar production, cane planting, agricultural practices, so decisions with long-term outcomes were supported by farmer representatives. | · Boards had high representation of farmers who lacked business understanding, and understanding of large-scale agricultural production.<br>· Decisions were made with short-term gains, especially related to farmer dividend and management costs. Long-term strategies to assure long-term productivity (maintenance, management stability, capacity building initiatives) were dismissed. |
| **Innovation** | | |
| Rigidity/Flexibility in management practices (e.g., Irrigation infrastructure) | · The pump is floating on the surface and is located away from floods and siltation (i.e., not vulnerable to climate extremes), and well managed. | · The irrigation pump was located unprotected from extreme floods and siltation, poorly maintained and easily damaged (Improvements only done recently). |

*(Continued)*

**TABLE 3 |** Continued

| Characteristic/sub-characteristic | Summary—Phata | Summary—Kasinthula |
|---|---|---|
| | · Management practices altered with needs and development in the industry. | |
| Rigidity/Flexibility in decision making around innovation | · Committees and farmer board representatives progressive and flexible.<br>· Management company allows innovations.<br>· Good relationships between farmers and managers. | · Incomplete set of managers and board members hampers progression and flexibility<br>· Short-term decisions hamper innovative decisions (see maladaptive practices in point 3 above).<br>· Conflicts and trust issues between farmers and managers |
| **Forward-looking decision-making** | | |
| Time-frame of management | · 5 year strategic plan. | · Previously no strategic systems thinking. 5/10 year plans with the onset of new management and loan terms from development financing company (AgDevCo). |
| Consideration of future uncertainties and projections. | · AgriCane uses climate projections for crop modeling.<br>· Reliance on Illovo for future pest projections and sugar market.<br>· Fairtrade provides safety in market, but restrictions in pesticide use. | · Before AgriCane there was none. |

the entire scheme to be flooded, affecting the cane growth. Furthermore, the main intake point in the Shire River, was due to its location in the river, exposed to large amounts of sand and silt from the floods that damaged the pumps. This, according to one manager at Kasinthula was "*the genesis of the yield drops*". The system silted up every day over a period of several weeks, resulting in unexpected maintenance costs. Reduced finances consequently led to reduced inputs of fertilizer, pesticides and irrigation, which in turn affected the cane growth negatively. The following season, 2015–2016, saw unusually low rainfall, that did not only affect the cane growth but also the national electricity generation (Malawi is dependent solely on hydropower for electricity). The drought in 2016 led to death of sugarcane, and in 2017 the electricity supply was still not sufficient for satisfactory irrigation, which led to further decreases in yield in 2018. Unlike Phata, Kasinthula did not have access to a generator for supplementary electricity. In 2018/2019 the scheme was going toward bankruptcy, and while it was in the process of getting financial relief through a bank loan, the change of management and an investment by an agribusiness investor, the floods and tropical cyclones in January–March 2019 hit the district. Similar to the lived experience by Phata, the Kasinthula did not see destruction to their cane or infrastructure. On the contrary, as expressed by one of the interviewed managers of Kasinthula: "*The cane stayed in water for a while, but this mostly helped. Kasinthula would have died before AgriCane (the new management company) came, if it wasn't for this water staying in the fields*."

## Adaptive Capacity of the Kasinthula and Phata Schemes

The adaptive capacity of the respective schemes provides a clear representation of the mechanisms and features that have led to different impacts for the two schemes following exposure to extreme events. **Table 3** presents a summary of the characteristics and sub-characteristics of the adaptive capacity of the two schemes, which is followed by a more detailed narrative of the differences and similarities between the two schemes.

As outlined in the table, the adaptive capacity of the two schemes differs in several regards, and in some display similar outcomes. There are some sub-characteristics where both schemes are displaying low capacity, which is related to the nature of the organization. The schemes have agricultural produce as their single source of income, and this produce is sugarcane alone (i.e., sugarcane as monoculture, highly dependent on irrigation, fertilizer, and pesticide application). Phata has over the years established other characteristics of the Asset base that buffer against the single income and monoculture, such as a stable financial situation where loans are paid off and some savings are in place. Kasinthula has struggled financially over several years, partly because of large debts that were negatively affected by a national finance crisis. Phata furthermore has a less vulnerable irrigation system than Kasinthula. The intake point is located protected from strong currents, and the pump is floating on the surface and therefore prevented from being flooded with water and sand—which was what happened to Kasinthula during the 2015 flood.

Kasinthula's insufficient adaptive capacity at the time of exposure, resulted in declining yields after the 2015 floods. The Kasinthula managers explained a range of factors that had contributed to the low adaptive capacity. One manager stated; "*The governance of the scheme had numerous issues, with several managers and key staff resigning or being dismissed, and not replaced. There was no trust from the shareholders (members)*." Shortage of human capacity, and sufficiently skilled such, according to the Kasinthula managers, led to a sequence of mismanagement that, alongside with the weather conditions resulted in the scheme going toward bankruptcy. Phata on the other hand, has had a continuous manager and staff base with high and appropriate expertise and decisions have been made accordingly.

Another factor that was mentioned with regards to the low adaptive capacity of Kasinthula, was the influence of unskilled board members (farmers) promoting decisions for short-term gains rather than long-term viability and sustainability of the scheme. At Phata, the governance structure is, according to the managers interviewed, set up to avoid such maladaptive practices. The boards at Phata are dominated by skilled professionals, with presence from farmer representatives who in turn give feedback to farmers. There is an extensive capacity building program in which every farmer is participating. In the program the farmers are trained in aspects that make them better understand the decisions made by the board. These include dividend policy, business understanding, entrepreneurship, sugar production, cane planting, and agricultural practices. This means that, when board positions become vacant, there is a trained cadre of farmers from which replacements can be drawn, ensuring appropriate skills to build and activate adaptive capacity when required. In contrast, Kasinthula has had very few and scattered initiatives to provide capacity building to (only a few of) the farmers, and many lack understanding of the highly technical agricultural system and business model that is required to run a sugarcane scheme of this scale. This means that the flexible, forward looking component of adaptive capacity in Kasinthula is less able to meet its potential due to limited capacity of the individuals filling the board roles. Kasinthula had thus brought forward decisions including reduced capacity building initiatives and fewer management positions in favor of paying out monthly dividends to farmers that were not adjusted according to the returns of the sales of sugarcane. The distinctly different management and governance approaches between the two schemes was confirmed by the manager at Illovo who is managing the contact with the outgrower schemes: *"Kasinthula was born out of a failed rice scheme, and government stepped in (to establish the sugarcane scheme). Kasinthula had issues around governance and who managed the money. Business understanding is missing, and there is an over-representation of (farmers) at board decisions, who are not interested in longer-term decisions. Farmers had high expectations and no capacity building. Phata was a community decision, where (the management company) AgriCane helped with management and it was professionally done from the beginning."*

Due to the recent onset of new management at Kasinthula, it is apparent that the scheme had realized the gaps in adaptive capacity and made alteration to amend these shortcomings. Many of the mechanisms and features that have strengthened the adaptive capacity of Phata over the years, have recently been put in place also at Kasinthula. This means, that the adaptive capacity of Kasinthula will have the prospect to be slowly built up, but due to the severely lacked capacity in many aspects including the Asset base, Knowledge and information, and Innovation, it is likely to take time. The trust in the scheme management among the farmers seems remarkably low, but has the potential to grow with the new management initiatives. The farmers of Kasinthula last received dividend in 2016, which was partly compensated—after pressure by the farmers—through a lump sum that was paid out in 2017 despite the scheme not having gained any profit the last two seasons. The lack of benefit from the scheme caused disappointment and mistrust, and farmers consequently ceased to participate in their work tasks in the scheme and the fields got overgrown by weed. Such issues of mistrust and unrest take time to build up and needs to be a joint effort between the (new) management, the farmer representatives in the boards, and the farmers.

# DISCUSSION

## Lessons Learnt From Two Contrasting Sugarcane Schemes' Adaptive Capacity

Despite being exposed to the same hazards, the Kasinthula and Phata schemes showed different outcomes in terms of the ability to maintain production in the occurrence of extreme events. This resonates with the findings of Zhao and Li (2015) who state that the degree of impact of climate extremes is not only depending on geographic location (i.e., the nature of exposure) but also on adaptive capacity. The most significant event—the unprecedented floods in 2015—according to Phata managers, did not affect the Phata scheme, while the Kasinthula scheme was severely affected. The framework developed for assessing the adaptive capacity highlighted the distinctly different levels of adaptive capacity of the two schemes. Overall, Phata's adaptive capacity was more comprehensive across all dimensions, and this resulted in production yields of sugarcane being maintained, even when exposed to extreme events. Kasinthula, on the other hand, had severe lack of adaptive capacity, which was shown in reductions in yields, notably so after the 2015 flood and 2016 drought. The comparison of the evidence of how different levels of adaptive capacity affect impacts in the face of exposure to the same extreme events provides important insights useful to other, similar, kinds of organizations such as other outgrower schemes, contract farming arrangements and agricultural cooperatives. Lessons can be drawn simultaneously from the scheme with lower levels of adaptive capacity, and from the scheme that has been more successful in maintaining yields despite being exposed to climate extremes.

As highlighted also by Cohen et al. (2016), the notably higher adaptive capacity of Phata confirms the importance of fulfilling several of the dimensions of adaptive capacity, but also that the various aspects of adaptive are interrelated over time. As seen with Kasinthula, when exposed to an extreme event, aspects of adaptive capacity, the Asset base in particular, were depleted after being drawn upon. This meant that if exposure occurred again with minimum time lag (for example the drought in 2016), the lower adaptive capacity led to a further reduction in yields. This drought did not significantly affect Phata, due to having invested in a generator. Kasinthula not only lacked financial capacity to irrigate but also had low innovative capacity and lacked capacity in Forward-looking decision-making. It can be argued that during high-yielding seasons, prior to the period of declining yields (i.e., when the financial capacity potentially were higher), an investment such as a generator could have been financially feasible. This shows that sufficient skills, and a sufficient level of commitment and flexibility in the leadership is needed for the financial capacity to be translated into, or activate the, adaptive capacity.

Although the primary concern with extreme events is to reduce risk, this study also shows that, depending on the context, extreme events can have positive effects. In the case of Kasinthula, due to drought, in combination with financial constraints and national shortage of electricity supply, the irrigation of the crops had been insufficient for an extended period of time and the sugarcane stock was close to succumbing toward the end of 2018. The floods that occurred in Chikwawa early 2019 thus provided the water that the fields needed. This has been confirmed to be the case across the agricultural sector in general in large parts of Malawi, Zambia and Zimbabwe, whereby the heavy rainfalls early 2019 provided relief in the dry conditions and helped recover some of the moisture deficits (FAO-GIEWS, 2019). Although not confirmed during the interviews, it is noteworthy that the yields in 2017 increased slightly after two consecutive years of decline. Similar to the 2019 cyclone, this could be attributed to heavy rainfalls in early 2017 that alleviated some of the moisture deficits that were caused by the 2016 drought. Related to the adaptive capacity characteristic knowledge and information, such experiences could be used to increase the scheme's adaptive capacity for future floods. As suggested also by Parsons et al. (2018), social learning from past events enhanced adaptive capacity among tourism operators in Samoa. Better availability of climate information (weather forecasts and early warnings) would not only warn and prepare farmers to reduce climate risk, but could also be used for innovations to be put in place to take advantage of the opportunity that arises with a flood to store floodwater. Elements of adaptive capacity, such as knowledge about these kinds of adaptation options, flexibility in decision making and of course financial assets, would however also have to be present.

### The Institutional Adaptive Capacity Framework—Contributions and Limitations

This study has developed and explored an innovative approach to assessing adaptive capacity of institutions, and contributes toward advancements of such assessments primarily in three ways. Firstly, through developing a framework at the management level of an organization or institution not typically explored, namely at the management level of a large-scale agricultural entity involving multiple beneficiaries or shareholders, producing cash crops in a poverty and development context. Such scale of assessment has provided detailed information about multiple aspects of the management and governance of the scheme in the context of extreme events, largely enriched by the lived experiences of the respondents. The relatively small organizations with few staff in management positions however led to a small available group of respondents. Although some level of triangulation of information was provided through the interview with the manager at Illovo, future studies building on this approach could benefit from expanding the scope of responses to also include board members, additional staff members and representatives of institutions or organizations within the direct networks of the schemes.

Secondly, taking a historical approach has enabled obtaining answers to what builds up or erodes adaptive capacity, which in forward-looking adaptive capacity assessment are only potential (Engle, 2011). Assessing the occurrence of extreme events over the last decade and what the effects have been on the sugarcane production—in combination with the lived experiences by the scheme managers, was useful in understanding how high adaptive capacity has better mediated the impacts that result from exposure to extreme events for the one scheme relative to the other with lower adaptive capacity. This study does not only highlight what is necessary for adaptive capacity, but provides nuances of individual choices and actions in both building adaptive capacity and activating it for maximum effect. Building on the framework we have developed in this study we propose future potential studies to further advancing the approach by assessing adaptive capacity using a set of given historical time slices (snapshots in history). This would enable exploring exactly how the adaptive capacity has risen and fallen in response to different drivers, including assessing efforts to increase adaptive capacity and how it was eroded after use following exposure to extreme events.

Thirdly, using productivity of sugarcane as an indicator of the success of adaptive capacity in enabling adaptation was a useful measure, particularly when relating the changes in yield to the lived experiences, occurrence of extreme events and the assessed characteristics and sub-characteristics of adaptive capacity. We do however acknowledge that if looking at other aspects of success, the outcomes of the analysis could have been more nuanced. Even though the sugarcane productivity of Phata was not affected, the effects of extreme events were reported to have been severe and detrimental in the district and caused losses for the people living in the district. Focusing on only sugarcane productivity as an indicator for success, thus disregards the effects these events have had of the scheme members, their households and villages, food crop fields and lives. Such effects inevitably cause decline in the schemes' adaptive capacity within the characteristics human asset, equity and fairness, and knowledge and information. Neither of the schemes provide climate information such as weather forecasts or early warnings to their members. Providing this kind of information—along with knowledge on how to use the information and act to improve adaptation—would have the potential to further build up adaptive capacity within the wider social network of the scheme and strengthen the human capacity (Vaughan et al., 2019). Assessing individual/household level adaptive capacity would thus require a framework with similar theoretical determinants but different, more scale-appropriate indicators.

## CONCLUSION

This study aimed to assess the adaptive capacity on sugarcane outgrower schemes in the Chikwawa district in southern Malawi using in-depth interviews with scheme managers to gain a deeper understanding of how the organizations meet the multiple dimensions of adaptive capacity. The extent of the adaptive capacity of the two schemes was described in terms of how it enabled adaptation, shown as sugarcane yield over the last decade, and viewed in the light of exposure to extreme events. This approach provided an opportunity to ground-truth the assessment of adaptive capacity by highlighting the role of different components and its overall effectiveness in enabling adaptation.

As well as providing indications to what kind of interventions are required to restore the deficient capacities and ensure future adaptation of sugarcane outgrowers, the development of this very specific framework for assessing adaptive capacity of this scale and type of organization is relevant also to other contract farming arrangements or similar kinds of agricultural systems in the developing world that similarly face increasing climate challenges.

This approach also contributes to the literature on adaptive capacity by reiterating the dynamism of adaptive capacity at any one time. Whilst the literature is increasingly recognizing that there are a variety of factors that determine the extent to which latent adaptive capacity is drawn upon, the application of the framework historically, as in this study, illuminates how adaptive capacity at any one time is shaped by what has happened in the past—including the extent to which it has been drawn upon in exposure to events. This temporal perspective on the evolution of adaptive capacity is particularly relevant in the context of climate change, which will likely see a decreased return period between extreme events. As a result, smallholder farming schemes—and other entities at different scales—will have less time to recover and replenish the adaptive capacity that they draw upon when exposed to one event before the next one arrives—leading to compound effects. Use of the framework outlined in this paper provides insights into the status of different components which, in turn, can highlight priorities for rebuilding adaptive capacity to reduce the risk of future exposure.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because of confidentiality. Requests to access the datasets should be directed to the corresponding author.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Humanities and Social Sciences Research Ethics Committee, University of KwaZulu-Natal. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

RH and KV contributed to the conception and design of the study and developed the theoretical framework. RH planned and performed field work and performed analysis and wrote the first draft of the manuscript. KN contributed to the literature review and wrote parts of the results section. KV contributed to manuscript revision. All authors contributed to final revision, read, and approved the submitted version.

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# Toward an Interoperable National Hazards Events Database for South Africa

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**Keywords: South Africa, disaster risk reduction, disaster loss data, interoperability, events database, disaster loss database**



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## INTRODUCTION

At the global scale, the frequency, extent and severity of natural disasters have increased notably over the last several years (Sapir et al., 2004; Field et al., 2012; McPhillips et al., 2018; Coronese et al., 2019). Climate-related disasters (floods, storms, droughts, wildfires, and heat waves) have come to dominate the disaster risk landscape accounting for upwards of 91% of the major-recorded events worldwide between 1998 and 2017 (Wallemacq, 2018). South Africa has faced a number of climate-related disasters over the last few decades including the 2014–2016 drought in which the country experienced the lowest annual rainfall amount on record (AgriSA, 2016; Engelbrecht et al., 2018). More frequent and intense events combined with a growing and urbanizing population, poor land-use practices, and an increasing number of people residing in informal settlements and high-risk areas, are likely to exacerbate the vulnerability of communities to climate-related events (Vermaak and Van Niekerk, 2004; Van Huyssteen et al., 2013; Thornton et al., 2014).

The shift toward proactive planning and preparedness that is closely tied to climate change adaptation requires reliable records of disastrous events to be collected, maintained, and managed (Kar-Purkayastha et al., 2011). Despite increasing access to data from a wide variety of sources, integration and reuse remains difficult due to a number of interoperability barriers to working with disaster data (Migliorini et al., 2019). Interoperability refers to the ability to create, exchange and consume data with common understanding of context and meaning of the data (Wilkinson et al., 2016). Barriers to interoperability of disaster databases include issues such as the lack of geospatial data that is comparable across communities, districts, and countries and which is consistent over time (Department of Environmental Affairs, 2014; Storiea, 2017; Li et al., 2019; Valachamy et al., 2020). Other issues include the use of different disasters classification systems and the lack of standardization in associated definitions. These inconsistencies are a result of the variations in how disaster data has been collected over time by a variety of countries and organizations, the types of disasters reported, spatial, and temporal data aggregations (Tschoegl et al., 2006; Integrated Research on Disaster Risk, 2014; Osuteye et al., 2017).

Due to the cross-sectoral nature of the disaster domain the exchange of data and the fulfillment of interoperability requirements is particularly critical. The minimum system requirements for an interoperable disaster loss database are outlined in South Africa's National Disaster Management Framework (Republic of South Africa, 2005). A shared disaster risk system must facilitate: "interoperability between systems and system components; sharing of common system components; common infrastructure components and common data/information; and reuse and customization of system solutions or components" (Republic of South Africa, 2005, p. 73).

This paper will consider some of the available sources of disaster data for South Africa and present a comparison between the recorded deaths as a result of natural disasters in South Africa from 1997 to 2016 based on data from the South African Vital Statistics and Emergency Events Database (EM-DAT) to demonstrate some of the challenges with existing databases. We then present our recommendations built into a prototype National Hazards Events (NHE) online reporting system. The proposed open-access system presents a standardized, scalable design method and implementation of a database that can be used to improve data collection and reporting.

## STATUS OF DISASTER LOSS DATABASES FOR DISASTER RISK REDUCTION IN SOUTH AFRICA

### International Databases

Currently, there are six major global open-access disaster loss databases that can be used to derive the baseline data for disasters in South Africa: United Nations Desinventar Sendai (United Nations Disaster Risk Reduction, 2020), Global Sustainable Development Goal Indicators Database (United Nations Disaster Risk Reduction, 2020), NatCatSERVICE (Munich Re)[1], Sigma (Swiss, 2020), Global Disaster Identifier Number (Asian Disaster Reduction Center, 2004), Global Risk Data Platform (United Nations Environmental Program, 2013), and EM-Dat [CRED (Centre for Research on the Epidemiology of Disasters), 2020]. Each of these databases provides access to records about disaster occurrence, damages, losses, and impacts, compliant with the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) monitoring minimum requirements (UNISDR, 2017).

The data available in these international databases varies between sources and calendar years resulting in inconsistencies between data outputs. For example, differences exist in the date of events in different databases. NatCatService and Sigma usually record a period for the disaster with a start and end date whereas EM-DAT records the day the event was declared a disaster or emergency. Moreover, international databases tend to record losses only from large scale events. In the cases of EMDAT and DesInventar this means that events are only recorded if 10 or more people are reported killed; 100 or more people need to be evacuated, provided with humanitarian assistance or otherwise affected; countries declare an emergency or call for international assistance (Osuteye et al., 2017). This conceals the diversity of the hazard landscape in South Africa, which experiences a far broader range of small hazards. These include mini-tornados, localized flooding and slow-onset flooding events, deaths due to lightning strikes and fires in informal settlements. Consequently international databases tend to underestimate the scope and prevalence of hazard events in South Africa.

### National Database

There is currently no internationally standardized database on loss or damage of disaster events for South Africa (UNISDR, 2019). In 2018, the National Disaster Management Center (NDMC) released an online Disaster Atlas Application (National Disaster Management Centre, 2018) to serve as the national disaster database. The portal enables users to view records of declared or gazetted disasters for the period of February 2006 to March 2017. The data is not currently available for download and the database has not been updated since March 2017 for more recent disasters. Events presented in this database were declared either local, provincial or national disasters and met the criteria laid out Section 1(1) of the Disaster Management Act No. 57 of 2002 (Republic of South Africa, 2002):

"Disaster" means a progressive or sudden, widespread, or localized, natural or human-caused occurrence which-

(a) causes or threatens to cause-
  - (i) death, injury or disease;
  - (ii) damage to property, infrastructure or the environment; or
  - (iii) disruption of the life of a community; and

(b) is of a magnitude that exceeds the ability of those affected by the disaster to cope with its effects using only their own resources;"

While understanding that not all extreme or hazardous events are declared a disaster (see Van Niekerk, 2014), there are inconsistencies in reporting that make it difficult for practitioners and researchers to access consistent information to inform Disaster Risk Reduction (DRR). For example, a fire in Joe Slovo, Langa in 2000 was declared a national disaster but subsequent fires in Hout Bay in 2004 and in Joe Slovo in 2005 were not declared disasters despite impacting more people than the fire in 2000 (Smith, 2005; Stewart, 2008). Furthermore, a number of important events, including the 2017 wildfires in Knysna (Forsyth et al., 2019), are excluded from this database.

To fill some of these data gaps, national sector departments and various organizations have created their own databases. The South Africa Weather Service (SAWS) maintains the CAELUM weather events database, a restricted commercial product, that provides a description of historical extreme weather events. Other sector departments such as the Department of Health, and the Department of Agriculture, Land Reform and Rural Development collect disaster-related data for monitoring and reporting purposes. Statistics South Africa (StatsSA) releases information on mortality and causes of death, which includes those attributed to natural disasters. For a full review of these see Storiea (2017).

Private insurance companies are also a source of data on the costs of recovery from disasters and the overall economic impact, but access to data and collaboration on disaster research is often limited by lack of public-private partnerships (Department of Environmental Affairs, 2014). Currently, insured properties are unlikely to be recorded as part of the pool of impacted stocks as disaster recovery is handled through private insurance agencies rather than the government, with no requirement for a disaster declaration.

[1] The NatCatSERVICE analysis tool became a paid for service in mid-2020.

### Issues of Interoperability: A Case Study Comparing Disaster-Related Mortality From EM-DAT and South Africa's Vital Statistics

The authors noted a number of key differences between the natural disaster deaths reported by the Statistics South Africa Vital Statistics (StatsSA, 2019) and EM-DAT [CRED (Centre for Research on the Epidemiology of Disasters), 2020] for South Africa between 1997 and 2016 (**Figure 1**). Firstly, the total number of deaths over the 20 years was markedly different between the two datasets and between the number of deaths per disaster class. The data from EM-DAT shows that the highest number of deaths were a result of epidemics (e.g., cholera, diarrheal disease, and SARS) and floods whereas the data from StatsSA shows that lightning strikes are the most common cause of disaster-related deaths with cold extremes being second. These differences are a result of the source of the data and how deaths are defined and classified in each of the databases.

The purpose of StatsSA Vital Statistics data is to report on national-recorded live births, marriages, and divorces as well as mortality and causes of death, based on civil registration data. The use of the mortality data to assess deaths due to natural disasters is secondary and has been used in the 2019 South African Sustainable Development Goal Country Report to describe the "number of deaths as a result of natural disasters" to provide evidence for Indicator 13.1.1D. As an international database, EM-DAT scrapes various sources for disaster data including, UN databases, national government repositories, inter-government organizations, reinsurance companies, and media sources [CRED (Centre for Research on the Epidemiology of Disasters), 2020]. Gaining access to accurate data, verified reports, and updated information as a disaster progresses is a key challenge and, as such, EM-DAT often underestimates the impact of events (Green et al., 2019).

Secondly, differences in the classification of disaster types by the two databases are evident where disasters such as "sunlight,", "lightning," "epidemics," and "forest fires" are reported in one database but not the other. EM-DAT uses the 2014 Integrated Research on Disaster Risk (IRDR) framework for hazard definitions (Integrated Research on Disaster Risk, 2014), putting it in line with the SFDRR. This is a five-tiered hazard classification framework with 46 "natural" hazards across the tiers and is extensible for specific descriptions of hazards such as "epidemics" which can be caused by a number of pathogens. StatsSA Vital Statistics uses the UN WHO International Classification of Disease (ICD) codes which define 8 hazards with a ninth catchall "other category." The ICD-10 codes for vital statistics define disaster mortality as death from "exposure to forces of nature" (Haagsma et al., 2016). This indicates that the data in this database references particular deaths rather than the actual disaster event.

The spatial resolution differs between the datasets where EM-DAT provides deaths at a location (provided by XY co-ordinates) whereas mortality statistics from StatsSA is provided at the provincial level. Publicly available vitality statistics in South Africa state the province in which the death occurred and as such, this is the highest spatial resolution of data available from this source. Due to the wide variety of data sources supplying EM-DAT, the records are highly variable in their spatial resolution and include anything from a specific suburb to the entire country for an individual event [CRED (Centre for Research on the Epidemiology of Disasters), 2020].

Lastly, the temporal resolution of the data (not shown here) is also quite different between the two sources. Mortality statistics record the day a person died while EM-DAT data is concerned with the date of the disaster event. Thus when comparing dates, those in EM-DAT may not be the date of death and the death date recorded in vital statistics may not indicate the date the disaster started.

## CREATING ENABLING TECHNOLOGIES FOR DISASTER RISK REDUCTION IN SOUTH AFRICA

### A Prototype of a Web-Based National Hazards Events Database for South Africa

A team of programmers and researchers at South Africa Environmental Observation Network (SAEON) have developed a framework for an interoperable web-based National Hazards Events Database (NHE) for South Africa in order to address the gaps in national and international disaster reporting. The open-access database is aimed at facilitating a better understanding of how people, infrastructure and different economic sectors are impacted by an event.

The data can be viewed in a dashboard containing location maps, charts, and other views which specify the areas impacted, the total number of disasters, the funding directed toward a specific disaster, and the breakdown of the total number of injuries and fatalities. The historical events are displayed on a timeline for a geographic region and are intended to give perspective on the frequency and impact of hazardous events over a period of time. The prototype landing page of the NHE is provided in **Supplementary Figure A**. At the time of writing, the data in the NHE consists of declared disasters from the NDMC database (National Disaster Management Centre, 2018). A key next step in the development of the database will be securing data sharing partnerships with both government departments, including the NDMC, as well as the private sector insurance companies.

### Developing an Interoperable Disaster Reporting Lifecycle

#### Disaster Reporting Lifecycle

A disaster reporting lifecycle should encompass actions or inactions of various parties at intermediate stages before, during and after a disaster occurs and link the stages throughout. Under the South African Disaster Management Act (Republic of South Africa, 2002) and the National Disaster Management Framework (Republic of South Africa, 2005) the three tiers of government (national, provincial, and municipal) are required to develop Disaster Management Plans (DMP). The Key Performance Areas (KPAs) of these plans align with aspects of the reporting lifecycle

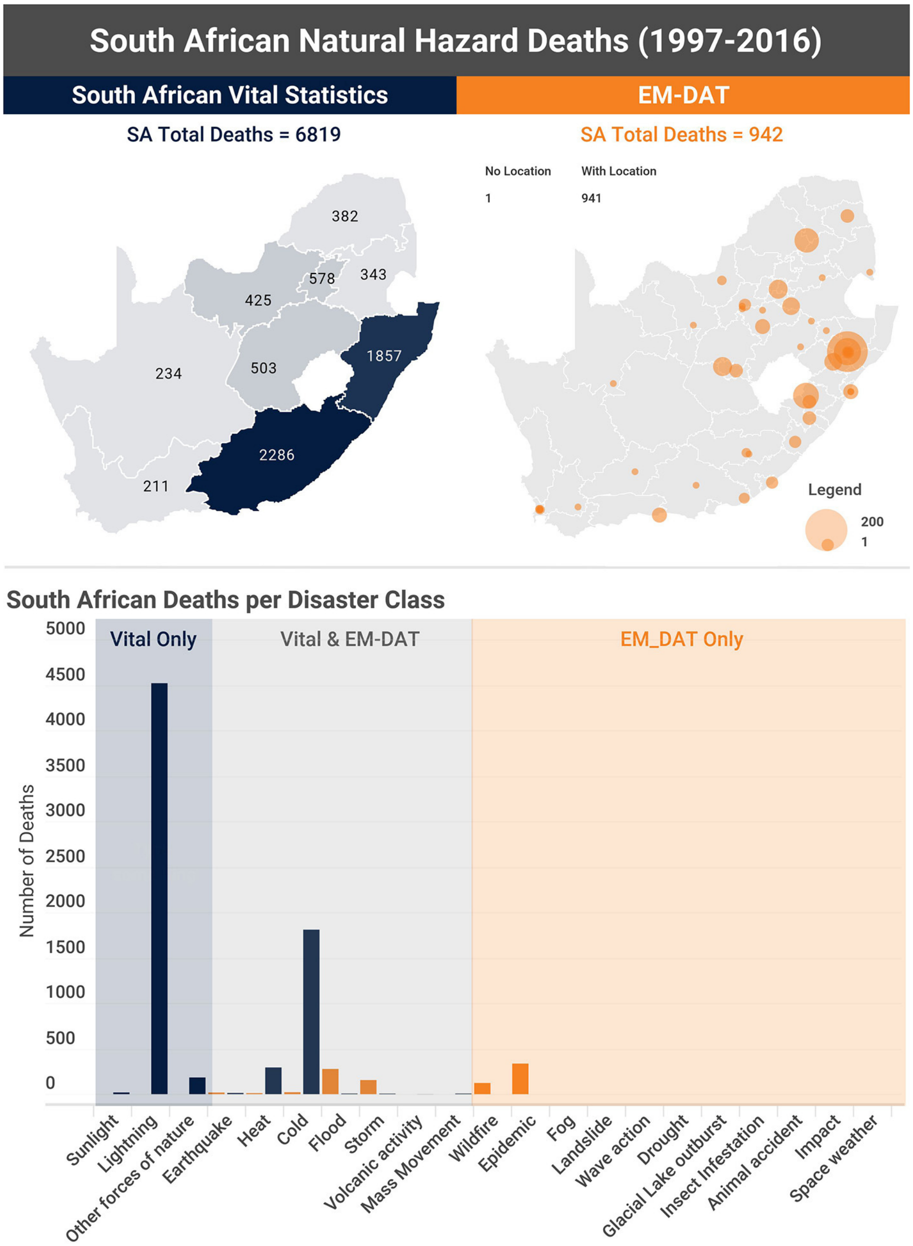


**FIGURE 1 |** Comparison of the number of disaster-related deaths for South Africa between 1997 and 2016 obtained from the South African Vital Statistics (left) and EM-DAT (right).

actions, outlined in **Table 1**. In order for responsible parties to be assigned to actions, the responses must be accessible and centralized.

The NHE was specifically designed to facilitate information uptake during the "Recovery and Rehabilitation" stage of the reporting life cycle. This is the stage in which impacts are effectively recorded as accounts are tallied during disaster recovery and rehabilitation. Ultimately, impact reporting underpins the rest of the lifecycle and helps to define future priorities. This is also the stage when disaster declarations occur.

## Hazard Type Classification

A standardized hazard classification system with associated definitions should be used between the different national databases so that data for a hazard type can be compared across years and regions and the reporting lifecycle. The first step is to ensure that reporting agencies agree on a common classification so that references made across a database correspond to the same hazard type (e.g., flood vs. riverine flood vs. storm). In the NHE, these definitions are actioned through controlled vocabularies such that only options from the list can be selected for entry.

In the NHE, we propose the use of a hazard classification system which integrates schemes provided by SFDRR Integrated Research on Disaster Risk (IRDR) with those used by the NDMC and the WHO International Classification of Disease (ICD) codes for natural disaster deaths. Hazards common to the South African context, such as mini-tornadoes and fires in informal settlements, are also included in the database. Hazard definitions are based on the SFDRR Hazard Definitions covering natural, environmental, biological, and man-made hazards but linked to the definitions outlined in the National Disaster Management Act.

### Disaster Impact Classification

Disasters are frequently classified according to their impact, measured by number of victims and economic damage. In order to consistently report on what losses have occurred as a result of a disaster, a standard impact classification system needs to be developed for South Africa and adopted by all reporting structures. We propose two impact units for South African disaster loss databases—economic loss at 2010 South Africa Rand (ZAR) value and the numbers of people affected. A common monetary value allows for quick and easy translation into national and international disaster reporting frameworks and makes data comparable across databases. In accordance with the SFDRR the number of people would extend to the number of people killed, injured, mising, homeless, affected, relocated, or displaced by a disaster.

The DMP planning KPA on "Preparation," includes "personal injury, health, loss of life, property, infrastructure, environments and government services." In the NHE questionnaire, this has been expanded to include data for indicators from SFDRR Targets A (reduce global mortality), B (reduce the number of people affected), C (reduce economic loss), and D (reduce damage to critical infrastructure and basic services) and broadly cover four key sectors:

- Human health and wellbeing (e.g., StatsSA, 2007, 2020a): based on census and vital statistics as well as UN reporting standards for demographic data that provides an output of the number of people.
- Ecosystems and ecosystem services (e.g., Reyers et al., 2015; Sitas et al., 2019): based on South African natural capital accounting reports that provide an output in ZAR.
- Human settlements and infrastructure (e.g., StatsSA, 2020b): based on national accounts that provide an output in ZAR of the value to replace or repair buildings and equipment.
- Economic sectors and workers (e.g., StatsSA, 2020c,d,e,f): based on national accounts and provides an output in ZAR of the loss of production or of lost revenue.

In the NHE, data inputted for these four sectors are automatically converted to a corresponding ZAR value by leveraging national statistics reports from relevant sectoral departments. As an example, a user might indicate that 50 hectares of maize were destroyed in a drought in a particular year and the incorporated national accounting-based calculator would indicate the value in rands for that region, for that crop, for that year. The database thus collects data through a questionnaire in great detail using units suited for the particular purpose or industry but provides a platform for interoperability across sectors. As the user is not responsible for an evaluation of the impact units, the results are based on consistent calculations across the framework.

## Evaluation of the Interoperability of the NHE

While the NHE faces the same challenges of data access as other efforts, it offers a platform where local, district, and provincial managers can capture hazardous events at local level occurring across South Africa and their impacts on urban and rural populations. The questionnaire design ensures that impacts to human health and habitation, various sectors of the economy and infrastructure are documented in a quantifiable and relevant way. The NHE's controlled vocabularies for South African sectoral accounts, vital statistics, and census practices and infrastructure reporting allow for impacts to be calculated directly within the data framework with the latest publicly available data.

Core interoperability literature for information systems is generally based on four dimensions: technical, semantic, syntactic, and organizational:

- Technical interoperability refers to the ability of the data to be easily accessed and shared through common protocols. The NHE is a web based interface for a Postgresql database making it technically interoperable.
- Syntactic interoperability refers to the packing and sharing methods for a dataset. Optimal syntactic interoperability indicates that data can be downloaded in an open source, machine readable format. As data from the NHE can be downloaded as csv files, the NHE is syntactically interoperable. Events are also georeferenced using GeoJSON such that events can be spatially recorded within current municipal boundary polygons.
- Semantic interoperability refers to the ability for databases to exchange relevant information through a common framework of understanding. In the NHE, APIs have been used for controlled vocabularies common to other systems including the National Climate Change Information System (NCCIS) (Department of Environment Forestry Fisheries, 2020) and the South African Risk and Vulnerability Atlas (SARVA) (Department of Science Innovation, 2020) making these bespoke government systems semantically interoperable.
- Organizational interoperability refers to the exchange of information between organizations. This includes data sharing agreements and data licensing. The data and codebase for the NHE are open source and shared under a creative commons (CC-BY) license.

## DISCUSSION

Open access to disaster-related data is critical to achieve Action Priorities 1 and 2 of the Sendai Framework for Disaster Risk Reduction for years 2015–2030 as well as the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement to reduce climate change and its impacts. While data gaps and inconsistencies between datasets are issues not unique to South

**TABLE 1 |** A South African disaster reporting lifecycle: Integrating disaster reporting into South African Disaster Management Plan planning.

| # | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **Phase** | **Preparation (mitigation)** | **Monitoring** | **Early warning** | **Response** | **Recovery and Rehabilitation** | **Disaster risk reduction linked to climate change adaptation** |
| Definition | Each municipality is responsible for 'development and adoption of integrated disaster risk management policy' as part of larger integrated Development Plan planning. | Principally, municipalities coordinate directly with the South African Weather Service and other sectoral departments. | The South Africa Weather Service is currently deploying an impact early warning system to municipalities. | Relief groups respond to the immediate impacts on the community. | The community is rehabilitated, rebuilt or redeveloped. | Measures are initiated by the municipal government in consultation with the community to adapt to future events through IDP planning. (Different from mitigation in that it is a response to a specific event). |
| Technology needed | Consolidated disaster database including occurrence and impact as well as the risk of recurrence | Databases of seasonal trends to indicate when and where problems are likely to occur and what signals to be monitored. | Real time database of current environmental conditions with automated threat assessments delivered to municipalities. | Database of logistics information for relocation and resupply for different scales of disasters | Database of disaster impacts and their costs. | Database of new and past adaptation measures and evidence of their success linked to specific hazard occurrences. |
| Contributing party | SAWS, NDMC, Other sectoral departments | SAWS and Sectoral departments | SAWS, sectoral early warning systems, research institutions, and private-public partnerships. | Three spheres of government, Sectoral departments, Emergency response units | Three spheres of government, insurance agencies, StatsSA (vital statistics) | Three spheres of government, private sector, researchers |
| Critical access groups | Three spheres of government, NDMC, Sectoral departments | Three spheres of government, NDMC, Sectoral departments | Three spheres of government, NDMC | Three spheres of government, NDMC, Emergency response units | Municipal government | Three spheres of government, DEFF, NDMC |
| Disaster management plans | *KPA2 Risk Assessment KPA3 Disaster Risk Reduction plans and programmes KPA4a Preparedness Plans that include the dissemination of early warnings and averting or reducing the potential impact* | *KPA1 Integrated Institutional Capacity—"Coordinate and align the implementation of its plan with other organs of state and institutional role players"* | *KPA1 Integrated Institutional Capacity—"Coordinate and align the implementation of its plan with other organs of state and institutional role players"* | *KPA4b Response—"implementing immediate integrated and appropriate response measures when significant events or disasters occur or are threatening to occur"* | *KPA 4c Recovery—"implementing all rehabilitation and reconstruction strategies following a disaster in an integrated and developmental manner"* | Regular testing and review of DMP |

*The blue indicates where the prototype National Hazards Events Database fits into the cycle.*

Africa, the country faces a number of challenges regarding the interoperability of national datasets. Multiple sources of data, the lack of consistency in output data as well as data gaps in these international databases has the potential to lead to confusion in the evaluation of the impact of a disaster situation by researchers and policy-makers.

The development of a database system that meets the requirements of users needs to consider findability, accessibility, interoperability, and reuse (Wilkinson et al., 2016). In this paper, we have identified various key factors where data can be harmonized and how interoperability in disaster databases can be achieved. This includes a common framework for a disaster reporting life cycle and a standard classification system for hazards and impacts metrics. With this minimum set of information, disaster data can facilitate risk-informed sustainable development.

To support this approach to disaster data management, we have developed a National Hazard Events database framework that guides data providers to enter data in such a format that becomes consistent with other databases in terms of interoperability aspects. The proposed system supports data compatibility and interoperability with data collected by the NDMC but also with international databases such as EM-DAT. The NHE is open access, user-friendly database that provides data and information on the spatial and temporal occurrence of hazardous events including risks such as floods, fires, droughts, sea storm surges, lightning strikes, landslides, heat waves, hail storms, wind storms, and tornadoes. Ultimately, the proposed NHE has the potential to substantially increase the value of disaster data to a wider range of researchers and applications and to better inform future disaster risk management at the local level.

### Critical Success Factors for the Implementation of NHE in South Africa

The NHE presented in this paper is a proof of concept and represents an investment of effort and goodwill by SAEON in the disaster response domain of South Africa. There are a number of critical success factors for the successful implementation of the NHE as a national resource and ensure that the information is regularly updated and system maintained. For the NHE to be completely interoperable, there needs to be the development and implementation of a standardized disaster classification system (e.g., IRDR framework for hazard definitions) across all national and sector departments. Such a process will be time consuming and will require substantial effort engaging the disaster management sector in South Africa.

Additional collaboration with National Sectoral Departments and partnerships with private sector insurance companies will need to be established to ensure open data sharing. Future plans for NHE also include the incorporation of tools such as events detected *via* remote sensing, social media, crowdsourced contributions, and online news items to give users a more complete view of the scope of disastrous events occurring in South Africa. This will assist in supplementing the information housed in the NHE as well as serving as a verification process. To facilitate collaboration, all the development code and algorithms are open source projects. The web-based NHE and associated databases and vocabulary services have been developed with re-usable open source code and support the ability to directly embed components into another website or to modify the source code and reuse in a website.

A comprehensive review of information needs in terms of policy makers, disaster management practitioners, and researchers will need to take place to ensure that the NHE meets the expectations of the users. This would include an assessment of local and district integrated development plans and associated key performance indicators to ensure that the information and data from the NHE serves a practical purpose. Engagement with local stakeholders such as the South African Local Government Association (SALGA), local NGOs working with municipalities and farmers are consulted to ensure not only the uptake of the NHE but also the bottom-up process of information gathering on local disasters. These engagements and partnerships will need to be on-going and iterative throughout the lifespan of the NHE.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are publicly available. This data can be found here: https://search.datacite.org/works/10.15493/sarva.270121-1.

## AUTHOR CONTRIBUTIONS

CD-R and AH have read and agreed to the published version of the manuscript. All authors contributed to the article and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.591020/full#supplementary-material

**Supplementary Figure A |** National Hazards Events (NHE) Database dashboard view.

**Supplementary Table A |** South African Natural Disaster Deaths (1997–2016).

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# Understanding the Role of User Needs and Perceptions Related to Sub-Seasonal and Seasonal Forecasts on Farmers' Decisions in Kenya: A Systematic Review

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One major challenge facing farmers and other end users of weather and climate information (WCI) in Kenya is the linkage between their perceptions, needs, and engagements with producers of the information. This is highlighted by increased interest in understanding the constraints on appropriate use of weather information by farmers in decision-making. The choice between sub-seasonal and seasonal forecasts can enable better decisions by farmers if the forecast information is reliable and integrated through a coproduction process. This study analyzes user needs and perceptions of crop farmers, pastoralists, and agro-pastoralists in relation to sub-seasonal and seasonal forecasts for five counties in Kenya. A total of 258 peer-reviewed articles and gray literature were systematically analyzed using Search, Appraisal, Synthesis and Analysis (SALSA) to understand how the needs and perceptions of users of WCI shaped access and use in decision-making. The study also evaluated factors influencing use and uptake of sub-seasonal and seasonal forecasts as well as the barriers to use. Results show that farmers' perceptions shaped the choice of WCI that is used and also highlight how sub-seasonal and seasonal forecasts were used for diverse applications. Gender, availability of resources, access, and mode of communication were key factors influencing the use of seasonal forecasts. For example, access to seasonal forecasts of farmers in drier counties enabled them to manage floods and reduce risk. One lesson learned was that farmers combined WCI with other coping practices such as agronomic practices and water efficiency management. Despite a number of challenges by forecast users such as insufficient resources and lack of access to information, there is potential to improve forecasts according to user needs through a coproduction process. This study recommends stakeholder engagements with producers in the development and evaluation of forecast products and communication pathways to improve uptake and use of forecasts in decision-making.

**Keywords: user needs, perceptions, sub-seasonal forecast, seasonal forecast, indigenous knowledge, farmer, co-production**

## INTRODUCTION

Kenya, like many other Sub-Saharan African countries, is highly vulnerable to extreme weather and climate risks associated with poor infrastructure and low adaptive capacity. Climate change impacts will alter agricultural production and increase pressure on communities' livelihoods (Brown and Hansen, 2008; Kipkogei et al., 2017). For example, droughts and floods are more frequent in Kenya and the region in the last decade (Bunyasi, 2012; Huho and Kosonei, 2013; Mugalavai and Kipkorir, 2013; Yvonne et al., 2016).

In efforts to address these problems, several studies highlight that weather and climate information (WCI) can play a significant role in minimizing the negative impacts of climate disasters (Carr et al., 2016; Ketiem et al., 2017). The use of this information can translate to social and economic opportunities when favorable weather and climate conditions occur (Coe and Stern, 2011; Mugi-Ngenga et al., 2016; Apgar et al., 2017; Ketiem et al., 2017; Ozor and Nyambane, 2018). Nonetheless, climate information services (CIS) in sub-Saharan Africa are already being developed, although with relatively little focus on end users and their specific needs (Carr et al., 2016). At the moment, increasing attention is shifting to engagements between users and producers of WCI, which is believed to promote user-centered climate services (Rarieya and Fortun, 2010). It is postulated that by identifying user needs and perceptions, producers of WCI can integrate farmers and other stakeholders in the formulation, production, and dissemination of WCI. It is within this context that we review user needs and perceptions in relation to sub-seasonal and seasonal forecasts for decision-making in Kenya.

To build this, global trends in understanding user needs and perceptions related to sub-seasonal and seasonal forecasts in agriculture and related sectors are first highlighted. Several examples on this area can be cited from the United States (Brewer et al., 2020), Europe (Soares et al., 2018; Damm et al., 2019; Kusunose et al., 2019), China (Golding et al., 2017), Sub-Saharan Africa (Jones et al., 2015; Singh et al., 2018; Nkiaka et al., 2019), and Australia among other regions (Tarhule and Lamb, 2003; Mase and Prokopy, 2014; Nalau et al., 2017; Williamson et al., 2017). Brewer et al. (2020) and Williamson et al. (2017) opine that users' perceptions are important as a guide to science, research, innovation, and capacity and have the capabilities of developing high-quality weather products that lead to improved services, access, and stewardship. Further, users' perceptions enable the identification of constraints to the use of weather information across diverse user attributes such as gender and socioeconomic status where, for instance, women are ignored from most farm decisions (Carr et al., 2016; Snorek et al., 2018). Several studies also show that knowledge on users' perceptions makes it easier to know the drivers and barriers to adoption and uptake of WCI such as limited resources and uncertainty of climate forecasts (Sitas et al., 2014; Damm et al., 2019; Nkiaka et al., 2019). Yet, Carr et al. (2020) and Stewart-Ibarra et al. (2019) show that users' perceptions are important in linking user needs and activities to climate services and promoting practices and concept of coproduction of climate services, which bring together users and producers of WCI. In contrast to the latter, Coe and Stern (2011) indicate that the perceptions of farmers in sub-Saharan Africa tend to overemphasize extreme weather impacts rather than opportunities that come when better weather conditions occur. Despite these, knowledge of users' needs and perceptions does not always lead to uptake and use of WCI where other constraints exist (Rasmussen et al., 2017). It is therefore useful to examine how users' perceptions on WCI can influence decision-making in agriculture and other farm-related activities. Notwithstanding the benefits of WCI, uptake and use of WCI require sustained interaction between the producers and users of WCI, which can bridge the gap between them (Guido et al., 2016; Jones et al., 2017; Haavisto et al., 2020).

Due to frequent threats posed by extreme weather, WCI is becoming necessary for early warning decision-making by users in minimizing agriculture-related climate impacts (Tall et al., 2018). This is one of the key reasons why meteorological forecasters regularly produce and provide a lot of information to users in the agriculture and other climate-sensitive sectors. This process of production and provision of climate information to users is also referred to as climate services (CSs) and comprise institutional arrangements, contextualizing of information, communication, stakeholder's engagements, capacity building, and research (Kwena, 2015; Pathak and Lúcio, 2018; Carr et al., 2020). The Global Framework for Climate Services (GFCS) by the World Meteorological Organization shows that CSs are meant to improve users' capabilities to adapt to the impacts of climate change (Vaughan and Dessai, 2014).

Where CSs and WCI are not utilized by users (Flagg and Kirchhoff, 2018; Singh et al., 2018), it might be due to the limited attention these pay to users' needs and requirements (Skelton et al., 2019; Manon et al., 2020), institutional barriers (Dilling and Lemos, 2011; Biesbroek et al., 2018), low forecast accuracy (Buizer et al., 2005; Morss et al., 2008), difficult terminology and clarity (Briley et al., 2015), and other producer-driven constraints (Feldman and Ingram, 2009). Producers of WCI presuppose that meteorological forecasters can develop products and services without involving the users or their needs and perceptions but anticipate that users will find the information usable and useful (Cash et al., 2006). While providing WCI that is tailored to the users' needs and demands may address some of the challenges highlighted, the user-driven process can be successful and translate to usability of the information if institutional support, dissemination, and communication strategy are put in place (Rasmussen et al., 2017; VanderMolen et al., 2020). According to Wilkinson et al. (2015), a useful forecast is one which satisfies a user's need in regard to accuracy, timeliness, space, and time resolution and other user-sensitive attributes. If this is achieved, increased uptake and use of WCI can be realized across sectoral needs. However, this will only be possible if we shift CSs from being producer-oriented to user-focused through the process of coproduction of WCI, which brings the user onboard through a multidisciplinary and participatory process (Dilling and Lemos, 2011; Lemos et al., 2012; Tall et al., 2012; Bremer et al., 2019). This concept of coproduction between producers and users of WCI is believed to have led to increased usability and dissemination of forecasts (Roncoli et al., 2011; Meadow et al., 2015), development of forecast products that are tailored to user's needs (Cash et al., 2006; Howarth and Morse-Jones, 2019), and increased efficiency, trust, and capacity for using the information to make decisions (Lemos and Morehouse, 2005; Buizer et al., 2016). In this regard, coproduction through use of participatory workshops infuses a better understanding of WCI and trust among farmers and other stakeholders in the uptake and use of WCI (Tall et al., 2012). Another issue that can be strengthened through the engagement process between users and producers of WCI is paying attention to the changes in forecast uncertainty at nowcasting to seasonal timescales. These changes influence user's decisions such as planting time and other agricultural practices as well as how the information is communicated.

This study recognizes the attention that development partners are giving to the challenges of climate change in developing and least developing countries (Sovacool et al., 2017; Teklu, 2018). One of the focus areas is the strengthening of capacity for WCI and the pathways to provide solutions to vulnerable communities. This can be achieved through climate data analysis and inclusion of user needs and demands within the climate services through code signing and co-development of products and services that address communities' socioeconomic concerns. The support for climate services can provide an opportunity to include users' needs, perspectives, and contributions of producers of WCI. The gains from the efforts by development partners are highlighted by several studies on WCI in Kenya and in Sub-Saharan Africa, which show that working with farmers and other stakeholders has improved the farmers' capacity and enabled better understanding and identification of users' needs and demands, enhancement of dissemination and use of WCI in decision–making, and also improved access to analyzed data for use in the management of climate risks in agriculture and related activities (Coe and Stern, 2011; USAID, 2013; Aura et al., 2015).

Specifically, this paper establishes user needs and perceptions of crop farmers, pastoralists, and agro-pastoralists (collectively "farmers") with respect to sub-seasonal and seasonal forecasts in five Kenyan counties. The specific objectives are to: (1) identify WCI needs of farmers in the five counties in Kenya; (2) establish the main drivers influencing the uptake, use, and adoption of sub-seasonal and seasonal forecasts by farmers in the target counties; (3) determine the barriers that hinder the uptake, use, and adoption of sub-seasonal and seasonal forecasts by users in the target counties; and (4) analyze how users' perceptions on sub-seasonal and seasonal forecasts influence farm decisions in the study counties.

## METHODOLOGY

Literature review was chosen as the ideal research approach to address the objectives of this study, which seek to get a better understanding of the existing information and research gaps on users' needs and perceptions related to seasonal and sub-seasonal forecasts in the study counties. It was deemed suitable, since it is a key component of research and allows a rigorous scrutiny process and comprehensive analysis of diverse and previous research work and theories by different authors collectively covering a longer period of time rather than a single exploratory study over a short period of time and using participatory rural appraisals and surveys in the study areas (Benzies et al., 2006; Ridley, 2012; Rahman et al., 2020). In addition, literature review in this study is used to provide a basis for a follow-up exploratory survey that was conducted later in four of the five study counties and to place the findings within the context of existing literature. In other words, the analysis of the survey data will be useful in validating the literature review findings from this study.

Specifically, our study adopts a systematic review approach that allows existing knowledge and case studies to be synthesized under common themes from previous research and for obtaining most and the best evidence for many review decisions (Booth et al., 2016). In contrast to traditional narrative reviews, this approach seeks to minimize bias and enhance transparency and has been preferred by several scientists to obtain and compare evidence from research studies (e.g., Nkiaka et al., 2019; Carr et al., 2020). The review approach is different from other reviews, since it is based on specific research questions. Other literature review approaches differ by the extent to which they are systematic and are also based on broad research questions and qualitative analysis rather than comparison of evidence between studies (Booth et al., 2016). The review targeted English-language peer-reviewed and non-peer-reviewed literature published between 1985 and 2020. We largely examined research studies in this period in order to have a better background on farmers' needs and perceptions related to sub-seasonal and seasonal forecasts in decision-making. The inclusion and exclusion criteria of research articles are described in **Table 1**. The process involved selection of research articles that addressed one or more of the following:

- Timescale of the forecast
- The type of climate information and combination provided (short- or long-term forecast, agronomic information, water conservation measures, market information)
- The needs and perceptions of farmers related to WCI
- Methods of communicating weather and climate forecast
- Information related to the use of indigenous forecast (IF) by farmers
- Barriers that impede the use of WCI in agriculture
- Factors that influence the uptake, use, and adoption of WCI by farmers
- Farmers' perception of forecasts being provided and how this can influence decision-making.

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) as the reporting guidelines for database searches, number of articles/abstract screening, and the texts retrieved (Liberati et al., 2009; Moher et al., 2015; **Figure 1**).

To ensure the review captured all relevant publications that address the scope of the study, we carried out preliminary scoping of literature to identify appropriate search terms. Additionally, we used our research scope to formulate four research questions and the research limits to determine and identify the review method. Scoping enables decision-making on the type of topics to be selected or excluded from the review. Several keywords were then captured consisting of "need," "perception," "use," "user,"

**TABLE 1 |** Inclusion and exclusion criteria.

| Criteria | Inclusion | Exclusion |
|---|---|---|
| Research article type | – Peer-reviewed research articles<br>– Gray literature (unpublished academic research, government reports, project reports) | – Conference proceedings, book series and chapters, book, conference series |
| Language | – English articles | – Non-English articles |
| Year of publication | – From 1998 to June 2020 | – Before 1998 |
| Citation Indexes | – H-Index among others (Google Scholar) | – Non-science citations |
| Countries and sub-national | – Kenya and study counties, few regional and global articles (for example, studies' references) | – Other countries (excluding example studies used for background and references) |

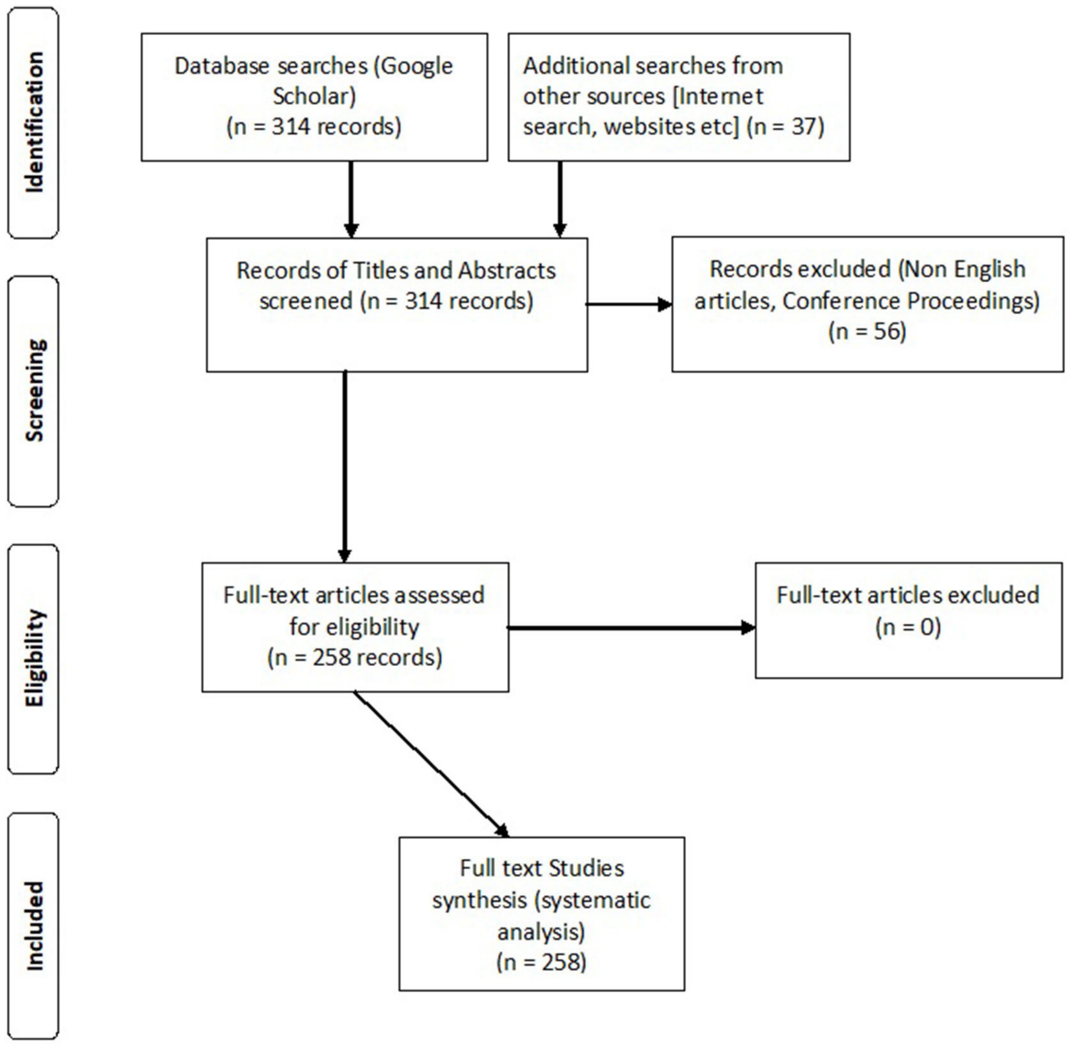


**FIGURE 1 |** Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram.

"forecast," "information," "demand," "weather information," "climate," "product," "access," "dissemination," "communication," "barrier," and "meteorological." These keywords and terms generally relate with or appear in the title of the study and also highlight aspects of the research questions and study objectives. For example, in the study by Kadi et al. (2011), "The State of Climate Information Services for Agriculture and Food Security in East African Countries," most of the keywords appear several times, e.g., Need, 86 times; Use, 248 times; user, 86 times; demand, 25 times; forecast, 121 times; information, 311 times; weather information, 8 times; climate, 505 times; product, 231 times; disseminate, 23 times; communication, 22 times; barriers, 14; and meteorological, 120 times. It is worth noting users' perception with regard to aspects or attributes of WCI (sub-seasonal and seasonal forecasts) that link with specific keywords. Subsequently, the keywords were useful in determining if the selected publication highlighted issues related to the study and whether they should be included or excluded in the review. We used the following search terms/strings based on the specific county name and, in some cases, country name and used Google Scholar as the main database to retrieve information. For gray literature, other databases including government websites and research/academic institutions' knowledge management systems were used in the search, which also utilized the search terms identified. The search terms included the following:

- User needs and perceptions of weather and climate information in Kenya
- Climate information services in Kenya
- Coproduction of weather and climate information
- Climate change impacts and mitigation on agriculture in Kenya
- Use of seasonal and sub-seasonal forecast by farmers and pastoralists in Kenya
- Use of IF in agriculture/pastoralism
- Farmers' perception of weather information and climate services.

The literature search strategy and selection criteria enabled a total of 314 publications to be retrieved from Google Scholar. A detailed examination of the article title and abstract led to the elimination of 56 articles, while 258 articles (both reviewed and non-peer-reviewed) were included in the systematic review.

Considering the four objectives of the study on user needs and perceptions related to sub-seasonal and seasonal forecasts, we formulated four research questions, as indicated below. The research questions were as follows:

1. What is the specific weather and climate information needs of farmers in the study counties?
2. Which are the key factors that promote the uptake, use, and adoption of weather and climate information by users in the study counties?
3. What are the barriers to the uptake, use, and adoption of weather and climate information by farmers in the study counties in Kenya?
4. How do farmers' perceptions on weather and climate information influence farm decisions in the study counties?

To answer the four research questions, our study used the Search, Appraisal, Synthesis and Analysis (SALSA) approach, which is described and used in the subsequent section.

This paper is composed of the following sections. Section [Study area description and systematic review process] describes the study area and data collection and review methods used in the study. Section [Results] gives the results of the study and is divided into four parts in line with the research questions. Firstly, reviews on user needs on WCI are discussed. Secondly, factors that influence the uptake, use, and adoption of sub-seasonal and seasonal forecasts are identified and examined. Thirdly, barriers to the uptake, use, and adoption of sub-seasonal and seasonal forecasts are established. The last part examines how user perceptions on WCI influence farm decisions in the study counties. A discussion of the review findings follows, and finally the review paper provides the conclusion with significance of the findings.

## Study Area Description and Systematic Review Process

To carry out the systematic review, we separately targeted each of the five study counties in Kenya. The analysis focused on three counties characterized by arid to semiarid agro-climates (Machakos, Isiolo, and Laikipia) and two counties with semi-humid to humid agro-climates (Trans Nzoia and Meru), which were selected because they represent typical different climatic regimes in the country in the context of food and agriculture production potential so as to capture a diverse understanding of the user needs and perceptions in relation to sub-seasonal and seasonal forecasts. Agriculture in Kenya is largely rain-fed, and the types of production, rainfall patterns, and needs for WCI vary between the arid/drier and the humid counties. The arid counties also provide ideal case studies representing populations with lesser resources and low adaptive capacity to climate change compared with the humid areas. Adaptive capacity with regard to communities and climate change impacts refers to the ability of individuals (or institutions and systems) to adjust to potential risks, take advantage of opportunities, and be able to cope with the consequences.

The systematic review and analysis of the selected publications follow the approach by Mengist et al. (2020). The approach utilizes the elements of the SALSA framework (Booth et al., 2016). The SALSA is a methodology that helps to decide the search protocols that a systematic review should follow and ensures comprehensiveness, systematic analysis, accuracy, and replication among other benefits. This method involves four steps: The search that defines the search keywords or terms and the types of search databases, the appraisal that describes the criteria used for inclusion and exclusion of literature articles and their assessment, the synthesis that defines the way the required information was extracted and classified/categorized, and the analysis that involves the narration of the findings and conclusions. In addition to SALSA, this study also linked the search protocol and reporting of the results in the review process (Mengist et al., 2020).

Using this approach, the study scope as applied in the systematic review was defined using the Population, Intervention, Comparison, Outcome, and Context (PICOC) framework (Booth et al., 2016). Within this context, the Population is captured as user needs and perceptions related to sub-seasonal and seasonal forecasts in Kenya and is applied in the systematic review to answer research questions dealing with needs and perceptions of farmers in the study counties. Intervention is used to address the problem identified (questions) on sub-seasonal and seasonal forecasts and applied to review barriers and to use of weather information and how these can be addressed. Comparison is used for determining techniques for testing different interventions in the use of WCI and perceptions of farmers on sub-seasonal and seasonal forecasts and how these vary between counties or farmers. According to Booth et al. (2016), outcome relates to the measure used to evaluate the existing knowledge and limitations in the selected publications. In this case, the systematic review may look for existing categories of forecasts being used by farmers, the purpose and decisions made through forecast use, and barriers related to use, access, and other factors in line with the research questions. Generally, barriers to use of WCI might be linked to a number of attributes such as usability, availability, credibility, responsiveness, and others (Dilling and Lemos, 2011). The context specifies areas of the population and application of the systematic review to examine the trends of research on user needs and perceptions on sub-seasonal and seasonal forecasts and categories of counties. Within the context of the scope of the study, the steps of the SALSA framework are described later.

To use systematic review within the scope of the study, we defined the concept of perception from Michaels (2000) who views perception as the various ways in which people are aware of or receive information from their environment through experiences from the past to help control their actions. In this study, perceptions about sub-seasonal and seasonal forecasts refer to farmers' behavior, attitude, motivations, judgments, and choices with respect to the use of sub-seasonal and seasonal forecasts in decision-making. We used WCI as the collective term(s) that describes all types of forecasts (and products) spanning from time frames of hours to seasons. Within our study context, we defined sub-seasonal and seasonal forecasts as forecasts of timescales of 2–6 weeks and 3–6 months, respectively (Jie et al., 2017; Schepen et al., 2018; Vitart and Robertson, 2018). This definition varies slightly with others like Jones et al. (2015) where short-term climate information is associated with 3 months' timescale and Wilkinson et al. (2015) who generalize climate information as forecasts of different timescales ranging from few days to several months. The concept of sub-seasonal to seasonal forecasts is a new and growing area in forecasting aimed to narrow the gap between weather and seasonal climate predictions. This is due to the fact that most management decisions in agriculture and climate disaster sectors are taken within this window (Robertson et al., 2019).

To review perceptions of farmers, we considered socioeconomic attributes such as gender and income that influence the uptake, use, and adoption of WCI (Kitinya et al., 2012), phenomena or events they observe, and the information they access among other factors that motivate uptake of forecasts and use of other technologies (Parita et al., 2012). To improve the understanding of the context of users' perceptions on sub-seasonal and seasonal forecasts, our review has also mentioned other interventions by farmers such as indigenous knowledge (IK) and other technologies due to their use by farmers in decision-making alongside sub-seasonal and seasonal forecasts.

Overall, 258 articles were obtained out of which 26.4% (68 articles) highlighted mostly the use of WCI by farmers; 20.9% (54 articles) indicated perceptions of farmers on the use of WCI and climate change; 29.8% (77 articles) related to adaptation to impacts of weather and climate change in agriculture; 12% (31 articles) on application of seasonal and climate forecasts in agriculture; 60.2% (153 articles) on mixed topics such as the use of IK forecasts, weather and climate forecasts, and other innovations by farmers, use of climate smart agriculture, and regional and global articles highlighting the use of sub-seasonal and seasonal/WCI in agriculture and water sectors. Themes on barriers and farmers' perceptions influencing farmer decisions are found across several of the articles. Using similar search terms, the final documents consisted of gray literature such as reports from national government ministries and agencies, counties, non-governmental organizations (NGOs), and unpublished Ph.D. and master's theses. A total of 56 articles were obtained/searched: 66.1% (37 thesis articles related to climate change preparedness including the use of climate information), 19.6% (11 governments reports) of diverse topics from mainstreaming of climate information in policy decisions, and 14.3% (eight other/project reports) articles related to agriculture adaptation to climate change, resilience, and livelihoods.

Under appraisal, we considered articles between the years 1985 and 2020 and in advanced article search for keywords: e.g., "need," "perception," "use," "user," "forecast," "information," "demand," "weather information," "climate," "product," "access," "dissemination," "communication," "barrier," and "meteorological." Under our systematic review, we considered reports and documents available up to 2020. Search for the keywords also highlighted the earlier ones and other additions such as "adaptation," "agriculture," and "farmers."

For the synthesis, we conducted qualitative content analysis. The information from the publications was organized in a tabular form with four categories of headings: title of article, thematic part, aspects analyzed per unit, context/link to research questions, and impact. Similarly, these were organized in a tabular/matrix form with four categories of headings: title of article, thematic/meaningful unit, issue analyzed unit, context/link to research questions, and impact.

The number of articles reviewed varied between 11.9% (Meru) and 26.4% (Isiolo) of the total number of publications reviewed. As can be seen in **Figure 2**, there were more research articles reviewed for arid and semiarid counties compared to the humid counties. The highest numbers of articles (40) were published in 2015, and only one article each was published in 2000, 2003, 2004, and 2011 consecutively.

From the methods presented, the results of this study are structured as follows. First, the results regarding the needs for WCI by farmers in the study counties are discussed. The factors that influence the uptake and adoption of WCI in the study counties are then reviewed. This is followed by presentation of the barriers and challenges that farmers face in the uptake, use, and adoption of WCI. Finally, the results concerning how farmers' perceptions on WCI influence their farm decisions are presented.

## RESULTS

### Weather and Climate Information Needs of Farmers

It is important to acknowledge that different farmers and users of sub-seasonal and seasonal forecast exist, with each having

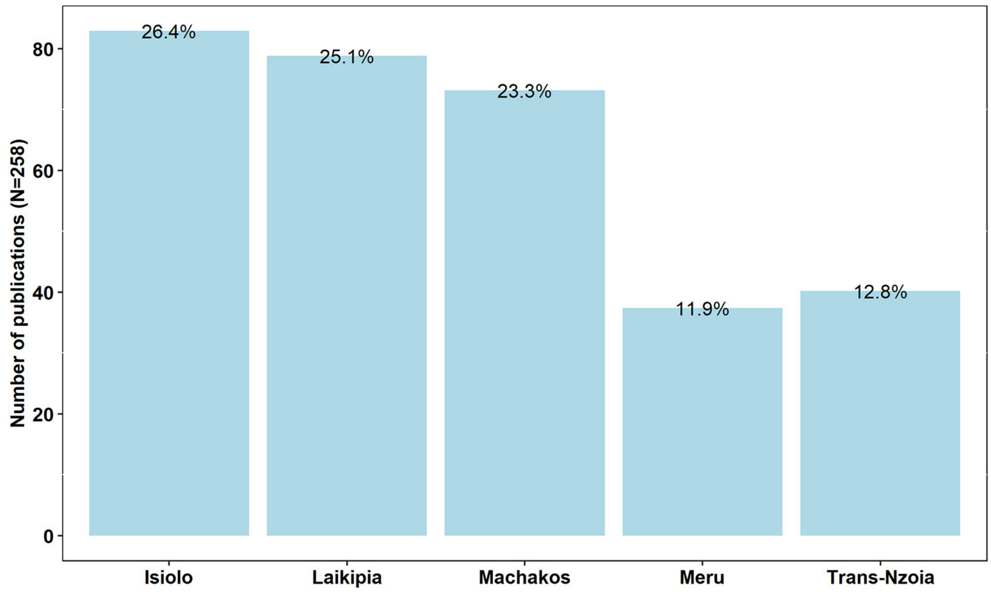


**FIGURE 2 |** Number of publications per county and depicted as a percentage of the total number of articles searched.

their own needs. Information on needs of farmers in Kenya can be obtained from perceptions related to climate information, which have extensively been studied (Ogalleh et al., 2012; Few et al., 2015; INTASAVE Africa, 2018; Mareverwa, 2018). Mogaka et al. (2005) noted that seasonal forecasts by the Kenya Meteorological Department (KMD) and Intergovernmental Authority on Development (IGAD) Climate Prediction and Application Centre provided in advance could solve the perennial water needs of farmers in Laikipia. The need for information on rainfall patterns by farmers in Laikipia is highlighted by Karanja et al. (2017) who studied drought patterns during rainy seasons in Laikipia and realized that the area experienced more than eight droughts between 1984 and 2010. Future rainfall projections in Laikipia further indicate declining rainfall in the short rains [October–November–December (OND)] season (Ogega, 2018).

According to the International Development Research Centre (INTASAVE Africa, 2018), farmers in arid areas like Laikipia require better communication channels, since the provision and dissemination of WCI to the farmers through combined communication such as community radio and TV have been shown to improve their ability to cope with climate disasters and also promote good agricultural adaptation practices such as planting of drought-tolerant crops.

While, Mwangi (2013) found that farmers accessed and used WCI in Laikipia, Parita et al. (2012) indicated that they specifically needed seasonal forecasts for decision-making than sub-seasonal forecasts. This suggests that farmers did not expect to cope with short-term or sudden weather extremes (e.g., storms) requiring sub-seasonal forecasts or advisories. Regardless, the 2019/2020 Laikipia County Development Plans seem to support dissemination of monthly weather bulletins to farmers and other users in order to deal with weather risks (County Government of Laikipia, 2018). One household baseline study in Laikipia revealed that farmers' needs for agriculture and climate information are relevant if disaggregated by gender and vulnerability (MoALF, 2014). In other words, for sub-seasonal or seasonal forecasts to be used, they should be tailored according to gender and level and degree of vulnerability to climate impacts. This can be compared with findings from other studies conducted in Machakos, Makueni, and Western Kenya Counties, where the roles and perceptions of male and female farmers differed with regard to uptake and use of WCI in managing climate impacts due to factors related to access to farm inputs and markets (Ifejika, 2006; Kalungu et al., 2013; Kristjanson et al., 2015; Mwangi et al., 2015; Mungai et al., 2017).

Similar to Laikipia, crop farmers and agro-pastoralists in Machakos often need seasonal forecasts compared to other forecasts (Ngugi et al., 2011; Kalungu et al., 2013; Mortimore, 2013; Mwalusepo et al., 2015). In contrast, however, Momo et al. (2013) found that 97% of the farmers in Machakos used sub-seasonal forecasts including daily forecasts and advisories. This two contrasting scenarios suggest that farmers in this region may have specific farm decisions that require both sub-seasonal and seasonal forecasts for their farm decisions. This is attested by the fact that the farmers in Machakos found the forecasts useful in addressing their needs to select the right type of crops and seeds and other farm inputs (Agesa et al., 2019). This contrasts with the perceptions of a majority of farmers and pastoralists surveyed in the neighboring counties of Makueni and Kajiado who said that while they needed and used seasonal forecasts that they deemed accurate, they were less useful for their farming decisions such as guiding grazing patterns and other decisions (Amwata, 2013). This shows that while the farmers need accurate information, it should also be usable and relevant to their farm decision-making.

Similar to many other semiarid areas in Kenya and the region, Bosire et al. (2019) indicates that increased temperature trends and declining rainfall found in Machakos are factors that trigger shorter growing seasons and need farmers to adopt to shorter duration maturing crops relative to long maturing crops. This is the situation reported by Kalungu et al. (2013) and Baaru and Gachene (2016) who found that farmers in Machakos cited declining crop production due to increased droughts, floods, and temperatures prompting them to adopt appropriate coping measures such as short maturing crops. In this regard, farmers and producers can work together to enable them to shift from seasonal forecasts to sub-seasonal forecasts in response to constraints posed by changes in the weather patterns. According to the farmers, they needed to know when the rains will start in order to decide what farm practices to follow in order to trigger early planting and new tillage methods. These were considered good coping mechanisms to respond to erratic weather patterns (Yvonne et al., 2016). To satisfy these needs, Recha et al. (2013) found that the farmers visited the local meteorological station in Machakos to obtain agro-meteorological information and agricultural advisories from meteorologists. Interestingly, the farmers preferred specific information such as rainfall amounts, distribution, and rainfall onset dates. These also included market and traders' information comprising the suppliers of inputs such as seed varieties and fertilizers that the meteorological office could not provide. Nonetheless, farmers can get the WCI integrated through agricultural advisories from agriculture extension services. According to Bourne et al. (2015) and Leal Filho et al. (2017), for agricultural advisories to be usable and relevant to farmers, they must be disseminated in a timely manner and through appropriate channels such as bulletins, radio, and TV. This suggests the need to promote a close relationship between users, WCI, and producers of weather information and agriculture-related actors to enable effective communication and use of the information. The importance of communication in helping farmers access climate and agricultural information is critical for management of climate risks (Casmir et al., 2012). In West Africa, such linkages between communications, needs of users, uptake and use of WCI, and dissemination processes are largely not documented (Ouedraogo et al., 2018). Nonetheless, Jones et al. (2015) have reviewed some cases where communication has enabled the access and use of forecasts in sub-Saharan Africa. According to Jones et al. (2015), communication of WCI can benefit from multi-stakeholder involvement at varied levels such as scientific communities, government, and the end user communities.

Pastoralists need IFs that have a seasonal timescale and are location-specific, use environmental indicators, and are the mostly used strategy to manage climate risks in Isiolo (Aklilu and Wekesa, 2002; Habane, 2010; Kagunyu et al., 2016; Okitoi et al., 2016; Gumo, 2017). Interestingly, pastoralists in Isiolo utilize IFs in probabilistic terms, although its usefulness has gradually weakened with increased frequency and severity of drought in recent years (Rao et al., 2019). Due to the latter reason, pastoralists in the area need and have been using seasonal forecasts. In this case, pastoralists need the forecasted rain amounts but also if they will guarantee sufficient pasture and water for their livestock (de Jode, 2015). Curry (2001) had earlier assessed climate information needs for institutions offering climate services in Isiolo and other areas in northern Kenya and the greater horn of Africa region and found that farmers needed the capacity to help them use and make decisions using the forecasts and strengthening of engagements with the producers of the forecasts. On the other end, it appears that pastoralists need information on droughts and other climate disasters in order to improve their resilience to climate shocks (Karani and Kariuki, 2017). This suggests that pastoralists need sub-seasonal and seasonal forecasts to enhance their resilience and productivity (Jillo and Koske, 2014; Kuria et al., 2016). In the meantime, the pastoralists have tended to diversify to subsistence farming. Further, Quandt and Kimathi (2016) found that farmers in Isiolo County needed information on how to adapt to climate change impacts. It has been shown that climate change impacts are closely linked to loss of pastoralist livelihoods (livestock) that require suitable strategies to deal with risks of floods and droughts through the use of weather advisories and seasonal forecasts (King-Okumu et al., 2016). Ofoegbu et al. (2018) suggests that early warning and response advisory services in Kenya can benefit from weather and climate forecasts tailored to the diverse needs of the pastoral communities. Effective early warning needs to be supported with other livelihood interventions (Leeuw et al., 2011; Maina, 2012).

In Meru, erratic rainfall patterns have been noted as a major problem to farmers' ability to adjust their agricultural practices and therefore raise the need for the development of specific forecasts for each season targeting farmers in the area (Ogalleh et al., 2012). Ogalleh et al. (2012) says that rains had been more predictable in the earlier years but now and in recent years have become erratic and a barrier to farmers due to climate change. Since significant advances have been made in improving seasonal forecasts in Kenya and the sub-Saharan (Tadesse et al., 2008), sub-seasonal and seasonal forecasts that are of broader resolution may need to be downscaled to provide finer information for easier use by end users in Meru and other regions (Shiferaw et al., 2014). In addition, farmers in Meru need capacity building considering that none of the farmers accessed WCI despite their knowing that they exist (Karani and Wanjohi, 2017). Nonetheless, farmers' needs in Meru are aligned to gender of the household, access to weather information such as onset and rainfall distribution, and type of farming activity among other factors (Karienye et al., 2019). According to Percy (2013), farmers in Meru prefer sub-seasonal and seasonal forecasts alongside other information such as farm inputs and market through extension services in order to make informed decisions.

In Trans Nzoia, one study indicated that more than 60% of the farmers need seasonal forecasts, and in particular, they needed early warning information on floods and droughts that they deemed useful (Chepkemoi, 2014). Few other farmers want reliable forecasts that can address their needs for climate information. Similar to Trans Nzoia, farmers in neighboring Bungoma County needed and used IF together with seasonal forecasts in their farm decisions (Barasa et al., 2017). In addition and in line with the other study counties, farmers in Trans Nzoia require information on when to plant their maize crops. Since most of the farmers prefer dry planting their crops before the start of the March–May seasonal rains and October–December rainy seasons, they need timely forecast at few weeks' lead time (Hassan and Ransom, 1998). Whereas farmers in this county need information and education on soil fertility improvement technologies, this was found to be strongly related to access of information on markets, WCI (Kanyenji et al., 2020). There is yet the need by farmers in Trans Nzoia to integrate IF with seasonal forecasts among local communities in order to benefit from both (Guthiga and Newsham, 2011). A similar study in Malawi found that there was a higher agreement between the need for IF and WCI, although end users were reluctant to use WCI (Kalanda-Joshua et al., 2011). While the push to integrate IF with WCI is gaining momentum, the skill of IF is yet to be tested empirically Ifejika et al., 2008).

In general, the review of farmers' perceptions on WCI needs shows that farmers in all the five counties in Kenya mentioned that they needed sub-seasonal and seasonal forecasts largely due to the frequency of climate risks such as erratic rainfall and droughts. Farmers required specific information such as rainfall amounts, distribution, and rainfall onset dates. However, demand for seasonal forecasts was higher in drier counties than in the humid counties. Farmers from each of the counties also had specific information preferences for communication channels, although radio was the most common mode for dissemination of WCI. Other needs from the farmers included need for accessible, timely, and usable WCI together with agricultural advisories.

The review on WCI needs reflects other findings from East Africa, West Africa, and Asia (Förch et al., 2011; Kadi et al., 2011; Lebel, 2013; Shackleton et al., 2015), which indicate that users' perceptions can enable the identification of users' needs for climate and agriculture information and help in managing climate risks. A comprehensive review of users' perceptions and needs related with WCI in semiarid areas over East Africa can be found in Few et al. (2015).

## Key Factors That Influence the Uptake, Use, and Adoption of Weather and Climate Information

To review the factors that influence the uptake, use, and adoption of sub-seasonal and seasonal forecasts, we must envision both scientific and the concept of IK where applicable considering that IK is part of the tools used to manage climate risk by a number of communities in Kenya. IK is used to develop IFs that have attributes highlighting culture, social, and economic and environmental aspects in a given community (Leclerc et al., 2013).

Different ways of communication and dissemination of sub-seasonal and seasonal forecasts influence the uptake, use, and adoption by farmers in Laikipia. For example, use of short messages through mobiles phones, provision of information through officers from the agriculture office and the KMD has improved the making of appropriate decisions on farming methods and production (Parita et al., 2012; The Ministry of Agriculture, Livestock and Fisheries, 2017). In Laikipia, Information Communication Technology has proven useful in bringing together different stakeholders including the KMD, county government, and NGOs to engage farmers through promotion of agriculture practices and climate information (Cox and Sseguya, 2015). Other incentives to the uptake, use, and adoption of WCI include frequent engagements and interactions by KMD that has encouraged users to continuously use sub-seasonal forecasts that include 5-day, weekly, and monthly forecasts and severe weather advisories (Parita et al., 2012; Shilenje and Ogwang, 2015). Even with the engagements between users, their needs, and improved use of WCI, it is argued that the efforts need to be supported by forecast-based financing mechanisms that can guarantee social security of users through an action-based anticipatory process (Eriksen et al., 2017). Another factor that affects the uptake, use, and adoption of forecasts is the shift of farmers from pastoral to smallholder agricultural systems due to erratic rainfall patterns and resultant impacts on livestock production (Huho et al., 2012). This highlights the need to use seasonal forecasts to manage changing and unpredictable rainfall patterns (Ulrich et al., 2012; Muthama et al., 2013). Potentially, weather-based crop insurance as a factor can draw value from seasonal forecasts to reduce climate risks, but low uptake by farmers in Laikipia suggests that improved provision and use of WCI and training may improve their coping capacity on climate risks (Wairimu et al., 2016; Njue et al., 2018). On the other hand, downscaling of sub-seasonal and seasonal forecasts at the local level is a key consideration by farmers to use the information, since it enhances forecast skill and relevance and usability by smallholder farmers and pastoralists in Laikipia and other arid areas (Parita et al., 2012).

Furthermore, in Laikipia, factors of human capital such as education and literacy level, social capital such age, gender, and types and quality of farm and food production, as well as financial capital such as size of livestock ownership and access to financial credit influenced the pastoralists' access, use, and uptake of WCI in Laikipia (Nganga and Coulibaly, 2017). For example, having a higher formal education and literacy levels enabled individuals to obtain employment and income that supported livelihoods and adaptation to climate risks through the use of WCI and other interventions. More financial capital such as larger livestock herd or savings resulted in better decision-making such as stocking of fodder during drought periods, timely livestock migratory schedules, and destocking. However, livestock ownership for most pastoralists was limited to smaller herds due to recurrent and endemic drought that suppressed pasture and water availability, leading to livestock deaths, which somewhat may have necessitated demand and use of WCI.

A highly variable rainfall pattern and resultant impacts are some of the main factors influencing the use of seasonal forecasts in Machakos (Ouma, 2015). It is for these reasons that many farmers have been using WCI in Machakos since rainfall patterns have changed in the last several years following occurrences of frequent droughts, pests, and diseases (Recha et al., 2016; Yvonne et al., 2016; Gichangi and Gatheru, 2018). In recent years, direct engagements with weather forecasters by farmers in Machakos have been important in motivating them to use forecasts in their decision-making. Another factor that is closely linked with the use of weather forecasts is the ease to integrate the information with other farm-based interventions (Recha et al., 2013). This encourages farmers to make informed decisions based on the forecasts provided. Forums such as Participatory Scenario Planning between farmers and other stakeholders motivate and generate better understanding, uptake, use, and adoption of WCI, since farmers' opinions are taken into account (INTASAVE Africa, 2018).

IFs are perceived to be reliable and useful in the management of climate risks in Machakos and neighboring Makueni counties (Gichangi et al., 2015). However, availability and use of sub-seasonal and seasonal forecasts to farmers from the two counties have encouraged the successful combined use with IF and resulted in increased farmers' ability to manage changes in weather patterns (Speranza et al., 2010).

The overarching factor driving the uptake and use of WCI in Machakos is over reliance on rain-fed agriculture. Another important factor influencing the uptake by farmers and pastoralists is their knowledge on technology and use of WCI in agricultural adaptation to climate risks (Kalungu and Leal Filho, 2018). It was found that those from more drier and warmer areas had better knowledge than those from semi-humid and cooler areas. This seemed to link well with a higher number of farmers from the warmer and semiarid areas using WCI compared to those in the latter areas. The motivation to use sub-seasonal or seasonal forecasts to manage climate impacts in Machakos and other semiarid areas may also be justified from declining maize and other crop yields relative to decreasing rainfall amounts and rising temperatures in the region (Nyandiko et al., 2014; Kiprotich et al., 2015; Gichangi and Gatheru, 2018). Other determinants of the uptake and use of WCI in the region included access of WCI, age of the household head, farm size, gender and size of the household (Muema et al., 2018), and declines in historical rainfall amounts (Okumu, 2013).

Mode of dissemination through radio is a key factor through which farmers receive weather information in Machakos (Vervoort et al., 2016; Apgar et al., 2017; Ndavula and Lungahi, 2018), while local meetings also influence farmers' need for WCI (Kitinya et al., 2012). The radio is an important factor for adoption of WCI, since it is an effective communication tool for influencing the use of WCI and triggering action among smallholder farmers in Kenya (Mwaniki et al., 2017). The findings in Machakos corroborate those from the East African region, which show the importance of using appropriate communication modes for WCI by vulnerable communities to manage climate risks (Kadi et al., 2011). Aura et al. (2015) indicate that workshops and farm visits from forecasters were key factors that improved the ability of the farmers to understand and use weather information on their farms in Machakos. These suggest that farmers in the region made better and informed decisions on their farms to manage climate disasters and opportunities. Coe and Stern (2011) recognize the need to assess the value of WCI to understand whether end users' needs are addressed adequately. Kristjanson et al. (2015) showed that socioeconomic factors related to gender also influence decisions on the use of forecasts and other inputs in Machakos. It was noted that women in Machakos make decisions on sale of crops, but men decided how the returns would be used. Like in other developing countries, men have a higher chance to access resources, skills, and climate information than women (Goh, 2012).

One of the drivers of the uptake, use, and adoption of sub-seasonal and seasonal forecasts in Isiolo by pastoralists is the belief that the use of IF integrated with WCI and other strategies was the most ideal means to manage drought patterns (Aklilu and Wekesa, 2002). Increased droughts often lead to water scarcity and conflicts between herders (Rao et al., 2019). Closely influencing the need and use of seasonal forecasts is the prevalence in livestock diseases in Isiolo (Kuria et al., 2016), where some pastoralists had previously resisted using weather forecasts to manage climate change risks due to cultural beliefs (Mosberg et al., 2017). Due to climate change threats, pastoralists and farmers in the county are also being motivated by combining both agriculture and business to improve their resilience and livelihoods against floods and droughts and hence the desire to use WCI in decision-making (Quandt and Kimathi, 2016; Quandt et al., 2017). Some pastoralists have slowly been replacing cattle production to rearing camels due to declining rainfall patterns (Kagunyu and Wanjohi, 2014). Financial support is also supposed to influence decisions on uptake and adoption of forecasts in any region. For example, the Climate Adaptation Fund initiated in Isiolo on climate resilience among pastoralists targeted direct financial support relative to enhancing early warning and actions (Greene, 2015) where management of drought expenditure between 2010 and 2014 was estimated at Ksh 400 million (Barrett, 2014).

Similar to Machakos and Laikipia, Kagunyu (2014) found that more than 70% of farmers sampled in Isiolo use WCI because of easier access through radio, and in recent years, WCI has been delivered in Isiolo and few other counties in Kenya through participatory scenario planning forums (Karani et al., 2015; Carabine et al., 2016; Karani and Kariuki, 2017). Despite these drivers, a number of pastoralists and agro-pastoralists have been reluctant to fully uptake WCI possibly due to their sedentary lifestyle (The Ministry of Agriculture, Livestock and Fisheries, 2017).

Another study conducted by Apgar et al. (2017) in Isiolo and Kitui counties showed that poor farmers in the area can be influenced to adopt WCI through using equity to improve their ability to make decisions in agriculture-related activities. While this was an issue that had been overlooked in the past, there have been some efforts to improve communication of WCI to the communities in the area through the establishment of RANET community radio stations in Isiolo and several other counties. These radio stations broadcast WCI through translation to local languages, which in turn encourage both the poor and others to uptake and use forecasts in decision-making (Ageyo and Muchunku, 2020). Gender desegregation is an important factor in Isiolo and the neighboring regions where women play a central role in identifying environmental indicators for forecasting local weather conditions (e.g., emergence of rare insects, change of color of leaves, etc.) and in carrying out other social responsibilities (Luseno et al., 2003).

The ability to sow early in March–May rainfall season may have influenced farmers in Meru to utilize forecasts. According to Ogutu et al. (2018), there is potential skill for seasonal forecasts over Laikipia and Meru for farmers sowing in the March–May long rainy seasons, a fact confirmed from onset dates from the historical data (Huho, 2011). This also reflects (Hansen et al., 2009) who show that forecasts can be used in making decisions on planting and fertilizer application. According to Ndambiri et al. (2013), adoption of climate information and other technologies by farmers in Meru and other eastern parts of Kenya is influenced by access of the information and extension services. Farmers receive information of agricultural inputs, practices, and climate information, which enable them to make timely and effective decisions. The KMD has been one of the key sources of localized weather information for crop farmers and pastoralists in Meru County (Percy, 2013). However, IK is also a key factor that plays a key role in weather forecasting and other decisions among this community (Kamwaria et al., 2015). Seasonal forecasts tested in the region suggest that forecast skill for dry conditions is higher in the semiarid areas of Meru compared to the wetter areas that indicate higher skill for wet conditions (Recha et al., 2012). This can create more interest for special and area-specific WCI for farmers in the region. This may be achieved through engagements with farmers and other stakeholders (e.g., through coproduction process) in order to understand and design the specific demand-driven WCI. Just like in all other study areas, frequent, and extreme weather conditions are major drivers of the uptake, use, and adoption of sub-seasonal and seasonal forecasts (Ngetich et al., 2014). In Meru, extreme weather is manifested in failed rains and other erratic weather patterns that trigger the need for WCI where it leads to crop failures and water scarcity. To influence the need and uptake of WCI in Meru and other regions, Amissah-Arthur et al. (2002) insist that the information must be useful, usable, and relevant as well as accurate both in time and space and aligned to users' adaptation measures.

Access to information and advisories is a major factor driving application of forecasts by farmers in Trans Nzoia considering that they can enhance the ability to improve their adaptive capacity to impacts of climate change (Thorlakson and Neufeldt, 2012). High levels of awareness, income, and education have enabled farmers in the Trans Nzoia County to adopt and uptake technology services to improve their resilience against climate risks and impacts (Olila and Pambo, 2014).

Like in the previous other study areas, uptake of technology and particularly mobile apps have influenced some farmers in the region to access farming information through sending a short message (Baumüller, 2016). Mobile phones can be extended to provide and disseminate WCI. This can improve access and timeliness of the information for decision-making. Closely linked to this is the influence of engagements between users, forecasters, and other stakeholders through a participatory process that brings together different actors including KMD, water, agriculture, Kenya Red Cross Society, and others in identifying how developed forecasts can be aligned and tailored according to user needs (Karani and Kariuki, 2017; KMD, 2018). This enables farmers and other users to understand how to design and apply the forecast information in their decision processes. Yet gender had influence on the level of vulnerability to climate risks, and hence, women who were perceived to be highly vulnerable to climate impacts on agriculture use WCI for preparedness and response to impacts. Cumiskey (2016) and Muhua and Waweru (2017) highlight the role of the media as a key factor and player in influencing end users to uptake and use WCI in Kenya. Most users end up accessing the information alongside listening to other news. In Kenya and across the region, there exists a multisectoral interaction between users, WCI producers, and indigenous forecasters and other actors such as agricultural advisers and NGOs (Waweru et al., 2013; Karani et al., 2015; Leal Filho et al., 2017; Ameso et al., 2018).

Whereas, various factors influence the uptake, use, and adoption of WCI, Flagg and Kirchhoff (2018) indicate that the relationship between users and forecasters does not always lead to uptake and use of forecasts and neither does usable WCI end up being used. In such situations, they observed that to increase the use and uptake of WCI, there was a need to align the needs of the user (farmer) in context of all other activities at the farm and other levels. This is not unusual, since forecast information is seldom used to trigger financing early actions or crop insurance unless integrated with other additional farm-related information (Nobre et al., 2019).

From the reviewed work above, various factors that influence the uptake, use, and adoption of WCI across all the study counties were reviewed. Changing rainfall patterns and extreme weather were key factors due to the impact they have on farmers' activities and decisions. Technology including the use and adoption of mobile phones plays a key role in enabling access and use of the information. Yet, the use of IF combined with WCI was found mostly in the drier counties to be important factors influencing uptake, whereas engagements between forecaster, users, and other stakeholders also seemed to strongly influence adoption of forecasts in farm management decisions.

## Barriers to the Use, Uptake, and Adoption of Weather and Climate Information by Farmers

Although farmers in Laikipia experience declining rainfall patterns, high temperatures, and deforestation that limit their adaptive capacity to climate risks (Speranza, 2013; Maoncha et al., 2016), one of the key barriers to addressing these problems is the lack of access to early warning information such as seasonal forecasts (Ojwang et al., 2010; MoALF, 2014). Similarly, the sedentary lifestyle of the pastoralists and agro-pastoralists in Laikipia is also a constraint to the provision of WCI in a timely manner (e.g., because pastoralists migrate from one place to another in search of pasture and water; Njoki et al., 2015).

Luseno et al. (2003) and Ryan (2005) showed that late access to forecasts in Laikipia and other northern regions makes them not useful in farm decisions. There is similarly a link between the later to limited access to information where, for instance, farmers have a slow tendency to uptake technologies such as mobile phones that play a crucial role in dissemination of WCI using the Short Messaging Service or through WhatsApp messages (Parita et al., 2012). Several studies on farmers in Laikipia suggest that having informal education reduced the uptake of WCI compared to having formal education (Waweru et al., 2013; Karanja, 2018). Similar findings have been reported showing low adoption of climate information and other disaster strategies related to high illiteracy levels among most pastoralists in Laikipia (Syomiti et al., 2015). This corroborates findings of a study in Bangladesh, which found that educated and medium- to large-scale farmers had higher adoption of agricultural and climate information and other practices compared to smallholder farmers due to disparity in levels of education (Baumüller, 2016).

Lack of financial support to farmers in Laikipia and Meru limited their ability to enhance their livestock production and adoption of technology, e.g., not able to buy equipment and inability to access WCI (Schäfer et al., 2008). Further, Krell et al. (2020) found that while use of smartphones by women was a key barrier to communication and dissemination of climate information, it is the high cost of ownership and use that made it difficult to use in Laikipia and Meru Counties. Whereas Laikipia and other semiarid areas have challenges in access of WCI, uncertainty in various types of climate information is also a major problem and only few farmers in Kenya and the region pay attention to uncertainty in their decision-making, opting to ignore (Luseno et al., 2003; Silvestri et al., 2012; Apgar et al., 2017). However, end users are also advised that when forecasts seem to report higher skill, there is a need to be careful before using them and that they should not assume lower uncertainty (McSweeney et al., 2010).

Lack of access and inadequate information were identified by several farmers in Machakos as some of the greatest barriers to adoption of WCI and hence the need for action on climate risks (Mabon, 2020). Yet in several other studies, most farmers in Machakos cited limited access to farm inputs or insufficient resources, new agricultural technologies and information and extension services as critical barriers to managing climate disasters (Momo et al., 2013). Similar findings have been reported in Embu County—a humid region where farmers identify access to farm inputs and extension services as a hindrance to adaptation to climate change (Oscar Kisaka et al., 2015). Lack of financial resources, farm inputs, and other enablers has also been identified in African agricultural systems as a key constraint to coping with climate change impacts (Bryan et al., 2013; Leal Filho et al., 2017). Whereas language barrier is a key constraint to the use of WCI in Machakos and other areas, the use of vernacular radio stations in the local language has increasingly made it easier for farmers to understand, uptake, and use WCI and agricultural advisories in their farm decisions (Mwalusepo et al., 2015; Mwangangi, 2015; Gichangi and Gatheru, 2018). Other barriers to the use of WCI include lack of trust and relevance of the WCI to farmers (Dilling and Lemos, 2011) and low adoption of technology, e.g., mobile phones (Aker, 2011; Tall et al., 2018). Further, sparse weather observational network is an overarching barrier to improvement of accuracy of information and if addressed can immensely improve weather and climate forecasting in Machakos and the country as a whole (Karuma et al., 2016).

In Isiolo County, Luseno et al. (2003) recognize the limited attention given to user needs for WCI among pastoralists in northern Kenya as one of the problems. This is closely related to lack of access and information as well as limited access to extension services and WCI, which are key barriers poorer pastoralists face in the region (Kuria et al., 2016; Apgar et al., 2017). This is evidenced by Kagunyu et al. (2016) and Okitoi et al. (2016) who show that most pastoralists in Isiolo have been using IFs when scientific forecasts are not available. But use of IF cannot predict climate change in this region, and this poses a challenge to addressing farmers concerns, and hence uptake of sub-seasonal and seasonal forecasts can help farmers and agro-pastoralists in this region to improve their resilience to impacts of floods, droughts, and high temperature (Quandt and Kimathi, 2016). Actually, Habane (2010) and Ontiri and Robinson (2015) confirm that drought and water scarcity are major issues affecting pastoralists in semiarid lands in Kenya, which strengthens the previous suggestion that such risks can be addressed using WCI. For example, reports of increasing droughts, floods, and temperatures in Isiolo are consistent with historical climate data (Ouma, 2015; Ouma et al., 2018; Recha, 2018). Lack of credit is a hindrance to adoption and use of WCI and ability to buy inputs in Isiolo and other semiarid areas as well as cultural and religious beliefs and poverty, which increases vulnerability (Luseno et al., 2003; Mosberg et al., 2017) and migration patterns of pastoralists (Syomiti et al., 2015; Zwaluw, 2015). Recha et al. (2013) report that credit advanced to farmers can enable them to acquire inputs and better deal with erratic weather conditions. In the Isiolo County, the government and other actors support farmers and pastoralists with farm inputs including storage facilities, WCI, and other information (Rao et al., 2019). Many studies suggest that barriers to uptake and use of WCI in Kenya are necessary to help address and strengthen gaps in climate services (Orindi et al., 2007). Other barriers to the use of WCI in Isiolo include social differences and status between wealthier households who have connections to providers, Internet, and radio or TV to access seasonal and monthly forecasts compared to poorer households owing to their low adaptive capacity (Apgar et al., 2017; The Ministry of Agriculture, Livestock and Fisheries, 2017). Overall, Carabine et al. (2016) argue that the difference between what end users need and what producers of WCI provide can determine how constraints to access and use of WCI can be addressed.

Percy (2013) identifies low adaptive capacity and inability to adopt new farming methods to address impacts of erratic weather patterns as other issues affecting farmers in Meru County, although they have better knowledge of accessing inputs and doing business. Ironically, Krell et al. (2020) found that access to WCI is shown to be a main barrier to adaptation to climate risks in Meru, although the cost of usage of technologies such as mobile phones poses a constraint to usage due to lack of credit to access seasonal and sub-seasonal forecasts. Similarly, the use of mobile agriculture/livestock services was seen as a key barrier to use of WCI by women than men. Factors limiting the use of mobile phone services (m-services) in Meru are lack of awareness, lack of availability, and lack of understanding about how m-services work. Ameru et al. (2018) show that challenge to access of weather and agricultural market information could be associated with poor technological infrastructure and lack of capacity by farmers.

In Trans Nzoia County, myriad constraints to the use of WCI exist. While access to and timeliness of forecasts have been cited as some of the barriers to efficient use and adoption to weather information, the most critical issue affecting farmers here is low soil fertility reported in the area (Hassan and Ransom, 1998). Similar to other regions in sub-Saharan Africa, Tittonell et al. (2005) and Sileshi et al. (2010) found that soil fertility in the area varied with farm size, farm type, and level of income, suggesting that for WCI uptake and use, these are potential factors that could hinder success and should be taken into consideration. One study across eight agro-climatic zones and particularly maize-producing county like Trans Nzoia found several constraints related to climate information such as poor access to agriculture and climate information and low adoption of technology, e.g., mobile phones, and concluded that there was a need to relate these to agro-climatic and soil characteristics for better management of climate risks (Tittonell et al., 2005; Bozzola et al., 2018). According to Lemos et al. (2012) addressing the barriers to use of climate information is strongly related to the difference between the scale and nature of the communities and their information needs and the producers of WCI.

Whereas farmers and other end users of WCI in Trans nzoia were constrained by lack of access and delayed weather information (Onywere et al., 2007), severe floods (Odira et al., 2010), and declining rainfall amounts in Trans Nzoia and shift in rainfall onset dates (Mugalavai and Kipkorir, 2013) may continue to create challenges to address the need for WCI in the area. While there has been contradicting results on increasing rainfall trends indicated in the same region, there is a need to provide user-specific weather information to address climate risks (Ouma, 2017; Mumo et al., 2018). This might be the reason why farmers in Trans Nzoia indicated that they found WCI to be insufficient in addressing their needs and required to be improved in order to address climate disasters and enhance their preparedness in a specific area (Onyango et al., 2014). Broadly speaking, one of the major challenges the KMD faces in the provision of WCI is the inability to provide site-specific weather information due to its sparse weather observation network (Guthiga and Newsham, 2011). This is also highlighted as one of the significant challenges in the use of WCI in the sub-Saharan Africa region, which mainly requires means and ways for addressing gaps in WCI to meet the needs of end users, including paying attention to timeliness, relevance, and sustainability for specific locations (Cooper et al., 2008; Caine et al., 2015).

Generally, a review on barriers and constraints to the use of WCI by Coelho and Costa (2010) showed that one of the key challenges to the use of seasonal forecasts by farmers and other users was the lack of integration in their applications and decision process in an objective manner. The World Meteorological Organization reiterates that it is crucial to examine barriers to WCI use in order to determine the usefulness of WCI (World Meteorological Organization, 2011).

In summary, for review on the barriers to the uptake, use, and adoption to forecasts, it appears that varied constraints are reported across the five study counties. The most common barrier is the changing weather patterns that constrain both farmers' resources and capability to cope with climate risks. Other barriers and challenges facing farmers include lack of access, insufficient resources and agricultural inputs, language barrier, timeliness, and spatial aspects in the provision of WCI and weak engagements between users and forecasters. Evident also is the challenge in the adoption of technologies such as mobile phones and the costs related to receiving WCI.

## Influence of Farmers' Perceptions of Weather and Climate Information on Farm Decision-Making

Meijer et al. (2015) indicate that perceptions of farmers about any given technology or innovation are closely dependent on the knowledge or view they have on the innovation. In agro-pastoral areas of Kenya, user needs and perceptions can inform how weather and climate services may be designed to suit and meet farmers' needs and how decisions can be made (Gichangi et al., 2015). Momo et al. (2013) and Zwaluw (2015) show that perceptions and knowledge of farmers can inform policy, provide a broader view of the communities system and thinking (Juana et al., 2013; Mortimore, 2013), and inspire the adoption of technology and adaptation to climate change (Muita et al., 2016).

In Laikipia, perceptions on the access to weather information (e.g., knowing the rainfall patterns expected), increased agricultural information, access to agricultural extension services, credit availability, and higher levels of education enabled farmers to increase the use of hybrid seeds and enhance productivity (Atsiaya et al., 2019). Farmers' expectations of upcoming seasonal weather are important measures of farm decision-making in Laikipia County where Rembold et al. (2014) analyzed the impacts of food security and found that KMD forecasts, European Centre for Medium-Range Weather Forecasts (ECMWF) seasonal forecast, and Global Forecasting System can predict varied food situations in the country. The perception of drier conditions informed farmers' decisions on measures that needed to be taken to address the problem in Laikipia County (Karanja et al., 2017). For example, farmers with larger farms opted not to cultivate maize crop when drought conditions were predicted to avoid crop failure and losses. While farmers' perceptions are important determinants of how climate forecasts can be used in decision-making, some regional studies over arid areas such as Laikipia that recognize strategies used to cope with climate shocks pay less attention to the role that climate forecasts can play in decision-making (Few et al., 2015; Ameso et al., 2018).

Gumo (2017) studied IF among several farming communities from Machakos, Kitui, Meru, and Kakamega Counties and indicated that IF integrated with WCI can result in improved decisions on planting and choice of agricultural practices. Similar context is mentioned by Flagg and Kirchhoff (2018) who suggest that decision-making through the use of WCI can be enhanced if knowledge from social groups (community) and organizations as well as interactions between users and producers of WCI is taken into account to address changes in the weather patterns. According to Ngugi et al. (2011), collective efforts between farmers and forecasters can lead to better decision-making to address diverse constraints in the use of WCI in Machakos. This will lead to improved resilience to climate-related impacts and other benefits. Further, Yvonne et al. (2016) indicate that weather information has been useful in planning early planting of crops and new tillage methods, which have helped farmers in the county to cope with weather impacts. It has also been acknowledged that farmer perceptions and knowledge on technology and use of weather and agricultural information have enabled better adaptation to climate risks in Machakos (Kalungu and Leal Filho, 2018). For example, farmers and pastoralists from more drier and warmer areas gained better knowledge on managing climate risks compared to those in wetter areas in the county. Farmers' knowledge on technology in Machakos also led to high levels of awareness especially in households led by male than female and resulted in increased adoption and use of WCI and better decisions on climate-related risks.

Similar to Laikipia and elsewhere, seasonal and sub-seasonal forecasts enabled farmers in Machakos select the right type of seeds, crops, and other inputs (Amwata, 2013). The use of sub-seasonal and seasonal forecasts by farmers in Machakos was influenced more by negative impacts of climate variations on farm yields (e.g., declining rainfall patterns and droughts led to reduced maize and other crop yields; Nyandiko et al., 2014; Kiprotich et al., 2015). Progress has also been achieved by farmers in Machakos in using information on the start and end of rainy seasons to guide their farm activities such as early planting and application of fertilizers (Omoyo et al., 2015). Farmers' perceptions were closely similar to the latter situation where decisions made in response to declining rains and hence shorter growing seasons forced farmers to revert to fast-maturing crops (Bosire et al., 2019). Kalungu et al. (2013) and Baaru and Gachene (2016) show that farmers in Machakos adopted suitable coping measures to manage declining crop production, which was resulting from increased frequencies of droughts and floods in the area.

In Isiolo, the use of IF, which is a key strategy to manage extreme climate risks (Habane, 2010; Kagunyu et al., 2016; Gumo, 2017), also motivated recognition and need for sub-seasonal and seasonal forecasts, leading to beneficial adaptation actions by pastoralists (Apgar et al., 2018). This follows the realization that IF fails to adequately address climate change due to increased frequencies and severity of dry conditions (Rao et al., 2019). It is for this reason that pastoralists in Isiolo have been diversifying to subsistence farming and business with expectation to enhance their resilience and productivity (Jillo and Koske, 2014; Kuria et al., 2016). Other perceptions related to WCI and influencing decision-making in Isiolo regard the impacts of livestock diseases and cultural beliefs constraining uptake and adoption of seasonal forecast (Kuria et al., 2016; Mosberg et al., 2017). Pastoralists and farmers in Isiolo have combined agriculture and other investments to strengthen their resilience and livelihoods against extreme climate disasters (Quandt and Kimathi, 2016). For example, in an effort to manage drought, pastoralists in Isiolo were destocking their livestock and replacing cattle production with camel farming (Kagunyu and Wanjohi, 2014). Subsequently, perceptions of pastoralists on their needs to cope with weather vagaries have led to the use of advisories and seasonal forecasts to manage floods and other climatic risks (King-Okumu et al., 2016). Interestingly, women who spend more of their time working on the farm compared to men have led to women taking the lead in identifying environmental indicators for forecasting of local weather conditions, which enables the community to be better prepared against weather extremes (Luseno et al., 2003).

Based on the previous assertion, in Isiolo, more women than men used better agricultural practices such as water conservation, minimum tillage, mixed cropping, and mulching to manage their farms' productions against climate-related risks and losses as well as practicing early planting, weeding, and sale of crops in order to guarantee food security and other family needs (Muthee et al., 2016). Ngetich et al. (2014) indicate that due to perceptions of failed rains by farmers in the county, they have improved their farming practices to enable them to cope with crop failures. According to Ameru et al. (2018), farmers have embraced weather forecasts and sought extension services in order to boost their adaptive capacity in their farm activities. This has also included the use of IK to strengthen weather forecasting and other on-farm decisions (Kamwaria et al., 2015; Gumo, 2017). It is interesting that seasonal forecasts have been found to show skill and usefulness in Meru (Recha et al., 2012). Similar to Laikipia and Machakos, farmers' perceptions have led to utilization of onset dates in planning planting times and choices of seeds to plant by farmers in Meru County (Philippon et al., 2016). Another perception influencing decisions in Meru regards farmers' combining forecasts and other agricultural and market information in managing climate risks (Percy, 2013).

Due to dependence on rain-fed agriculture and maize production, farmers in Trans Nzoia County have developed various strategies to manage extreme weather occurrences (Dixit et al., 2011). Farmers' perceptions about combination of IF and seasonal forecast have enabled farmers in the county to make better informed decisions against weather risks including changes in choice of seeds and planting times and other agricultural practices (Guthiga and Newsham, 2011; Kipkorir et al., 2011; Barasa et al., 2017). Mubangizi et al. (2018) show that shorter seasons due to declining rainfall patterns have also made farmers in Trans Nzoia to prefer the use of seasonal forecasts than other innovations. This can be corroborated from Bernier et al. (2015) who indicated that availability of weather forecasts did not make farmers adopt them in conservation agriculture but their decision to use seasonal forecasts was driven by extreme or severe weather patterns and occurrences. Farmers in Trans Nzoia have also reverted to dry planting of their crops early in the season in order to increase their chance for higher yields (Hassan and Ransom, 1998). In general, farmers in Trans Nzoia perceive that access to early warning information and advisories improved their adaptive capacity to impacts of extreme climate including managing floods and droughts (Thorlakson and Neufeldt, 2012; Chepkemoi, 2014).

In summary, perceptions related to WCI were found to influence decision-making across all the study counties. Declining trends in rainfall and other climate extremes led farmers to develop better coping mechanisms including the use of either seasonal or sub-seasonal forecasts or IFs. Pastoralists in arid counties reverted to reducing the number of livestock to avoid losing them to drought conditions. Farmers also tended

**TABLE 2 |** Summary of findings of the review on perceptions and needs related to weather and climate information (WCI) in five counties in Kenya.

| Research question | Findings per county | | | | |
|---|---|---|---|---|---|
| | **Laikipia** | **Machakos** | **Isiolo** | **Meru** | **Trans Nzoia** |
| 1) What is the specific weather and climate information needs of farmers in the study counties? | – Seasonal than sub-seasonal forecasts<br>– Tailored WCI products<br>– Accessible and timely WCI<br>– Better communication channels | – Seasonal forecasts<br>– Onset dates and amounts<br>– Agricultural and market information<br>– Better communication channels | – Indigenous and seasonal forecasts<br>– Rain amounts and droughts<br>– Capacity to use WCI<br>– Integrate WCI with other interventions | – Sub-seasonal forecasts<br>– Capacity to use WCI<br>– WCI access<br>– Onset dates and rainfall distribution<br>– WCI integrated with market and agriculture information | – Seasonal forecast–indigenous forecasts<br>– Information on drought and floods<br>– Timely forecasts<br>– Integrate WCI with IF |
| 2) Which are the key factors that influence the uptake, use, and adoption of weather and climate information by users in the study counties? | – Changing rainfall patterns<br>– Type of communication modes<br>– Access to technology<br>– Downscaled forecasts<br>– Training | – Changing rainfall patterns<br>– Engagement with forecasters<br>– Combined use of IF and WCI<br>– Use of technology<br>– Declining yields<br>– Type of communication modes | – Increased droughts<br>– Combined use of IF and WCI–Combining agriculture and business<br>– Availability of accessible communication modes and WCI<br>– Translation of WCI local language<br>– Gender desegregation | – Changing rainfall patterns<br>– Timely and ability to sow early<br>– Adoption of technology<br>– Ability to obtain other agriculture information<br>– Accurate forecasts for drier areas | – Accessibility to forecasts<br>– Higher levels of awareness<br>– Levels of income and education<br>– Adoption of technology<br>– Engagement with forecasters<br>– Availability of accessible communication channels |
| 3) What are the barriers to the uptake, use, and adoption of weather and climate information by farmers in the study counties in Kenya? | – Poor access<br>– Sedentary lifestyle<br>– Slow adoption of technology<br>– Having informal education<br>– Lack of inputs –Limited resources<br>– High cost of mobile phones | – Poor access<br>– Lack of access to inputs –Limited financial resources<br>– Lack of access and high cost of technology<br>– Uncertainty in forecasts<br>– Language barrier<br>– Sparse observational network | – Limited attention to forecasts<br>– Use of IF<br>– Lack of credit<br>– Limited financial resources<br>– Limited access to inputs<br>– Cultural and religious beliefs<br>– Sedentary lifestyle<br>– Social status | – Poor access<br>– Lack of access to inputs –Limited financial resources<br>– Lack of access and high cost of technology/mobile phones<br>– Uncertainty in forecasts<br>– Uncertainty in weather patterns<br>– Low adaptive capacity<br>– Lack of awareness | – Poor access and timeliness<br>–<br>– Low soil fertility levels<br>– Weak engagements with forecasters<br>– Poor access to other inputs<br>– Low adoption of technology |
| 4) How do farmers' perceptions on weather and climate information influence farm decisions in the study counties? | – Perceptions help the farmers to improve their knowledge on how to better suit WCI and other interventions into effective farm decisions, e.g., when to plant<br>– They inform farmers ability to choose between interventions, e.g., use of hybrid seeds instead of other seeds as informed by WCI and agriculture information<br>– They help farmers to select which components to use in WCI, e.g., rainfall probabilities or amounts to deal with drier/drought conditions<br>– Perceptions enhance farmers' ability to use their education and literacy levels in making effective decisions from WCI<br>– Farmers' perceptions also inform how financial resources can be used to access WCI and other inputs for better farm decisions<br>– Farmers' perceptions enable them to notice accuracy in WCI and make appropriate decisions | – Perceptions of reduced reliability of IF to tackle climate risks force farmers to integrate WCI in decision-making<br>– Perceptions of past experiences, e.g., failed rains informed farmers to make better decisions using WCI, e.g., early planting<br>– Perceptions of farmers on the value of WCI increase engagements with forecasters<br>– Perceptions (e.g., experience and knowledge of technology) enable collective efforts between farmers and forecasters leading to increased use of WCI<br>– Perceptions on the usefulness of agricultural information interfaced with WCI enable better adaptation to climate risks<br>– Farmers' perceptions on changing weather patterns lead to increased levels of awareness and WCI use<br>– Perceptions on WCI enable farmers to notice accuracy in WCI and make appropriate decisions | – Pastoralists' perceptions on limitations of IF necessitated farmers to use seasonal forecasts in decision-making on suitable interventions<br>– Perception that WCI was useful promoted farming diversification<br>– Perceptions of WCI accuracy encourage combination of agriculture and other interventions<br>– Farmers' perceptions of changing weather patterns encouraged the use of advisories (WCI) to manage climate risks and chose appropriate actions, e.g., avoiding flood risks<br>– Pastoralists' perceptions on benefits of using WCI enhance participation of women in weather observations, since they spend more time in the farm than men<br>– The perceptions of increased reliability of WCI influenced use in decisions such as destocking and stocking of fodder | – The perception of reliability of WCI in farm decisions encouraged the use of extension services that help in choice of appropriate seeds and other farm inputs<br>– Farmers' perceptions of changing weather patterns have necessitated the use of WCI to enhance their adaptive capacity on climate risks<br>– The perception of reduced reliability of IF has made farmers integrate seasonal forecasts in decision-making<br>– Perceptions and recognition of skillful forecasts have led to increased use of WCI in informing when to plant and to buy seeds and other inputs<br>– Perceptions of farmers combining forecast information and agricultural and market information have led to improved adaptive capacity toward climate risks | – Farmers' perception of changing rain patterns influenced the uptake of seasonal forecast and decisions on selection of appropriate maize seeds and planting times suited to their rain-fed agriculture systems<br>– The perception that combining of WCI and other information, e.g., agricultural and market information, has enabled farmers to choose the right coping strategies that minimize loss to crop failure and heavy rainfall<br>– The perception of reducing rainfall patterns and shorter growing seasons has led to the use of seasonal forecasts that enabled the use of proper agricultural practices such as what crop varieties to plant, early, and dry planting to reduce failure<br>– Perception of increased floods and droughts has necessitated increased use of WCI in developing coping actions, e.g., terraces |

to adopt and plant early-maturing crops among other measures against extremes.

The summary of findings from this study is presented in **Table 2**.

## DISCUSSION

Farmers' needs in the study counties comprise the choice for forecasts, where seasonal forecasts were more needed and preferred compared to sub-seasonal forecasts, need for IFs and combination with seasonal forecasts and particularly information on when the rains start and end, and other specific information such as rainfall amounts, types of crops and seeds to plant, and when to plant. In this regard, seasonal forecasts were more preferred in the drier counties such as Laikipia and Machakos compared to humid counties such as Meru and Trans Nzoia. This reflects a study by Ingram et al. (2002) who found out that the use and preference for forecasts for farmers in West Africa varied across different climatic zones. The need for reliable communication channels revealed that radio was the most preferred mode of dissemination and communication of WCI in the study counties. Yet, farmers felt that WCI can be more valuable if it was accompanied by agriculture advisories and other innovations as these would enhance their ability to manage climate risks through better decision-making.

Factors that influence the uptake, use, and adoption of WCI across all the study counties suggest that rainfall patterns and extreme weather events formed the most disastrous threats to farmers for the negative impact they posed on their lives and activities. Other factors that influence uptake and use of WCI include technology use in accessing and using climate information. Use of IF and combination with WCI in the drier counties influenced how sub-seasonal and seasonal forecasts are adopted. Ziervogel and Opere (2010) show that combining IF and WCI could solve the challenges of climate change experienced by farmers and other users of WCI.

Further, the review revealed several barriers to the uptake, use, and adoption of forecasts, including climate extremes and changing weather patterns, lack of access, insufficient resources and agricultural inputs, language barrier, and other constraints. These findings on barriers to the use of WCI in Kenya corroborate findings of others in Europe (Soares and Dessai, 2016), the US (Bolson et al., 2013), and South Africa (Wilk et al., 2017) where farmers and other users of WCI identify barriers that constrained them from making better decisions using WCI. Briley et al. (2015) discuss some ways of overcoming the barriers in the coproduction of forecasts between users and producers in Africa. They identify three main barriers, namely, different and difficult terminologies between forecasters and users of WCI, unrealistic demands and expectations from users on the availability and dissemination of relevant WCI to solve climate risks, and inadequate capacity or knowledge on how users and stakeholders should integrate or translate WCI into decision-making. Subsequently, the review highlights that these barriers can be overcome through myriad ways. Generally, most of the barriers can be overcome through identification of the most important needs demanded by users and developing tailored and context-appropriate products and services. Difficult terminologies and mismatched expectations can be overcome by translating climate information to locally relevant, simple, and understandable narratives, e.g., using local languages and images, downscaling WCI to the types of information stakeholders find usable, and packaging the information in accessible formats. The review revealed that users preferred information summaries and other simpler ways of displaying forecasts and required data, e.g., spatial detail. Integration and fitting of WCI in the stakeholders' decision-making process require direct interactions and engagements with forecasters. This helps to reduce vulnerability and uncertainties in the climate information that could lead to losses and other impacts due to wrong or weak decisions.

Subsequently, perceptions related to WCI and influencing decision-making across all the study counties included declining trends in rainfall, adjustment in farm management practices such as change of crop, or choice of seasonal or sub-seasonal forecasts and IFs. Availability of farm inputs and access to resources and technology were some of the factors that influence users' perceptions and enhance the uptake, use, and adoption of WCI and improve decision-making on climate risks and impacts. These findings support others that show that adoption of WCI by farmers depends on social capital, resources, and awareness as opposed to the knowledge of forecasts by users (e.g., Marshall et al., 2011).

## CONCLUSION

This study addressed four objectives that sought to identify and analyze WCI needs of farmers, key factors influencing the uptake, use, and adoption of sub-seasonal and seasonal forecasts, barriers that hindered the uptake, use, and adoption, and how farmers' perceptions on WCI influenced farm decisions in five counties in Kenya. All the objectives were addressed through a systematic literature review of research articles published between 1985 and 2020.

The review revealed that farmers needed both seasonal and sub-seasonal forecasts, specific communication channels for dissemination and access of WCI among other needs. This finding is important in providing users' specific WCI that is suitable for decision-making on climate-related impacts and agricultural productivity. Income, education, and other human capital resources among other factors influenced the uptake, use, and adoption of sub-seasonal and seasonal forecasts in the study counties. Nonetheless, numerous barriers such as lack of access, lack of resources, e.g., farm inputs, and lack of access to technology (e.g., mobile phones) constrained the use of WCI. Farmers' perceptions on WCI were found to influence farm decisions in myriad ways where for example access to agricultural extension services and credit availability enabled farmers to increase the use of better farm inputs and practices to improve productivity, depressed seasonal rainfall leading to shortening of the growing seasons made farmers to plant fast-maturing crops, and the integration of IF with WCI enabled improved decision-making against climate risks such as shifting of planting times and dry planting. Yet farmers' ability to access loans or resources, income, and having education enabled them to make access and use technology and apply WCI in decisions that minimize climate-related risks and losses.

The findings from this study stemmed from a number of questions relating to user needs and perceptions on WCI. These questions were in the context of the literature reviews from several studies and pertaining to constraints existing in the uptake, use, and adoption of WCI by farmers, how climate services can adjust from being producer-centered to being user-focused, the importance and role of coproduction in understanding users' needs and perceptions, interactions between users and forecasters, and the overarching aspect of dealing with changes in weather patterns and forecast uncertainty at sub-seasonal and seasonal timescales among others. The review findings showed that there is tremendous evidence that numerous barriers to the use of WCI exist and limit the use of WCI in the study regions, which necessitates the development of suitable climate services that can address and limit impacts of the changes in weather and climate. Numerous users' needs for either or both sub-seasonal and seasonal forecasts as well as IFs add to the knowledge that farmers in Kenya still demand that these be accurate, reliable, and appropriate for decision-making in addressing the myriad climate-related risks. To enable these, there is a need to strengthen institutional capacity, access, dissemination, and capacity of users to utilize WCI in decision-making.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

RM, AD, JM, and RG developed and rationalized the concept idea and methodology. SA, DA, and EN shaped and edited the review of literature. LH and FO conducted the analysis of literature on meteorological aspects of the study. JM and AD secured funding for the work. LH edited the final manuscript. All authors contributed to the article and approved the submitted version.

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# An Assessment of the 2015–2017 Drought in Windhoek

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Namibia is the most arid country in Sub-Saharan Africa. In Windhoek, the capital city, accelerated population growth and expanding economic activities, coupled with highly variable rainfall and multiyear droughts, have jeopardized water security and put enormous stress on socioeconomic development. This paper offers a review of the 2015–2017 drought and the responses that were implemented during it, with a focus on engagement with the public, industries, and public institutions to achieve water-saving targets. It also considers how the use of the Windhoek Drought Response Plan during the 2015–2017 drought furthered preparedness efforts for future droughts. The assessment ends with a discussion of government responses, challenges faced, and lessons learned—lessons that can hopefully pave the way for more effective responses to future drought situations in the country.

**Keywords: Windhoek, Namibia, drought management, climate change, institutional responses, residential water demand management, industry engagement**



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## INTRODUCTION

The scale of threat to populations throughout the world is on an upward trajectory, as climate variability and extreme weather events increase in both magnitude and frequency (Inter-governmental Panel in Climate Change, 2014). Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (intensifying competition among sectors) and increase them at high latitudes (Jiménez Cisneros et al., 2014). These natural stressors, superimposed on existing socioeconomic conditions, will ultimately have adverse impacts on the availability of water resources, food production, energy generation, the environment, and overall incomes and livelihoods all over the world (Water and Climate Change, 2019).

Globally, in 2019, droughts severely affected areas in northeastern China, North Korea, North Ontario (Canada), large parts of Europe, Southern Australia, Angola, Botswana, Namibia, Zambia, South Africa, and Zimbabwe. Current projections indicate that severity of droughts in Southern Africa may increase in both frequency and duration, exacerbating climate-related risks such as overall water and food insecurity in the region (World Bank, 2012; Niang et al., 2014; Funk et al., 2016). Of great concern is that the region supports a great many people, two-thirds of whom are in situations in which endemic water scarcity can be expected (Water and Climate Change, 2019).

Yuan et al. (2016) illustrates that, like in other parts of the world, there is a substantial increase in concurrent droughts and heat waves in Southern Africa. The 2015–2016 flash drought (droughts with a rapid onset and short duration but with high intensity and devastating impacts) that affected the region was characterized by severe heat waves and soil moisture deficit, the highest since 1948. Flash droughts have increased by 220% from 1961 to 2016, and they are likely to further increase in the future (Yuan et al., 2016).

Regarding the following 2019 drought in the region, NASA Earth Observatory (2019) considers it to have been unprecedented. The combination of reduced and late rainfall and long-term increases in temperature threatened the water, food, and energy supplies of millions of people.

In the case of South Africa, the recent Cape Town drought was estimated to have been a 1-in-590-year event (based on historical rainfall records) whose impacts on the people and the economy were exacerbated by poor planning and management of the event (City of Cape Town, 2019).

In the African context, in Namibia, water has always been a scarce resource (Niang et al., 2014; Scott et al., 2018). With frequent dry periods lasting for as long as 4 years, Windhoek, in particular, has had an uphill battle when it comes to water supply. Being not only the nation's capital city but also its largest city, Windhoek supports most of the country's economic activities.

**Figure 1** illustrates the high variability in rainfall and runoff to the Windhoek supply reservoirs and highlights the most challenging recent droughts, among them those of 1980–1982, 1994–1996, and 2015–2017.

Leading into the drought of 2015–2017, the 2012–2013 rainy season brought exceptionally low and erratic rainfall, resulting in zero inflow into the Von Bach reservoir, the primary source of supply to Windhoek (Institute for Public Policy Research, 2017), for the first time since the reservoir was built in 1970. This also resulted in a presidential declaration of state of emergency (Haeseler, 2013). Rainfall in 2014 was again highly variable and unpredictable, leading to a prolonged period of drought from 2015 to early 2017 (Scott et al., 2018). Looking back at the data, it is clear that the drought really started with the poor rain and runoff in 2012/2013, yet the effects only became fully visible about 2 years later, when supplies were running dangerously low due to the continuous below average precipitation. Most recently, 2019 saw the lowest recorded rainfall in Windhoek since 1891 and the worst in the last 90 years in Namibia (Shikangalah, 2020).

Through the rapid implementation of targeted drought management interventions, Windhoek thankfully managed to survive this critical period. Without a doubt, this achievement points to some success in the measures employed. However, the narrative also reveals missed opportunities, shows the limited effectiveness of certain initiatives, and illustrates how responses to drought by governments (in this region specifically but also perhaps throughout the world) tend to be reactive, focusing on crisis management rather than a critical level of preparedness (Wilhite et al., 2014).

Reflecting on the key lessons of the 2015–2017 Windhoek drought enables an assessment of policies that can facilitate the implementation of drought preparedness to increase adaptive

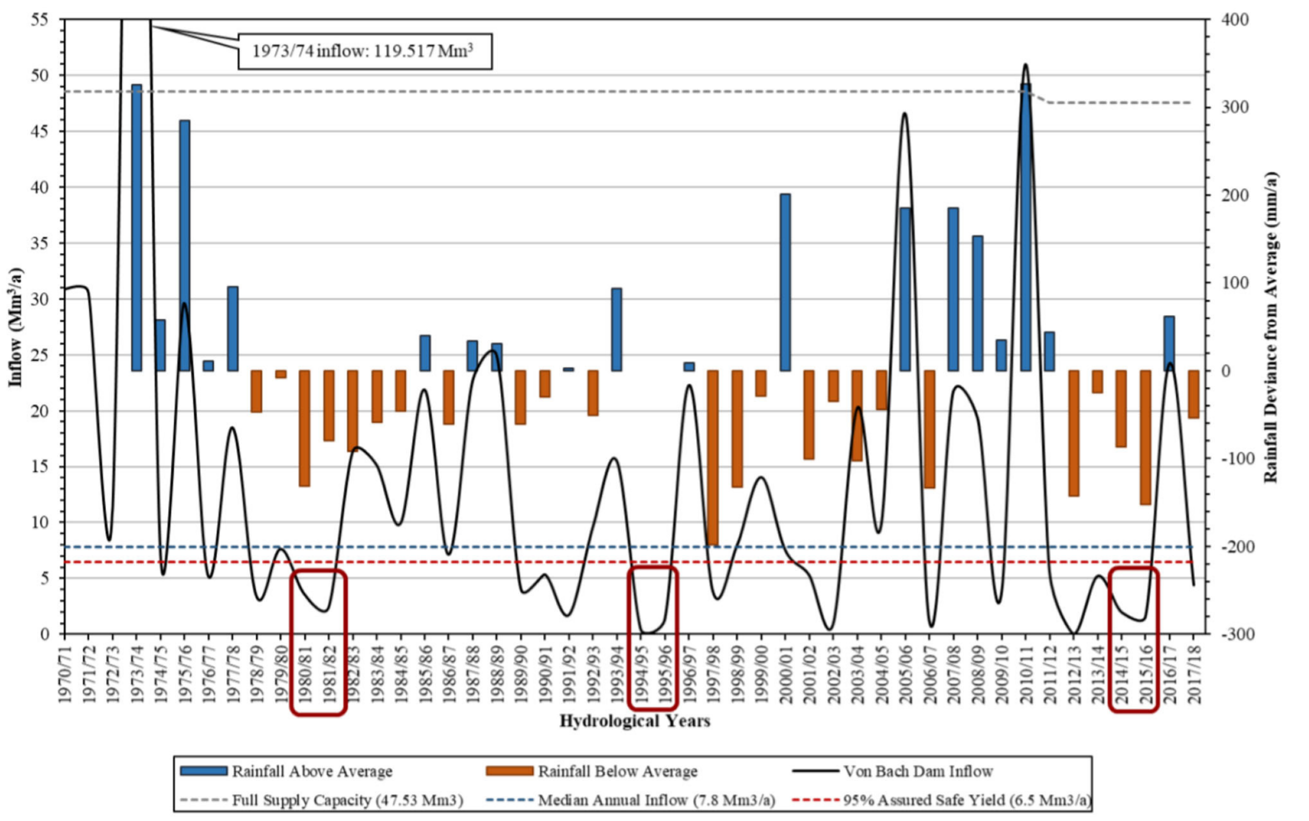


**FIGURE 1 |** High variability in rainfall and runoff to the Windhoek supply reservoirs, with challenging droughts highlighted. Source: Historical assessment of water resource management and development in Windhoek and the Central Area of Namibia (Bruce and Burger, 2019).

capacity and resilience of water resources management under similar conditions particularly in a region affected adversely by poor governance and planning (Engle, 2013).

With this objective in mind, this paper presents a perspective of the drought response strategies implemented by the City of Windhoek (CoW) and the engagement with domestic and industrial users. This article argues that without long-term communication on the importance of prudent water usage, the motivation to save water during dry periods is unlikely to have the desired response, or at least not for the initial period when this may be required. Next, the article draws on the CoW's experiences in engaging with industries and public institutions to encourage multistakeholder support in complying with drought-response strategies. Experience shows that there can be real difficulties in obtaining support from certain business sectors, with the city administration facing challenges in balancing the economic needs of the various stakeholders while ensuring a sustainable water supply. Finally, challenges and lessons learned are discussed.

## BACKGROUND SETTING

### Overview of Drought Management in Namibia

Droughts are naturally occurring phenomena in all climates, with characteristics that vary among regions (Food and Agriculture Organization, 2015). They have a complex series of impacts that differ in reach and intensity but often include numerous chain effects that affect all sectors of society either directly or indirectly (Grigg, 2014).

In Namibia, droughts are frequent and thus require well-prepared frameworks to guide timely responses, the most appropriate decisions, and the management of water demand, as necessary. In 1995, the National Drought Task Force was established, and in 1997, the National Drought Policy and Strategy, a long-term drought management plan, was released following a 2-year series of workshops. The document attempted to address the shortcomings of previous drought relief programs and put forward several policy objectives for drought management. A stricter definition of drought was developed according to scientific criteria to estimate both extent and severity of droughts, moving away from what were considered conditions of normal aridity and an emphasis on "disaster drought." Future drought relief was to be based on programs and action plans, which would be funded by the National Drought Fund. These included programs for water supply, food security, health, livestock, and crops (FAO/AGRIS, 1997).

The document later guided the National Climate Change Strategies and Action Plan of 2013. This document in turn was designed to facilitate building adaptive capacity to increase resilience and enhance mitigation (Ministry of Environment and Tourism, 2015). Regarding water resources, the document acknowledges that water scarcity is already a challenge in Namibia and that, historically, it has been a limiting factor for socioeconomic development, a situation that is likely to worsen with climate change.

According to the National Climate Change Strategies and Action Plan of 2013, future features of the water sector in Namibia may include prolonged and more severe droughts and floods, declining soil moisture and increased evapotranspiration, low groundwater recharge, and decreased water availability in both quantity and quality. Proposed strategies to counteract these impacts comprise the following: improving the understanding of climate change and related policy responses; using monitoring and data-collecting technologies for surface and groundwater at the basin/watershed level; harvesting and capturing more water during the rainy seasons; promoting more efficient water use in all sectors; improving access to sanitation and safe drinking water for all, particularly in flood-prone areas; promoting conservation and sustainable utilization of water resources; improving transboundary cooperation on water resources; and supporting institutional and human capacity building in integrated water resources management and use.

At the local-government level, and dealing directly with the consequences of the drought, the CoW Department of Infrastructure, Water and Technical Services developed a Drought Response Plan in 2015 (City of Windhoek, 2015) and broader Water Management Plans in 2017 and 2019 (City of Windhoek, 2017a, 2019)[1]. All these plans provide guidelines on managing water supply and use during drought events, taking the water available in the three reservoirs that primarily supply water to the city as an accurate indicator of the drought's impact on supply. The documents also define drought severity indicators that will be used to choose responses and program elements (City of Windhoek, 2015, p. 3). Responses are intended to increase water supply, reduce water demand, establish water scarcity tariffs, minimize adverse financial effects, implement extensive public information and media relations programs, and/or provide integrated development planning.

The next section provides details on Windhoek's continuous efforts to supply water to its growing population and industrial sector. We then review the 2015–2017 drought and the drought response actions, and focus on public engagement and cooperation with industries and public institutions to achieve water-saving targets.

### City of Windhoek

Despite its challenging environment and the poverty of a large portion of its population, the CoW has been a forerunner in water resource management, constantly developing solutions for transitioning to more adaptive systems (Lafforgue and Lenouvel, 2015). The lack of perennial rivers within Namibia means that most of Windhoek's water needs are met by the "three-dam system" of the Von Bach, Swakoppoort, and Omatako dams, which are 70, 90, and 160 km from the city, respectively (Lafforgue, 2016; Murray et al., 2018; Scott et al., 2018). This system supports the NamWater supply scheme for the Central Areas of Namibia (CAN), including Windhoek. NamWater (Namibia Water Corporation Ltd) is the national water agency

[1]The department is responsible for the supply, distribution, and quality of potable water in the urban area.

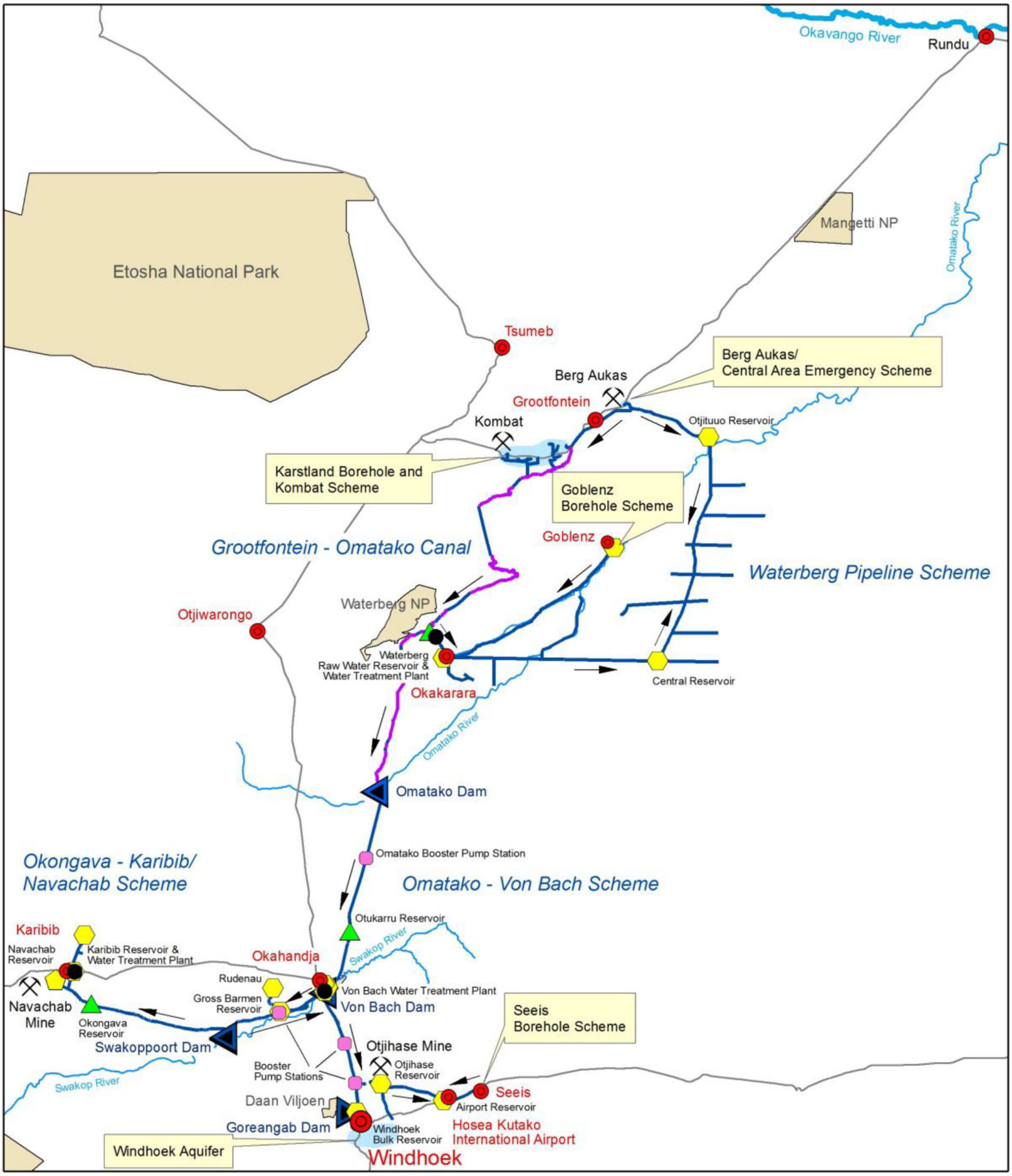


**FIGURE 2 |** Layout of the bulk water supply infrastructure in the Central Area of Namibia (Bruce and Burger, 2019).

that owns, operates, and maintains this potable water supply scheme (**Figure 2**).

Under average meteorological conditions, water from the three-dam system supplies 70–75% of the city's water. The rest (20–25%) is mostly reclaimed water, with groundwater used on a sustainable basis (5% or less).

By the end of the 1990's, following an extreme dry period and as the urban population continued to grow after independence, the CoW again looked at ways to supplement its water supply (Lafforgue, 2016). The alternatives discussed included pumping groundwater from the Karst Aquifer (490 km away) and transferring water from the Okavango River (730 km away). Finally, the managed aquifer recharge scheme in the southern extremities of Windhoek was identified as the most cost-effective option, as it could store up to 33 $Mm^3$ of water, and even 60 $Mm^3$ when deep aquifers are included (Lafforgue, 2016; Murray et al., 2018). Under this scheme, surplus water from higher rainfall periods would be injected into the aquifer space to reduce water loss to evaporation and to build up a reserve for drier years (Lafforgue, 2016).

Nonconventional sources of water has gained the CoW world recognition as a pioneer in closing the water cycle by adopting direct potable reuse (DPR) at an early stage. Born out of Windhoek's water emergency in the late 1950's, the Goreangab Water Reclamation Plant was introduced into the water supply system in 1968 with a starting capacity of 4,800 $m^3$/day. The objective was to reclaim potable water directly from domestic sewage effluent to augment conventional sources.

After the drought of 1996–1997, in the absence of feasible medium-term supply alternatives, the CoW expanded capacity and built a new DPR facility. The New Goreangab Water Reclamation Plant was commissioned in 2002 with a capacity of 21,000 $m^3$/day (Lahnsteiner and Lempert, 2007; Lafforgue, 2016). The continued success of DPR in the city hinges on its public health track record, with no DPR-related health problems recorded to date, as well as its economic viability. Thanks to a direct "pipe-to-pipe" approach, no environmental buffer is needed to store the reclaimed water, reducing the cost of the conveyance and blending of the purified water with other potable sources (Lahnsteiner et al., 2018). Building on this success, the city's dual reticulation system supplies about 2 $Mm^3$/year of semipurified irrigation water from the old reclamation facility to meet the needs of the city's parks and public greenery (Van Der Merwe et al., 2013). Reducing the demand for potable water ensures that the primary water sources can be used solely to provide potable water to the domestic consumers in Windhoek (Van Rensburg, 2016).

## METHODOLOGY

This paper presents a perspective of the institutional responses during the peak of the drought in Windhoek in 2015–2017. However, as mentioned earlier, one could say that the drought started in late 2012. Before the onset of the drought, the last time average rainfall was received in Windhoek was the 2011–2012 rainy season. From then on, rainfall and runoff were far below the historical average, until late in the 2016–2017 season, when relief finally arrived.

The analysis that informs this perspective is qualitative in nature. It includes review and analysis of academic and policy literature, as well as news articles, to understand the significance of drought events in Namibia, in general, and in Windhoek, in particular, as well as the measures taken by the CoW during the 2015–2017 period of the drought. The analyses on the overall government response, the challenges faced, and the lessons learned are based on the first-hand knowledge and experience of the first author, who formed part of the response at the time and worked with representatives of federal and local government institutions.

## DOCUMENTING THE DROUGHT RESPONSE PROCESS

### Initial Drought Response

Leaning heavily on alternative sources of drinking water, such as managed aquifer recharge and potable reclamation, proved to be key to the CoW's survival of the 2015–2017 drought. Following previous poor rainy seasons and only 197 mm of rain in 2015 (against a long-term annual average of 360 mm), at the end of 2015, the Central Area Forecasting Model (CA-Model) predicted that the water supply from the surface dams would fail by the end of August 2016[2]. With surface water being rapidly depleted, NamWater began pumping groundwater from the Northern aquifers, about 450 km away, to the overall supply system for the Central Area and CoW (Die Republikein, 2015; Lewis et al., 2019). Given the state of readiness and their smaller implementation requirements, groundwater reserves and DPR presented themselves as the most feasible alternatives, and the CoW committed itself to finding ways to immediately increase transfers from these water sources. This was primarily done by rapidly financing and implementing emergency abstraction from the Windhoek Aquifer in line with the Windhoek Managed Aquifer Recharge Scheme (Murray et al., 2018), which had been proposed in the early 2000's but not yet implemented.

As part of the Water Crisis Management Strategy, the emergency abstraction entailed the drilling of 12 additional large-diameter boreholes, up to 500 m deep (Murray et al., 2018; Scott et al., 2018), at an approximate cost of N$160 million (∼USD 10.7 million)[3]. The finalization and coming on line of the project were timed to coincide with the now extended "run-dry" date of the surface water dams (Institute for Public Policy Research, 2017). Concurrently, measures were put in place to increase production from the DPR facility from around 4.2 $Mm^3$/year at the start of 2015 to around 5.75 $Mm^3$/year, which, during the most critical periods of 2016, represented about 30% of the overall supply to Windhoek.

From the demand-side perspective, the newly established 2015 Drought Response Plan (City of Windhoek, 2015) provided guidelines for responding to the emergency situation. They were designed to maintain the health, safety, and economic vitality of the community; to avoid adverse impacts on public activity and quality of life for the community; and to consider individual customer needs as much as possible. The document

[2]NamWater's CA-Model is a computer model that simulates the hydrological water balance of the Central Area of Namibia on a monthly scale. "The CA-model performs statistical analysis to quantify the security of water supply in terms of statistical probabilities and can also be used to predict the earliest run-dry date given current water storage volumes and no future inflows into the dam (worst case scenario)" (NamWater, 2019).

[3]One Namibian dollar equals USD 0.067.

was structured to identify drought severity indicators and link them to drought response actions and program elements.

Regarding these actions, and regardless of the state of readiness, in semiarid regions with consistent patterns of recurring droughts, droughts should not be considered as disasters that warrant a crisis response. Instead, they should be seen as part of a region's condition, posing risks that can be managed with proactive policy approaches and a general preparedness for such events. In this regard, the CoW deserves commendation for putting in place options to augment its water supply long before the onset of the 2015–2017 drought. However, the eventual crisis response was based on planning done more than a decade before, meaning that the CoW were fortunate to have suitable alternatives when they were urgently needed. Often, this is not the case, leading to forced decisions, which, although they may provide short-term relief, may also be very costly and with undesirable environmental impacts. In the case of the City of Windhoek, had the augmentation schemes been implemented earlier, this would have undoubtedly provided much greater resilience to the drought.

Thus, a crisis approach can not only unduly burden the public but also threaten sustainability. Furthermore, hastily chosen solutions are unlikely to consider broader aspects such as resiliency to similar future events or the long-term effects of climate change.

## Further Drought Response Actions

In past endeavors, the CoW had notable examples of successful water demand management (WDM). For example, a leak detection program put in place in the late 1990's to reduce water losses resulted in an impressive distribution system efficiency near 90% (Lafforgue and Lenouvel, 2015). In the same period, WDM through public engagement reduced overall demand by 20% (CoW Operational Data—1994–1997). However, with the onset of what turned out to be persistent dry conditions in 2012/2013, it appeared that much of the improvements in WDM gained in the mid-1990's had been lost. In fact, in a 2006 study of various aspects of WDM in the CoW, assessments clustered around "nothing done" or "not implemented," with isolated instances of "well-implemented" (Van Rensburg, 2016).

Most notable is the observation of a "neglectful attitude" among CoW WDM personnel: they did not seem concerned about the lack of adherence to WDM policies when sufficient water was available. In retrospect, the structure of the measures introduced during the 1996–1997 drought were not really sufficient to sustain "water-conscious" behavior beyond the end of that crisis, which impacted public response the next time these were needed. Therefore, as soon as the crisis passed, everyone, including the public officials who were meant to continuously drive the initiatives, resumed their past behavior. Thus, poor enforcement of WDM policies during times of sufficient water may allow the public to become accustomed to irresponsible and wasteful consumption patterns. Consumers would then need to readapt from scratch each time water becomes less available (Van Rensburg, 2016).

Within this framework of previous poor enforcement of WDM policies, the following are actual drought response actions that focused on the domestic and nondomestic sectors pursued during the drought of 2015–2017.

### Domestic Sector

Communication with the public regarding water savings did not start in 2015. Due to the earlier onset of the drought as a result of the failed 2012–2013 rainy season, already in 2014, the CoW and NamWater started to urge residents to reduce their water consumption by at least 10%. However, despite this persistent communication, in 2015, the overall drop in consumption (year on year) was only 6%. As the drought intensified, the call for savings was increased to 20% in 2015 and became a mandatory 30% in 2016. This was in addition to firming up the price disincentive by introducing, in 2016, a structure whereby the allocation to each household during Severe Water Scarcity (Category E in the Drought Response Plan) dropped to 30 $m^3$/month, with the tariff doubling for use up to 40 $m^3$/month and then quadrupling above 40 $m^3$/month (Die Republikein, 2016). Consumption of more than 40 $m^3$/month also risked termination of supply, a penalty of N$2000 (∼USD130), and a formal written warning before reconnection (Lewis et al., 2019). After about 3800 households whose water consumption exceeded 40 $m^3$ were identified, a task team was formed to engage them (Schnegg and Bollig, 2016). "Chronic high consumers," or customers who regularly exceeded the 40 $m^3$ limit, were asked, in writing, to limit their water use and required to visit the city administration offices to explain their water bills and receive advice from officials on identifying and fixing possible leaks (Institute for Public Policy Research, 2017). Those who did not respond to these warnings within a certain period could then have their water disconnected and be fined for repeat transgressions (New Era, 2016).

**Table 1** shows the changes in the tariff structure that were implemented during the drought. As one of the goals of public engagement was to inform consumers and obtain cooperation, rather than to penalize violators, different public engagement strategies were also put in place to garner support for water savings. For example, the #DontWashMeNAM campaign (**Figure 3**) aimed to create awareness through encouraging people to stop washing their cars (informal carwash businesses hampered demand management), an important social status symbol in Namibian society. Using art created from the dirt on unwashed windscreens, the campaign was hugely successful and well-received by the general public (The Namibian, 2016b).

Various other platforms were also adopted to engage and address the community. For example, information on the severity of the drought and on water-saving techniques was displayed in communal gathering places such as markets; drought monitors were used to distribute educational material and answer questions about the drought; and a dedicated CoW hotline, website and social media platforms were set up to allow customers to report water wastage (Die Republikein, 2015).

The effect of all the combined measures introduced at the end of 2015, when the Windhoek Drought Response Plan was unveiled, was an annualized saving of 25% in 2016 until the end of the drought (**Figure 4**).

**TABLE 1 |** List of the tariff structure changes implemented during the drought as part of water demand management (WDM) initiatives.

| Tariffs before the 2015–2017 drought (2014) | | New tariffs defined under the 2015 Drought Management Plan | | Further amendment in the 2017 Water Management Plan | |
|---|---|---|---|---|---|
| 0–0.2 kl/day (0–6 kl/month) | N$12.60 | 0–0.2 kl/day (0–6 kl/month) | N$17.77 | 0–0.2 kl/day (0–6 kl/month) | N$19.25 |
| 0.201–1.5 kl/day (6–45 kl/month) | N$20.93 | 0.201–1 kl/day (6–30 kl/month) | N$26.47 | 0.201–0.73 kl/day (6–22 kl/month) | N$29.91 |
| More than 1.5 kl/day (45 kl/month) | N$38.59 | 1.01–1.33 kl/day (30–40 kl/month) | N$48.82 | 0.731–1 kl/day (22–30 kl/month) | N$55.17 |
| | | More than 1.33 kl/day (40 kl/month) | N$112.50 | More than 1 kl/day (30 kl/month) | N$127.13 |

*Source: City of Windhoek, http://www.windhoekcc.org.na/info_tariffs.php; City of Windhoek (2015, 2017b).*

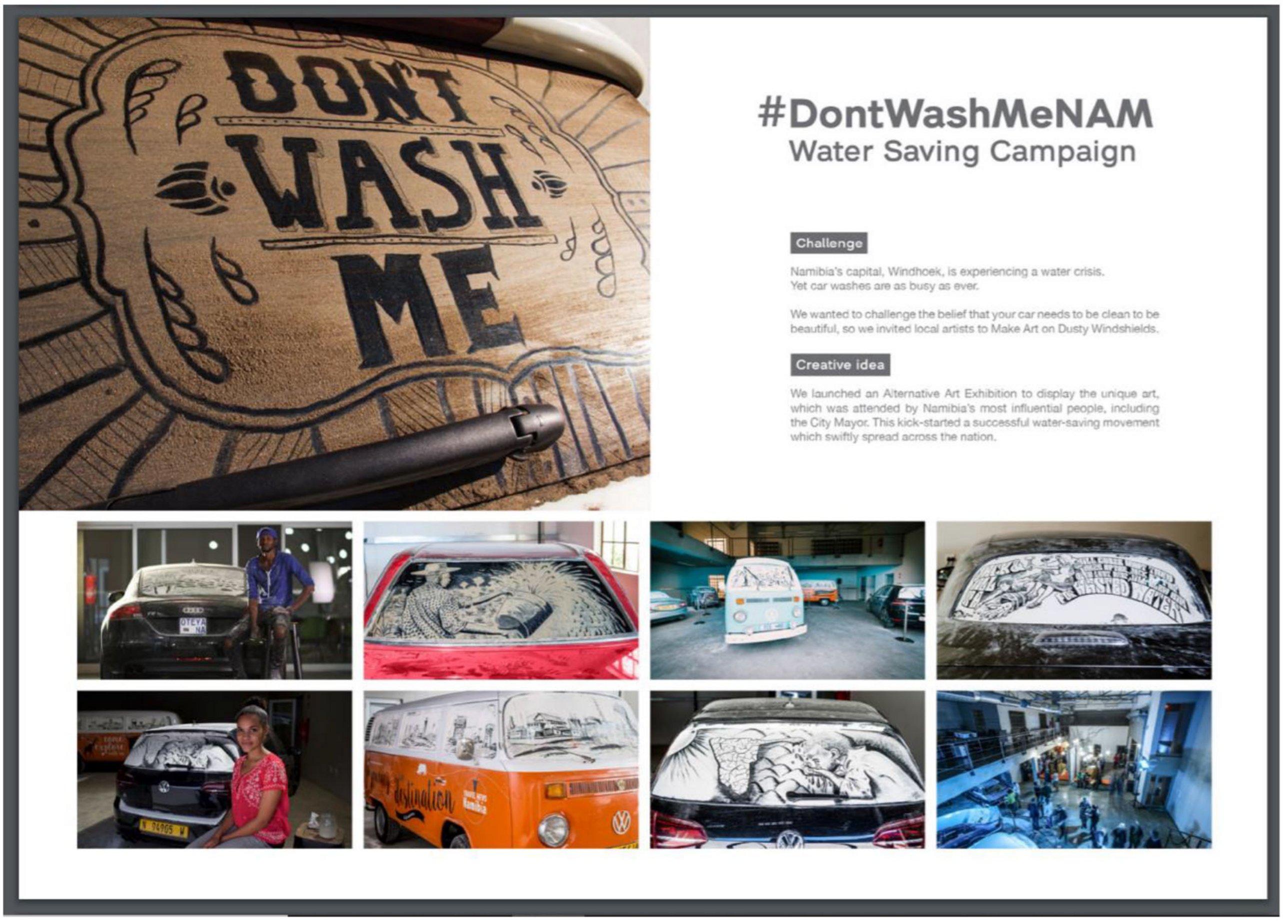


**FIGURE 3 |** #DontWashMeNAM campaign.

Despite their eventual success, the impact of these measures had an unacceptably long lead time, and the actual savings achieved during the whole drought period from 2015 to 2017 were only 15% or less, despite much higher targets. It is also clear that the campaign only achieved real momentum in the latter parts of the drought, and the missed opportunities early on could have had dire consequences had the drought continued beyond the start of 2017.

Furthermore, although public engagement and awareness raising was part of the CoW's strategy to reduce domestic water consumption, the overall communication strategies were, at times, inadequate and not robust enough. For example, despite the announcement that a large-scale awareness campaign would be implemented by the central government to inform residents of the crisis and urge them to reduce water consumption, the campaign was never formally launched, and materials such as posters and stickers were not formally distributed. Instead, communication was left to individual public institutions, which often produced small-scale, uncoordinated, and poorly conceptualized public education efforts. The effectiveness of

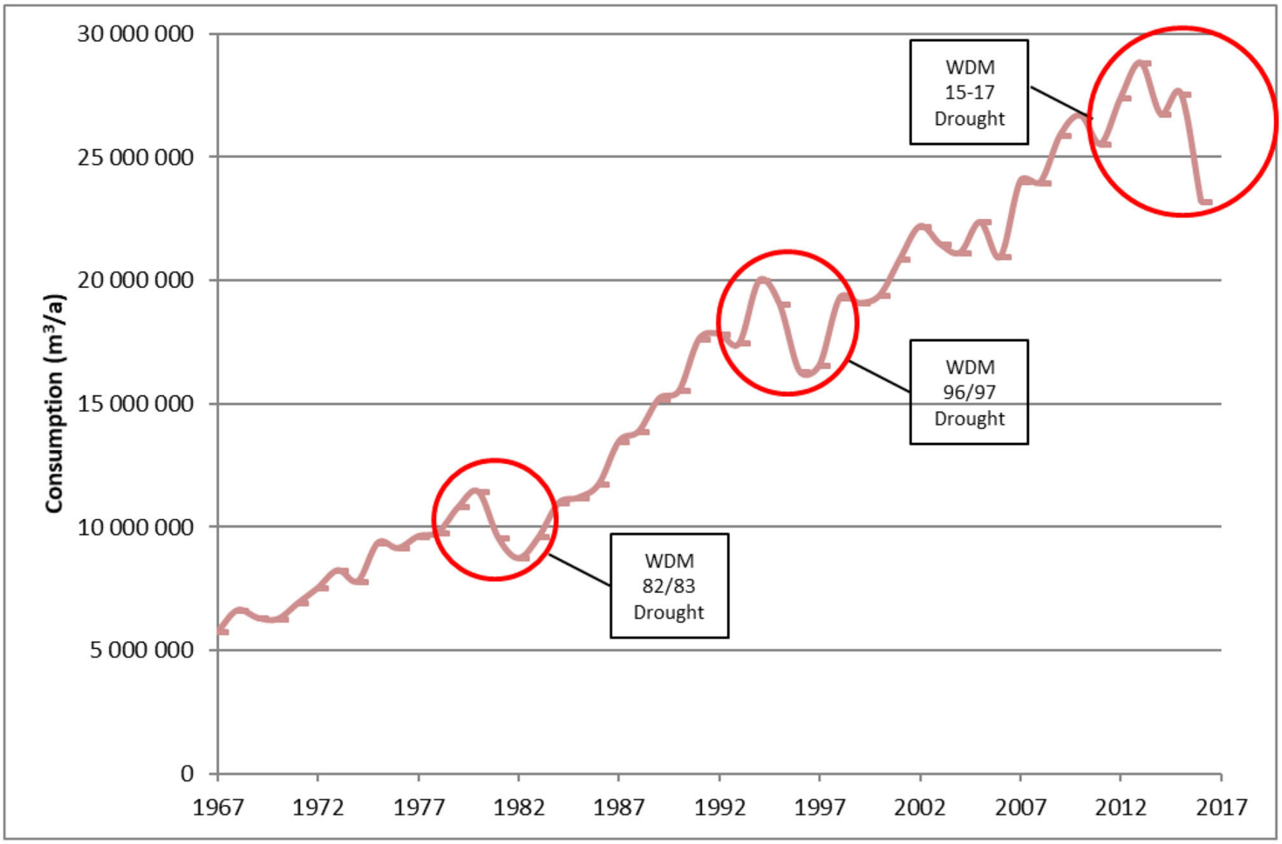


**FIGURE 4** | Periodic water demand management successes in Windhoek (CoW Operational Data).

public engagement strategies was further hampered by the mixed and conflicting messages from the authorities. For instance, in September 2016, as the drought intensified, the CEO of NamWater claimed that the Windhoek aquifer had enough water to supply the city for 10–13 years. But a few weeks later, the CoW said that the reserve could last no more than 2 or 3 years (Institute for Public Policy Research, 2017).

Not directly under the control of the public authorities, but equally important, was the inaccurate and unverified reporting in the media. For example, after an announcement in April 2017 that restrictions on water use would be maintained (despite an increase in dam levels during the rainy season) because residents were still using more water than could be supplied sustainably (The Namibian, 2017), the CoW declared in May of that year that the water restrictions would be relaxed on June 1, 2017 (City of Windhoek, 2017b). Although the action by the CoW was correct, and in line with their then recently released Water Management Plan (City of Windhoek, 2017a), the conflicting messages in the media caused confusion in the public, which at that time was hyper-alert to water issues, and impeded consumer confidence in the public authorities. A consistent, uniform message from all stakeholders that aligns with the public perception of reality is critical to any successful WDM campaign, and this includes managing the media.

### Engaging Industries and Public Institutions

Involving consumer sectors across the board can foster a sense of legitimacy and collaboration in saving water and increase support for drought response strategies (Turner et al., 2016). Hence, during the 2015–2017 Windhoek drought, targeted water-saving initiatives were also extended to various highly water-consuming industries. As 10% of the CoW's water supply was used by water-intensive industries at that time, and as these customers generally have effective control over consumption, the CoW was quick to engage them to help maximize water efficiency in their production processes (Institute for Public Policy Research, 2017).

For example, Namibia Breweries, the largest industrial water user in Windhoek, initiated several projects to reduce their water consumption and augment internal supply, including the drilling of boreholes in a saline aquifer to secure more of their own supply and reclaim water in their brewing and packaging plants to reduce overall consumption in line with the 30% target (LCE in joint Venture with SCE Consulting Engineers, 2019; Namibia Breweries Limited, n.d.). Namibia Dairies improved their water-use efficiency, reducing the water required to produce 1 L of product from 3.5 to 2.6 L. Measures included additional flow meters that are monitored and noted on a daily basis, water-saving devices throughout the plant and ablution facilities, and various buffer tanks, pumps, and pipes to accumulate and redistribute the water (The Namibian, 2016c). The Meatco Windhoek abattoir attempted to go beyond the CoW's water-saving target of 30%, setting its own target of 50% (Meatco Namibia, 2016). Coca-Cola temporarily closed two of their production lines in Windhoek, stopping the production of returnable glass products and all can products, while making a commitment not to adjust prices in the short term (The Namibian, 2016a).

In general, the engagement with industries had a good degree of success. This was fostered by close cooperation between the CoW and industries, with the CoW committing to minimize the financial and economic impact of water-saving measures. However, reducing water use in a few specific sectors, namely, construction and car washing, was more challenging.

Finding a middle ground between the short-term need to sustain livelihoods and the long-term need to ensure a sustainable water supply for the CoW proved difficult, with proposed actions often met with much resistance and complaints from business owners and their employees. For example, while restrictions could be placed on the washing of cars in residential settings, it was hard to limit people's access to illegal carwash businesses, especially in the informal areas. Attempts by the CoW to fine and shut down businesses that failed to comply with the laws on business water connections and use were strongly resisted, and there were over 300 such operations in the city (Institute for Public Policy Research, 2017).

Although the Windhoek Drought Response Plan recommended that businesses delay construction until more water was available (City of Windhoek, 2015), this guidance also met strong resistance from the Construction Industry Federation, among other groups. The federation said that about 40,000 direct jobs and up to 400,000 dependents could be affected if companies stopped construction (The Guardian, 2016). Given the city's position as the economic center of the country and its high urbanization rate, any business closure or layoffs in Windhoek could reduce future investment prospects (Pendleton et al., 2014; Institute for Public Policy Research, 2017; Scott et al., 2018). Therefore, although this idea was already embedded in the CoW Drought Management Plan of 2015, it was not effectively implemented by that sector, as it was deemed of national economic necessity to ensure the viability of the construction businesses in Windhoek. The guide to water users under various levels of supply scarcity related to the WDM Response Index (WDMRI) (City of Windhoek, 2019) can be found in the **Supplementary Material**.

Even though the CoW and NamWater applied a variety of coordinated approaches to target a wide range of stakeholders, there were missed opportunities to implement best practice citizen and institutional engagement processes to encourage all-round involvement and support for the drought response strategies. In August 2016, through the Cabinet, the Ministry of Agriculture, Water, and Forestry (MAWF) formed a committee and instructed all public institutions to appoint two "water marshals" from their staff. They would hold the 2-year responsibility of educating all users on responsible water use, conducting regular water-meter readings and basic maintenance, and identifying and reporting leaks to the utilities, as well as providing broad support to the water-saving campaign (Scott et al., 2018).

This initiative, however, had limited effectiveness, as it was difficult to ensure that public institutions complied with the water-saving measures. Despite 55 water marshals being identified by the end of 2016 and receiving basic water management training, cuts in the government budget meant reduced management support and an overall lack of motivation for individuals to ensure implementation of the initiative. The budget cuts also reduced resource availability and made it difficult for public institutions to develop and build capacity to carry out necessary maintenance in cases where technical capacity was lacking, especially since they were expected to use in-house maintenance budgets for the required repairs (Save Water Namibia, 2018). Furthermore, for certain public institutions, such as schools and hospitals, disconnecting their water for breaching of rules or failure to pay their bills was difficult (Institute for Public Policy Research, 2017). This failure to effectively manage public institutions as part of the WDM strategy highlights the critical need for government at all levels to be involved in the process. Management processes by the CoW were often ignored or overruled by institutions that answered to government ministries, which were seen by many as authorities with greater standing. Despite valiant effort, the CoW could not manage to get buy-in from some ministries to ensure top–down support for its initiatives.

## Government's Responses and Decision Making

As mentioned earlier, effective drought responses do not result from the mere understanding of the event. While resources should be invested in improving the accuracy of drought monitoring and early warning systems, equal or greater attention has to be paid to the improvement of drought governance structure to ensure a more effective division of responsibilities between the national and local governments. In the uncoordinated and delayed response of the national government, the Windhoek drought exposed the limitations inherent in the lack of decentralization in the country. As in many Southern African cities where the national government retains decision-making power (Makara, 2018), there was confusion over the responsibility of the various stakeholders in drought response.

A Drought Response Committee was formed by the CoW already in 2015 to monitor drought conditions and assess the effectiveness of the various strategies in the Windhoek Drought Response Plan (City of Windhoek, 2015; Scott et al., 2018). However, it was more effective in theory than practice, as there was uncertainty with respect to the authority of the committee, the reporting structure, and whether it was only an internal CoW committee or other stakeholders could be included (Institute for Public Policy Research, 2017). Although it guided some critical early management strategies to reduce water consumption and prepare emergency projects, the uncertainty around the management of the committee and the participation of external stakeholders limited real progress. The main problem, which proved to be crucial, was that the initial committee was only represented by the CoW and did not include the other two main stakeholders: NamWater and MAWF.

It was not until mid-2016 when a briefing to the State President resulted in the formation of a Cabinet Committee on Water Supply Security (CCWSS), supported by a Technical Committee of Experts (TCE), consolidating the three critical institutional stakeholders, namely, MAWF, NamWater, and the CoW. The CCWSS/TCE immediately went to work, and building on work already done at that stage by the CoW, a three-phase emergency plan was put in place to devote attention and resources to the immediate crisis in Windhoek and the future water needs of the area (City of Windhoek, 2018; Scott et al., 2018).

Phase 1 revolved around short-term interventions and emergency projects over a period of 18 months to address the precarious water supply situation in Windhoek (Namibian Sun, 2016). This included the development of new municipal boreholes, the piping of water from the karst aquifers at Kombat and Berg Aukas to the Omatako Dam, groundwater sourcing around Karibib, and the installation of special floating pump stations to extract the remaining water from the Swakoppoort and Von Bach Dams. Phase 2 evaluated proposed measures for water security in the Central Area for the medium term (Scott et al., 2018). Phase 3 comes into the picture by looking at the region's and the country's future and long-term water requirements to ensure greater security and resilience to droughts in the long term. Despite initial difficulties with funding and the structure of the CCWSS/TCE, Phase 1 has since been completed, Phase 2 is well underway, and initial planning has started on Phase 3. This intervention was critical to the survival of Windhoek during the 2015–2017 drought, as well as the country's overall readiness for future similar events (World Meteorological Organization, 2016).

## CHALLENGES AND LESSONS LEARNED

The following section outlines the most important challenges faced during the 2015–2017 drought as well as lessons learned. As mentioned earlier, these reflections are based on the first-hand knowledge and experience of the first author, who formed part of the response at the time and worked with representatives of public and private sector groups.

### Climate Change and Climate Risks

Impacts of climate change and associated risks have been acknowledged by governments in Southern Africa. In the case of Namibia, the National Policy on Climate Change (Ministry of Environment and Tourism, 2010) discusses the importance of long-term planning, institutional arrangements that would be necessary for policy implementation, resource mobilization, and roles and responsibilities of the different stakeholders (public and private sectors, civil society and nongovernmental organizations, and faith and community-based organizations). However, as it is the case with most of the countries in the developing world, main limitations for implementation of plans and policies in all sectors are, among many others, lack of institutional capacity and resource mobilization. Additionally, long-term plans have to be updated regularly to reflect new climatic, socioeconomic, and environmental developments in these countries, as well as advances in the state of knowledge and technology. At present, very few countries have managed to establish such long-term plans, including the necessary budgetary considerations for proper implementation.

Specific to Namibia, climate change considerations at governmental level have very much moved to the background since the establishment of the (Ministry of Environment and Tourism, 2010) and rarely feature in discussions centered around the long-term planning of relevant infrastructure or development strategies. In spite of the critical importance, it could be speculated that issues of a more pressing nature on a day-to-day basis is the primary reason for climate change enjoying a diminished importance in the country.

However, and certainly not unique to Namibia, the unpredictability of the impacts of climate change poses a major challenge for planning purposes. Engineering water supply solutions can no longer depend on steady historical data when unprecedented climate phenomena are happening with frightening intensity or frequency. This raises questions of the usefulness of long-term strategic master planning, which has traditionally been the backbone of infrastructure development, including in the water sector. A new reality is surely setting in, and preparedness is urgently needed. The diversified supply developed for Windhoek in response to the drought was crucial in avoiding a main disaster, and it shows the value of water supply systems with sufficient redundancy to span multiyear droughts and where individual elements can counter the possible impact of climate change on a particular portion of the supply. In this regard, the planning developed for the Central Area of Namibia hinges on a multipronged approach, using surface water and groundwater, for resilience to direct climate factors.

### Governance

Proper cooperation between the responsible government agencies is crucial to effectively tackle any crisis. In this case, poor or nonexistent intergovernmental relationships played a significant role in the poor initial response to the looming crisis. At that time, the various actors had a history of mutual mistrust, and, in some instances, their representatives did not clearly understand their respective roles and responsibilities. Even after the crisis was recognized, some preferred to ignore the problem rather than admit to any failure on their part, which, for the primarily government entities, might have had political implications and also affected community trust in government structures.

However, in mid-2016, there was swift progress through the establishment of the Cabinet Committee on Water Supply Security. The supporting Technical Committee of Experts was made up of representatives of the National Department of Water Affairs, the bulk supplier (NamWater) and the CoW. This created the ideal opportunity for the various stakeholders to actively integrate and coordinate planning and implementation in the water sector, enabling not only faster implementation but also better allocation of resources. This initiative not only worked well during the crisis but has been sustained since the drought, fostering the hope that it will help to resolve future problems with timely implementation of the necessary projects.

## Response Plan

As the drought began, it became clear that none of the primary responsible entities had prepared a response strategy. The region had faced similar events in the past, but the responses had been short lived, and documentation was poor or nonexistent. The CoW responded well, but drafting a coordination document and gaining the necessary authorization used up valuable time when it could least be afforded. In addition, the document, being from a single entity, was poorly received at first by other stakeholders jointly responsible for water supply and management.

## Slow or Delayed Project Implementation

One of the biggest challenges, and one that arguably exacerbated the crisis, was the responsible authorities' failure to timely implement the necessary augmentation infrastructure. A 2004 NamWater study predicted that, by 2013, the water demand in the Central Area of Namibia would exceed the supply (NamWater, 2004). With the onset of the drought in 2015, the area was consuming ∼10% more than the long-term yield of available sources. The eventual failure of surface water sources (around 75% of supply), triggered by the persistent drought, was accelerated by the overabstraction of available sources, hence worsening the impact of the drought during this critical time.

## Ongoing Water Resources Management

With increasing pressure on water supply globally, along with uncertainties around the impacts of climate change, no water supply authority should be without specific management tools, which are well-documented and known by all stakeholders. The value of the original Drought Response Plan (put forward by the CoW in 2015) in coordinating WDM efforts and dispersing vital information on residents' expected contributions cannot be overstated. After the end of the drought in 2017, and following the realization that demand management is not a "switch on/switch off" tool, the plan was adapted to include the necessary linkages to the supply sources; it was adjusted again in 2019 to ensure that it can effectively guide water management on a continuous basis.

## Non-residential Water Demand Management

Although industry collectively represents only 10% of demand, engaging primary industrial consumers was hugely successful. Not only was the response rapid, but the focus on water consumption established water monitoring and management as standard business processes, leading to efficiency gains that will persist for the long term. Due to the uncertainty around the expected duration of the crisis and its possible recurrence, many industrial consumers preferred to focus on private augmentation, which was facilitated through special supply arrangements. At the same time, the prevailing social inequality in the city was clearly visible in the push-back from certain business sectors. Given the potential economic impact on low-earning residents, initiatives to curb water use in construction and the many informal carwash businesses were not successful, and the negative publicity around these projects undermined the overall objective of soliciting public cooperation.

## Residential Water Demand Management

The loss of the gains in terms of water demand management and public awareness/participation made during the 1996–1997 drought can be blamed for the slow initial response of residential consumers to the new savings targets. Great initiatives were established during that previous drought, but then, they were abandoned for almost two decades. Had that awareness and those practices been maintained, a much stronger and prompter response to the demand management initiatives could have been expected. Even after a response was finally established, other challenges cropped up, such as the market drive toward the installation of gray water systems, which undercut the CoW's initiative to harvest wastewater for DPR supplementation.

## Communication to Bring the Citizens on Board

Effectively reaching the public requires a careful balance between technical and political voices, but messages should include the right degree of technical information to enhance the public understanding of the drought. In the case of the 2015–2017 drought, efforts to communicate the severity of the drought were hampered by the inability of the various government organizations to find effective ways to engage the public. Along with the inconsistency of the messages from the various institutions, this can be considered one of the biggest failures during the drought. The fragmented and conflicting messages, along with inaccurate media reporting, inevitably led to the public questioning the credibility of information and transparency in general. Later on, the correct type of data and comprehensive explanations of the various aspects related to the crisis were key in supporting public perceptions. Citizens were more responsive when they had a clear understanding of the nature of the problem and how they could contribute to the solution.

In 2016, water savings of up to 30% (compared to previous consumption) helped extend the run-dry date of the surface water storage far enough, allowing time for alternative supply strategies to be implemented. This can be attributed to a careful "bundling" of price disincentives with restrictive targets, implemented in late 2015 and maintained through the end of the drought. This strategy, together with better communication and the distribution of critical information, helped combat the once-prevailing mentality of "as long as I can pay for it, I can have as much water as I want." Water demand management remains one of the best tools for tackling an urban water crisis, and communication is an essential part of it.

# FINAL THOUGHTS

Although the CoW deserves recognition for its proactive stance through the years in securing nonconventional water sources such as the Windhoek Managed Aquifer Recharge Scheme and

DPR and for taking an early lead in responding to the drought, there should also be mechanisms to assess and quantify the cost of delayed action or inaction (Verbist et al., 2016). There is widespread criticism of the national government, the CoW, and the national utility provider for being unsupportive and passive in putting forth measures to timely address the impacts of the droughts. In this regard, the 2015–2017 Windhoek drought was an important lesson in the importance of government policies and decisions at the various levels being aligned, integrated, and consolidated in national drought responses rather than individual and uncoordinated efforts. Due to the lack of these elements, initial cooperation was critically lacking and resulted in delayed action, which was detrimental to the overall response and could have had more serious consequences.

A shift from reactive to proactive approaches does not happen overnight. One important lesson learned by the CoW is reflected in its Water Management Plan, released after the 2015–2017 drought. A substantial revision of the 2015 Drought Response Plan (V1/2015) was the Water Management Plan first released in 2017 (City of Windhoek, 2017a) and then in 2019 (City of Windhoek, 2019), which adopted a more holistic approach to WDM as an ongoing initiative instead of an emergency fallback for times of drought (LCE in joint Venture with SCE Consulting Engineers, 2019). The plan is based on scarcity severity indicators from NamWater's demand/supply modeling, using the Central Area Forecasting Model and monitoring indices, aligning the CoW's WDM response with NamWater's supply forecast on an annual basis. At the core of it is an attempt to match supply and demand on an annual basis and in the process provide constant feedback to the public on the status of water supply affecting their consumption.

As mentioned, people are more likely to save water if they understand the reasons for doing so and are constantly kept informed. This lesson from the 2015–2017 drought were very useful after the failed 2018–2019 rainy season (the second driest in over 100 years of record keeping) prompted renewed intensification of demand management. This time around, the response was immediate and the news much better received.

Finally, the story of the 2015–2017 Windhoek drought shows that feasible and effective solutions are context specific. What is common practice elsewhere could be less common on the African continent and perhaps even less in Southern Africa. Yet, the challenges are the same, if not bigger, in an environment where it may not be so easy to find readily available solutions and or a well-integrated response. Thus, the lessons learned here might be considered "ordinary" or "old news" by someone in the developed world, but they are still very relevant in Southern Africa and need to be advocated and supported to bring preparedness to the region as climate change looms.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

PR: writing submission and providing in depth information on situation analyzed. CT: writing submission and background research. All authors contributed to the article and approved the submitted version.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.602962/full#supplementary-material

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# What Do Weather Disasters Cost? An Analysis of Weather Impacts in Tanzania

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Weather-related disasters negatively impact livelihoods and socioeconomic activities and often lead to the loss of lives and homes. This study uses disaster data from the Disaster Management Department (DMD) in Tanzania to describe the spatial distribution of weather-related disasters, their socioeconomic impacts and highlight opportunities to improve production and uptake of weather and climate information by climate sensitive sectors. Between 2000 and 2019, severe weather accounted for ∼69% of disasters in Tanzania. The Government spent over 20.5 million USD in response to these disasters, which destroyed over 35,700 houses and 1,000 critical infrastructures (roads, bridges, schools, and hospitals), affected over 572,600 people, caused over 240 injuries and 450 deaths. To reduce these impacts, it is important to understand the decision-making process in terms of what and how national guidelines create and enabling environment for integration of weather and climate information into disaster risk reduction strategies. For example, the National Transport Policy which is supposed to provide cross-sectorial guidelines on the use of weather and climate information addresses the use to marine industry but remains silent to other climate sensitive sectors and the public. Whilst weather warnings are available Tanzania continues to suffer from the impacts of weather-related disasters. There is a clear need to better understand the value of weather warning information at short timescales (1–5 days) and how this information can be better used in the individual decision-making processes of those receiving advisories and warnings. The review of policies to guide on cross- sectoral actions to foster the uptake of weather and climate services, decisions across climate sensitive sectors, both nationally and sub-national level is recommended.

**Keywords: weather, disasters, weather warnings, climate information, policy, Africa**



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## INTRODUCTION

Weather events profoundly affect human well-being, health, food security, infrastructure and economic development (CRED, 2018). A changing global climate is contributing to the increase in extreme weather events and associated threats to lives and livelihoods across Africa (Bedarff and Jakobeit, 2017). Globally, 91% of all disasters during 1998–2017 were caused by floods, storms, droughts, heatwaves, and other extreme weather events (CRED, 2018). These events have led to losses in human life as well as major damage to property, infrastructure and the environment (Masson-Delmotte et al., 2018; Formetta and Feyen, 2019); disproportionately affecting people in developing countries (UNISDR CRED, 2015).

Like other countries in sub-Saharan Africa, Tanzania is particularly vulnerable to the impacts of extreme weather, including severe floods, frequent and prolonged droughts, and to coastal storm surges (Watkiss et al., 2011). These events have been linked directly to significant societal and economic impacts including declining crop yields, increased incidences of crop pests and diseases, loss of livestock, decreased water availability as well as increase in vector-borne and water-borne diseases. Both recent and historical experiences indicate that infectious disease outbreaks often follow extreme weather events, as microbes, vectors, and reservoir animal hosts exploit the disrupted social and environmental conditions of extreme weather (McMichael, 2015). Human health also suffers as a result of heat stress, weather-related changes in vector-borne diseases, higher incidence of food-related and waterborne infections, air pollutants, and conflicts driven by the depletion of natural resources (Costello et al., 2009; Ncube and Tawodzera, 2019).

Weak adaptive capacity and reliance on rainfed agriculture makes Tanzania extremely vulnerable to climate change impacts (Mkonda and He, 2018). It is projected that by 2100 Tanzania will experience increases in storm surges and sea-level rise, putting more people at risk from coastal flooding (Schaeffer et al., 2014). The Government of Tanzania has continued to spend thousands of US dollars in response to the impacts of severe weather and climate change (Shemsanga et al., 2010; WMO, 2014; UNISDR CRED, 2015), but with critiques highlighting some of the delays and institutional challenges in mainstreaming the better use of climate information (e.g., Pardoe et al., 2018). It has been recently predicted that climate change could lead to net economic costs that are equivalent to a loss of almost 2% of GDP each year by 2030 (Watkiss et al., 2011). However, to date few studies are available on the impact of severe weather events in the developing world or on the situation in Tanzania specifically. The UNISDR and CRED published a global report on economic losses, poverty, and disaster from the year 1998 to 2017 using the CRED's Emergency Events Database (EM-DAT). The EM-DAT contains the world comprehensive data on the occurrence and effects of occurrence of technological and natural disasters from 1900 to the present day (CRED, 2018). The reports classified disasters, according to the type of hazard that triggers them where hydrological, meteorological and climatological events were collectively being termed weather- or climate-related—plus geophysical disasters (CRED, 2018). The report mostly made comparisons of the impacts between high income and low-income countries with a focus on human cost rather than economic impacts.

Tanzania has kept a record of large-scale disasters since 1872. These records were established following a tropical cyclone that made landfall in Zanzibar and Bagamoyo in April 1872 (Lindström, 2019; Trove, 2020). An expert from the DMD noted that: "*Since the tropical cyclone incidence of April 1872, the government has continued keeping and improving disaster data based on national guidelines and international agreements.*" It is important to note that, the disaster risk management system in Tanzania came to major reform after the establishment of the Disaster Relief Coordination Act No. 9 of 1990. The Act established an Inter-Ministerial Committee known as the Tanzania Disaster Relief Committee (TANDREC) to oversee and coordinate the overall relief operations in the country. The TANDREC was under the Minister responsible for disaster management in the Prime Minister's Office (PMO).

The 1990 Act also established the Disaster Relief Coordination Unit, which in 1998 was elevated to Disaster Management Department (DMD). The DMD was specifically created as a secretariat to the TANDREC to coordinate and supervise all disaster management activities in the country. In 2015, Disaster Management Act No. 7 was enacted to replace Act No. 9 of 1990. The 2015 Act established an Emergency Operation and Coordination Center (EOCC) as additional section to strengthen the functions of the department. Furthermore, it established the Tanzania Disaster Management Council (TADMAC) to replace TANDREC. The TADMAC advice the minister in charge on disaster risk management activities in the country. The Act provides the overarching legal framework for DRR implementation in the country. The disaster risk management initiatives in Tanzania are supported by a number of sectoral policies, laws, strategies and plans. These sectorial collaborations has enabled the department to collect and improve its existing disaster data profile. Despite this data offering important insights into the characteristics and costs of severe weather events in Tanzania, no systematic analysis has been attempted to understand the contribution of severe weather events to the country's disaster profile and associated socioeconomic impacts. The available data cannot fully explain the cost of weather-related disasters in Tanzania, however, they can help to inform and shape management, mitigation and improve development of early warning system to save more lives in future. They can further help to strengthen disaster management plans, visions, guideline, polices, and coordination across sectors responsible for disaster risk reduction in the region.

Early warning systems are fundamental to reducing impacts of weather-related hazards (UNDP CIRDA Programme, 2016; WMO, 2017). To support the development of early warning systems for disaster risk reduction, it is important to be able to appropriately characterize extreme weather events and their impacts on society and the economy. Furthermore, it is important to understand how weather warnings are made available and how are they are used in various climate sensitive sectors and their decision-making process. It is also necessary to have policy that address the use of weather and climate information. Availability of policy allows collaboration among organization and the integration of weather and climate information to plans, actions, and setting out priorities (Pardoe et al., 2018). Tanzania Meteorological Authority (TMA) uses National Transport Policy to guide on the production and application of weather and climate information in Tanzania (URT, 2003). However, this policy emphasizes the use of climate and weather information in the marine sector predominantly. These shortcomings in this policy context contributes to the observed socioeconomic impacts of weather-related disasters.

The aim of this paper is to examine the weather—related disasters and their associated impacts in Tanzania through the following research questions:

- What are the spatial distributions and socioeconomic impacts of weather-related hazards in Tanzania and how are they associated with the rainfall?
- What is required to reduce the impacts of weather-related disasters?

## RESEARCH DESIGN AND METHODS

This section presents the description of the study area, methods and data used in this study.

### Climate of Tanzania

Tanzania lies within 1–12°S and 29–40°E, between the great East African lakes of Lake Victoria in the north, Lake Tanganyika in the west and Lake Nyasa to the south. To the east lies the Indian Ocean. The country includes Africa's highest and lowest elevations: Mount Kilimanjaro (5,950 m above sea level) and the floor of Lake Tanganyika (358 m below sea level), respectively. The majority of Tanzania, except the eastern coastline, lies above 200 m above mean sea level (Basalirwa et al., 2002).

The country experiences a bimodal rainfall regime in the northern parts, which includes areas around the Lake Victoria basin, Northern Coast, and Mount Kilimanjaro. The first rainfall season occurs during March, April, and May (MAM) and the second during October, November and December (OND) (Walker et al., 2019). The Central, South and Western areas are characterized by a unimodal rainfall regime from November to April. The rainfall over Tanzania is controlled by many factors, including large-scale teleconnections such as the El Nino Southern Oscillation (ENSO), the quasi-permanent systems such as the Inter Tropical Convergence Zone (ITCZ), tropical cyclones, more local-scale circulations such as sea breezes (Nicholson, 2018). Although the country exhibit bimodality rainfall characteristics over the northern sector, the rainfall analysis used for this data did not consider these variations. The recorded disaster events may not necessarily follow the rainfall regime, secondly there is a lag in reporting the impacts associated with hazards, for example for the case of slow onset disaster such as drought. Thirdly observed impacts may have been caused by a in far field severe weather events example rains over the high grounds may results to flooding in low laying areas. However, it is important future studies to explore the relationship between disaster events and the rainfall patterns to assist improvement in generation and provision early warning information.

### Disaster Data

The disaster data were obtained from the Disaster Management Department [DMD—Prime Minister Office (PMO)] during field visit to assess the value of weather information to decision makers in disaster risk reduction in Tanzania between July and August 2019. The database composed of natural and man-made disasters (fires, transport accidents, mining accidents, building collapse and civil strife) from 1872 to 2019. A 20-year data period from 2000 to 2019 was used for this study. There were few events records prior to 2000 and are only reported yearly, with little information in terms of temporal distributions, scale of the impact, cost (estimated damage and money provided), which are reported from 2000 onwards. These may be due to the fact that the department (the then unity) was responsible for relief activities and not disaster management, and only disaster event that needed relief aids from government were recorded. Due to these limitations, the most recent 20-year period from 2000 to 2019 is used in this study to assess the economic impacts of weather-related disasters in Tanzania.

In this study events are classified according to the type of hazard that triggered them. All hydrological, meteorological, and climatological natural disasters in this paper are collectively termed weather-related disasters (CRED, 2018). Events such as tropical cyclones, heavy rain, drought, floods, storms, strong winds, thunderstorms, lightning, landslides, and epidemics were identified and grouped as weather-related disasters. Epidemics were included due to the substantial role that weather plays in these outbreaks (Ncube and Tawodzera, 2019). Events such as fire (both urban and bush fire events), earthquakes, accidents, vermin infestation, structural collapse, mine accidents, explosions, civil strife, locust, and other pests were grouped together and termed as "Other" disasters. The number of people and households directly (these are people who suffered injury, evacuated, displaced, died, relocated, or have suffered direct damage to their livelihoods etc.) or indirectly affected (these are in addition to direct effects, over time, due to disruption or changes in economy, critical infrastructure, basic services, work, or social, health, and psychological consequences), animals killed; and farms (acres) and houses affected (damaged and destroyed) were identified. Roads, hospital, schools, and bridges affected were identified and were termed as public infrastructure. The annual number of weather-related disasters events for the 20-year period (2000–2019) were then correlated with annual rainfall of the same period.

It is important to note that not all the weather-related disasters and associated impacts are in the profile. Until June 2018 the national dataset only includes information on the events that had a sufficiently large impact to require intervention by the central government, thus this analysis does not reflect the full cost of all severe weather but only the scale and cost of the most extreme weather events. Furthermore, the DMD keeps and maintains the country disaster data profile, events, and its associated impacts information is collected and reported by the affected sector. For example, events and impacts to the agriculture sector, the responsible ministry to assess and report is the Ministry of Agriculture and Food Security, for health-related impacts is the ministry responsible for health issues. Further research to understand the data collection processes and the criteria used may provide more comprehensive understanding of how events and its associated impacts are ranked, defined and categorized.

In June 2018, there was a step-change in reporting methodology and more local-scale events began to be reported. An expert from the DMD noted that, Tanzania has improved its reporting procedures after the inauguration of the Emergency Operations and Communication Center (EOC): "*Since the* *establishment of the EOC ......we designed and established the Situation Report (SITREP), we also strengthened communication with the disaster management focal person at the regional and district level.... this has enhanced data capturing and following up of events even at local level ....".* These comments were echoed by the Centre for Research on the Epidemiology of Disasters (CRED) who noted that the information about the occurrence and severity of disasters has greatly improved, with an upswing in data reported to CRED, encouraged by increasing international cooperation on disaster risk reduction, a growing number of national disaster loss databases and efforts to accelerate implementation of the Sendai Framework (CRED, 2018).

## Rainfall Data

Daily mean rainfall from the Climate Hazards Group InfraRed Precipitation v2.0 (CHIRPS) dataset has been used to analyze rainfall over the country. CHIRPS is a processed gridded rainfall product at 0.05° x 0.05° resolution, comprising of satellite retrievals and *in-situ* station data (Funk et al., 2015). An area-weighted mean was taken over a box with the bounds between 11.77°S−1.01°S and 29.34°E−40.62°E for the years 2000–2019. The CHIRPS data are used as it has higher skill, low or no bias, and lower random errors in Tanzania compared to other operational satellite data such as the African Rainfall Climatology version 2 (ARC2) and the Tropical Applications of Meteorology using Satellite data (TAMSAT) (Dinku et al., 2018).

# RESULTS

This section is divided into two parts based on the two main research questions of this study. The first part presents the analysis of secondary disaster and rainfall data which explain the characteristics of weather-related disasters, their socioeconomic impacts to the community and the livelihood and how these events correlates with rainfall. The second part looks at the available weather information and develops a set of guidelines to support the greater use of weather and climate information for Disaster Risk Reduction.

## What Are the Spatial Distributions and Socioeconomic Impacts of Weather-Related Disasters in Tanzania?

A total of 498 disasters were recorded in the disaster profile from the PMO-DMD between 1872 and 2019, of which 363 occurred between 2000 and 2019 while 135 occurred between 1872 and 1999 (**Figure 1**). Weather-related disasters accounted for 250 (69%) of the 363 observed disasters in Tanzania. The period of 2000–2019 has a similar distribution of disaster type as the whole period 1872–1999 (**Figure 1**). Flooding is the most frequently occurring event, contributing ∼35% to all-natural disasters affecting Tanzania in both periods. Strong winds and drought contributed to 8.1%, and 4.4% of the total disasters, respectively, during the 2000–2019 period. With respect to events that are frequently associated with severe weather (directly or indirectly), epidemics, and marine accidents accounted for 21.2 and 16.2%, respectively, of all-natural disasters within the last 20 years (**Figure 1**). Weather impacts are viewed as a causal factor in a number of epidemics including cholera, dengue, and plague (Chersich et al., 2018; Fadda, 2020), while severe weather events and poor attention to weather conditions are among the factors contributing to marine accidents (Pike et al., 2013; Oluseye and Ogunseye, 2016).

There is a relatively high rate of occurrence of flood events over the northeastern part of the country, especially the coastal areas (**Figure 2**). A number of flood events are also observed in the Lake Victoria basin, north-eastern highlands and the central parts of Tanzania. Droughts are more prevalent over Arusha, Mara, Shinyanga, Dodoma, Tanga, and Lindi regions. Strong winds are reported to affect the coast areas of the Indian Ocean Dar es Salaam, Pwani, and Mafia Island; Lake Tanganyika, Rukwa, Njombe, Ruvuma, Mtwara; Dodoma; and the Lake Victoria basin; Mara, Mwanza, and Kagera regions (**Figure 2**). Coastal areas of the Indian Ocean have a higher number of strong wind events and are disproportionately affected by most types of disasters. This is due to a combination of various factors such as higher population density, poor infrastructure, urban development in risk-prone locations, land use changes, and poverty (CRED, 2018; Anande and Luhunga, 2019). In addition, Dar es Salaam and Zanzibar are developed business and political hubs, where reporting may be more comprehensive. Events of heavy rainfall are more frequent Dar es Salaam, Pwani, Mtwara, Mara, Mwanza, Kagera, and Singida regions. There also reports at Lindi, Shinyanga, Geita, Rukwa, Kigoma, Tabora, Dodoma, and Kilimanjaro regions (**Figure 2**). Landslides were reported over Kilimanjaro and Mwanza while few cases of lightning strikes were reported over Rukwa, Geita, and Kaskazini Unguja (Zanzibar Island). High number of epidemics (mostly cholera) were reported over Zanzibar Island and Kilimanjaro regions. Marine accidents were reported over Zanzibar Island with one case over Mwanza (Lake Victoria). This analysis provides important information in improving weather and climate forecast communications, it feeds onto vulnerability and exposures of particular regions and thus the communities. Other disasters (such as road accidents, urban and bush fire, building collapses, earthquakes, oil explosions, volcano eruptions) are more frequent in the regions of Lindi and Zanzibar Island. There also reports at the remaining parts of the country except over Tabora, Kigoma, Rukwa, Njombe, Ruvuma, Tanga, Shinyanga, and Mtwara regions.

Damage to property is one of the major causes of tangible loss due to weather-related disasters. During the 20-year period from 2000 to 2019, weather-related disasters destroyed or damaged more than 35,730 houses, affected 25,460 households and caused 450 deaths and 240 injuries. **Figure 3B** shows the total annual recorded number of people affected and the number of houses damaged and destroyed and **Figure 3A** shows the total annual number of injuries and deaths from weather-related disasters. The impact of the reported events on property and people increased in 2018 and 2019, which could be due to the change in reporting methodology in June 2018.

Apart from the direct impacts observed in **Figure 3**, communities are also impacted by indirect losses related to damage to properties, income losses linked to resultant

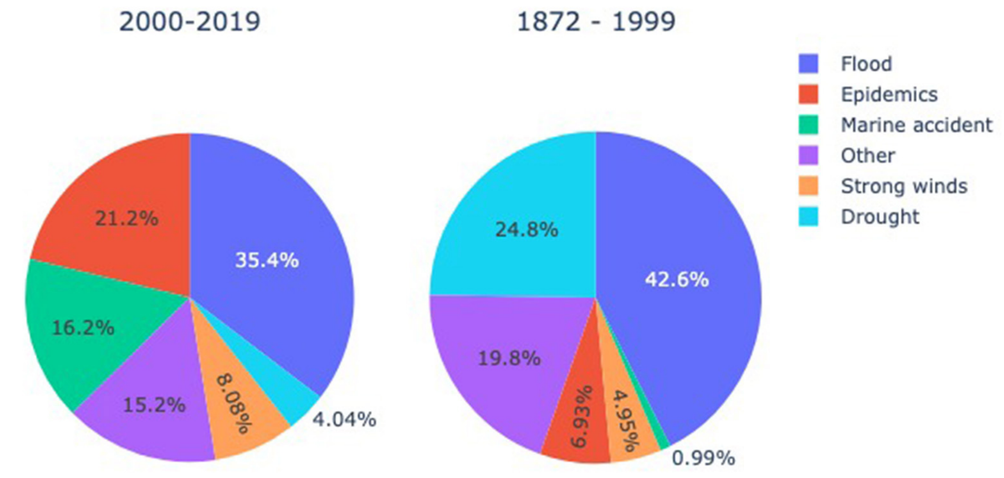


**FIGURE 1 |** Classification of weather-related and other non-meteorological disasters in Tanzania for the period of 2000–2019 and 1872–1999.

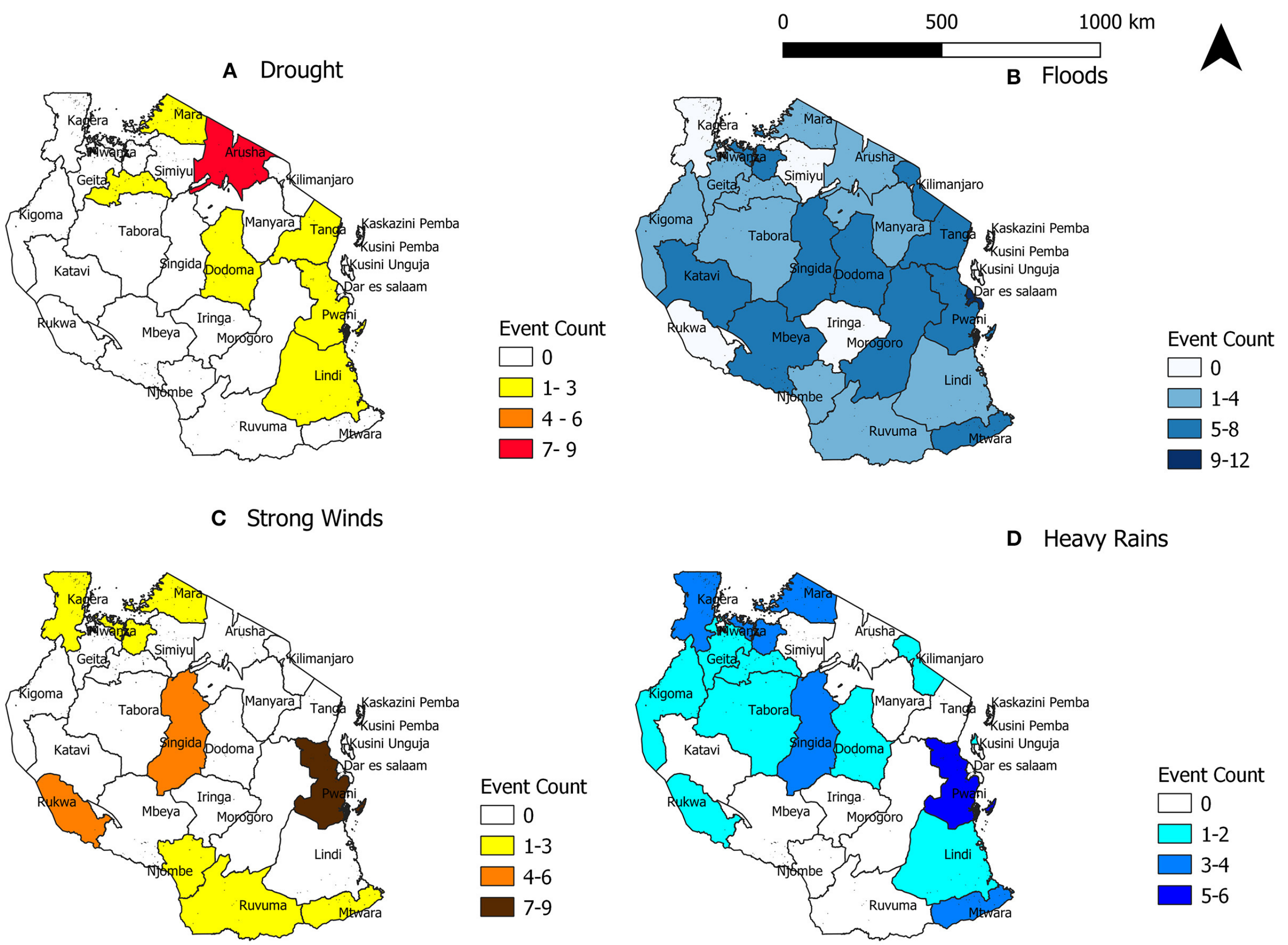


**FIGURE 2 |** Distribution of weather-related disasters events (drought, floods strong wind, and heavy rainfall) in Tanzania (2000–2019).

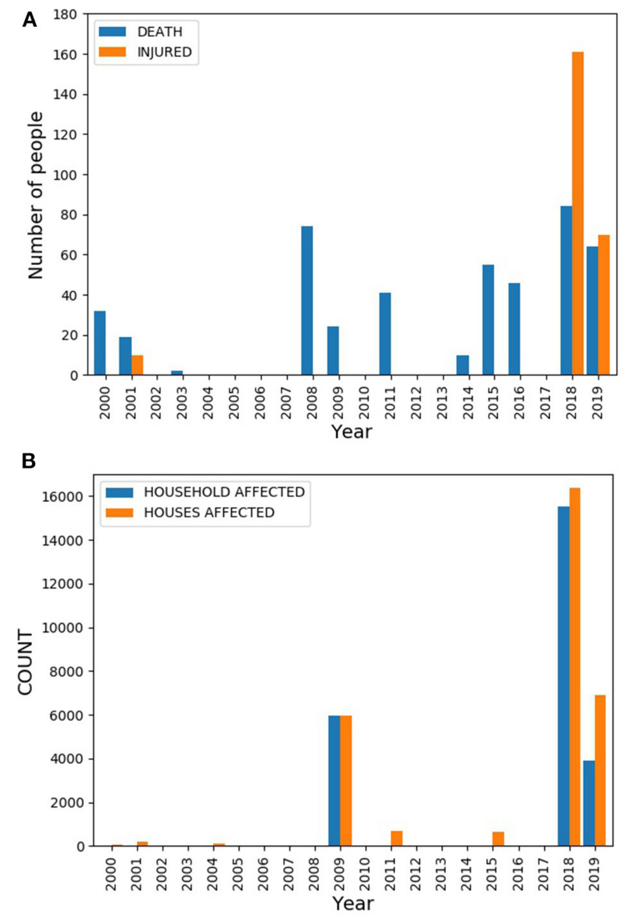


**FIGURE 3 | (A)** The annual number of deaths and injuries and **(B)** the annual number of people affected and houses destroyed and damaged by weather-related disasters.

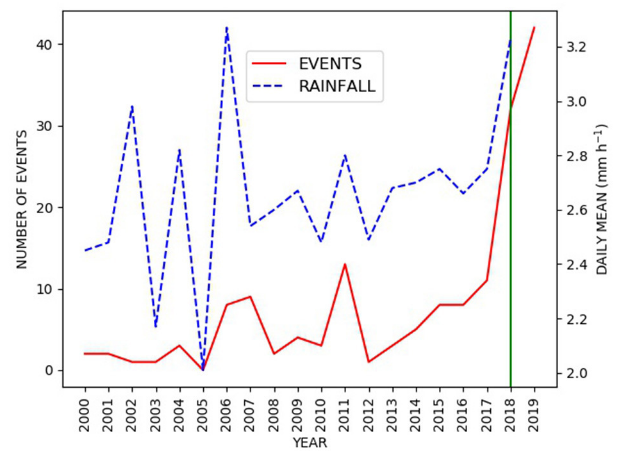


**FIGURE 4 |** Annual number of severe weather disaster events and mean annual rainfall over Tanzania from 2000 to 2019. The green line indicates the start of improvement in data capturing system at the DMD-PMO.

unemployment and disrupted provision of essential services. People suffer non-tangible costs such as physical, emotional, and psychological health problems, which can be challenging to measure or assign a monetary value (Chersich et al., 2018). Weather-related disasters affect way of life, culture, community, political systems, environment, health, and wellbeing (World Health Organization, 2020). Communities are forced to relocate to safer areas, which disrupts their day-to-day lives, personal and property rights and their fears and aspirations. For example, the 2011/2012 floods in Dar es Salaam left about 10,000 people homeless and the government allocated them a new location on the outskirts of the city (Anande and Luhunga, 2019).

The dataset also indicates that weather-related disasters destroyed more than 1,080 public infrastructures (bridges and railways, hospitals, schools, and roads) during the period of 2000–2019. Disruptions in the transportation system affects the functioning of socioeconomic activities, access to work places, social services and markets. Furthermore, many transport facilities and other public infrastructure are exposed and vulnerable to weather-related hazards such as floods, strong winds and heavy rains (Koks et al., 2019). More than 24,620 acres of farms for various crops were destroyed and 4,860 domestic animals (goat, sheep, cattle, donkey, chicken, and ducks) killed. These have negative impacts on food production, availability and prices thus putting many people at risk of malnutrition and increased illness due to poor health (World Health Organization, 2019). They further affect the food quality and safety; increase risks of outbreaks of animal and crop diseases and pests (Richardson et al., 2018; World Health Organization, 2019).

**Figure 4** shows the total annual number of weather-related disasters and the mean annual rainfall over Tanzania from 2000 to 2019. The number of disasters is variable between 2000 and 2012, but then gradually increases from 2013 onwards, until sharp increases were recorded in 2018 and 2019 (**Figure 4**). There is a statistically significant correlation between the annual mean rainfall over Tanzania and the number of events over all 20 years (Spearman's rho = 0.7, $p < 0.05$) The high correlation shows that seasonal forecasts, which provide predictions of seasonal or monthly mean rainfall predictions but not extremes, could provide advance warning of periods with a large number of disasters.

The clear peak in event numbers in 2018 and 2019 could be due to the change in reporting methodology. Even with 2018 and 2019 removed, the correlation is still strong (Spearman's rho = 0.54, $p < 0.05$), suggesting that in years with more rainfall, there is a higher likelihood of a large number of weather-related disasters. It is not possible to determine how much of the peak in events in 2018 and 2019 is due to changes in reporting and how much is due to the high rainfall levels recorded in these years (TMA, 2019). Tropical cyclone and sea surface temperature evolution over the Indian Ocean basin was associated with the observed above normal rainfall in 2018. Five tropical cyclones occurred over the South-Western Indian Ocean in 2018 and enhanced westerly winds, which dragged abundant moisture from the Congo forest over much part of the county (TMA, 2019). Other

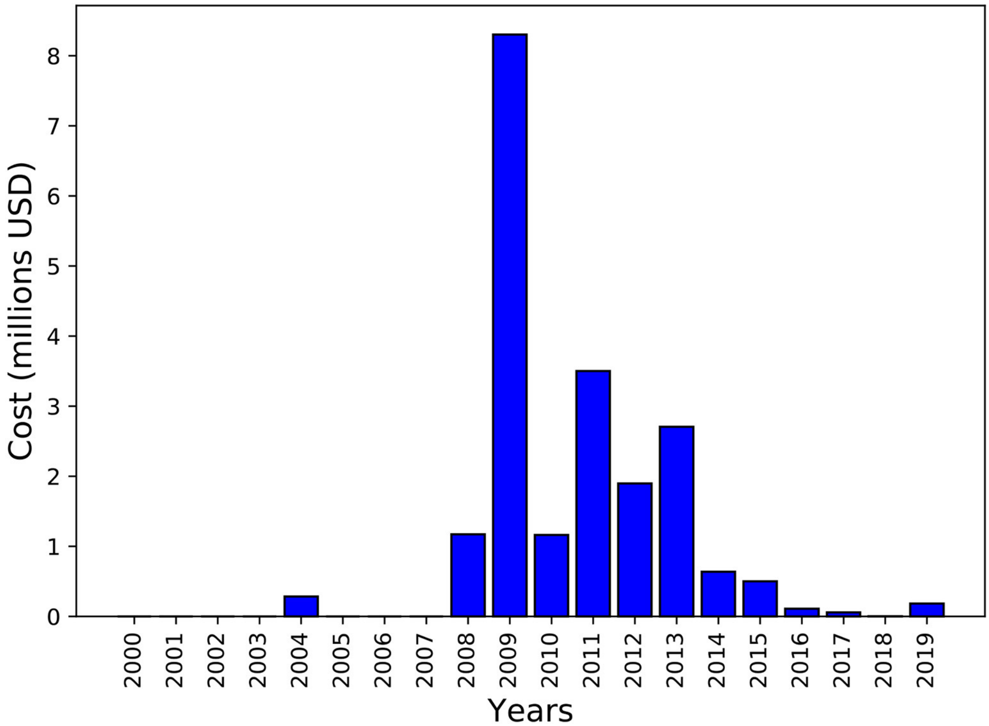


**FIGURE 5 |** The recorded annual amount of money spent in response to weather-related disasters.

climatic systems such ITCZ and the Near Equatorial were also associated with the observed enhanced heavy rains.

In 2019 the national mean annual rainfall was 1283.5 mm, which is equal to 125% of the long-term (1981–2010) average (TMA, 2020). The OND 2019 rainy season received above normal rainfall and is the second wettest OND on record since 1970 and October 2019 was the wettest October ever since 1970 (TMA, 2020). The heavy rainfalls were a result of positive ENSO conditions (El Niño) and Indian Ocean Dipole, Tropical Cyclone Idai deflected moist winds away from the country whereas Tropical Cyclones Desmund, Eketsang, and Kenneth induced westerly winds that dragged moisture from the Congo basin toward the country.

The government spent 25.9 billion Tanzania shillings (20.5 million USD) in response to weather-related disasters between 2000 and 2019. The annual expenditure for weather- related disasters shows no consistency across and between years (**Figure 5**) and there was no information on how much the government spent in the years 2000–2002, 2004, and 2005–2007, even though the country recorded weather-related disasters in these years (**Figure 4**). The data indicate the government provided food and non-food items, however, there was no cost attached.

Much of the cost was in 2009, which was an El Niño year, generally associated with enhanced rainfall conditions in the country (NWS, 2020). However, there is no significant peak in mean rainfall over the whole year and whole country in 2009 in **Figure 4**. The government used the money in 2009 to respond to the impacts of heavy events that resulted in floods in the Kilosa district in Morogoro region and landslides in the same district in Kilimanjaro region and for a widespread drought event in Arusha, Dodoma, Kilimanjaro, Iringa, Kagera, Lindi, and Mara regions. A total amount of 16.4 billion Tanzania Shillings (8.3 million USD) was used for the provision of humanitarian assistance for the affected population and construction of damaged infrastructure (**Figure 5**). From 2016 onwards relatively, little money has been spent, even though the number of reported events and damaged has remained constant or increased (**Figure 5**). This could be due to the increased availability of warnings and advisories (**Figures 6**, **7**), which have been issued since 2012, although further research is required to evaluate this.

The data in **Figure 5** does not reflect the cost of responding to the secondary impacts of heavy rains, floods and drought such as disease outbreaks. It has been noted that the majority of disaster reports contain no economic data and loss inequality between low and high incomes countries is much larger than reported due to a systematic under-reporting by low income countries (CRED, 2018). A disaster expert from the DMD office noted that, "*there has been less spending in humanitarian assistance in recent years [2016-2019] because most of the affected population from the past events were relocated to safer areas and in recent years the department improved its disaster reporting system so even small-scale disasters, which require no central government interventions are reported. The expenditures are mostly on public infrastructure such as roads, bridges, hospitals and others.*"

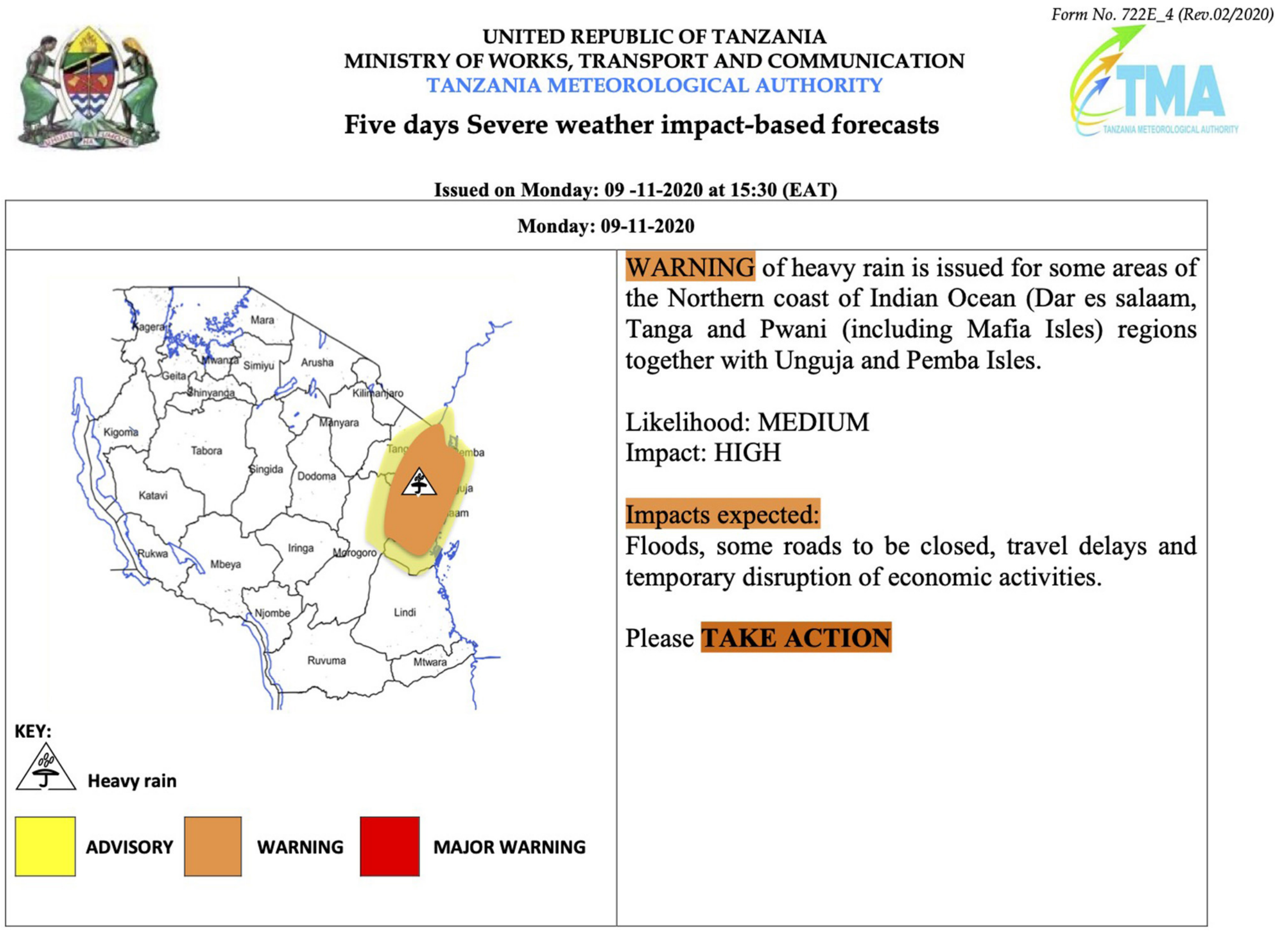


**FIGURE 6 |** An example of day 1 of a TMA severe weather impact-based forecast (Forecasting Division, TMA).

The amount spent on weather-related disasters including drought is about 0.04% of the Tanzania annual GDP for 2018 (WB, 2020). For example, in a study conducted by Anande and Luhunga (2019) on the assessment of socio-economic impacts of the December 2011 flood event in Dar es Salaam showed that flood events damaged properties worth 7.5 million Tanzania shillings and Tanzania Government spent a total of 1.83 billion Tanzanian shillings to rescue and relocate vulnerable communities to safer locations (high ground). These findings not only provide insight on how weather-related disasters are characterized and their cost but also calls for measures to build or strengthen community resilience to weather-related disasters.

## What Is Required to Reduce the Impacts of Weather-Related Disasters?

To address this research question, we looked at the available guidelines that enables the use of weather and climate services to reduce the impacts of weather-related disasters. We found that TMA as the authoritative source of weather and climate services uses the transport sector policy from the parent ministry (Ministry of Works, Transport, and Communications) as its main framing. This policy does not provide explicit directives/guidelines on the production of weather and climate services and application to climate sensitive sectors or for Disaster Risk Reduction explicitly. Its main emphasis is on marine services to use weather information (URT, 2003). However, TMA also implements regional and global initiatives which aim to improve integration of weather and climate services into cross-sectoral planning, policy, and practice. These include the ClimDev-Africa, Global Framework for Climate Services (GFCS), and the Integrated African Strategy on Meteorology (weather and climate services of the African Ministerial Conference on Meteorology, or AMCOMET). TMA also developed and endorsed the National Framework for Climate Services (URT, 2018). Although these national, regional, and international initiatives have been taken into consideration in the generation of weather and climate information, it is necessary for the sector to have a policy instrument that enables the uptake of weather and climate services.

Secondly, we looked at the availability of weather and climate services for disaster risk reduction sector. We found that since April 2012, the TMA has issued 5-day severe weather impact-based forecasts for strong winds, heavy rainfall, tropical

| Tuesday 10-11-2020 | Wednesday 11-11-2020 | Thursday 12-11-2020 | Friday 13-11-2020 |
|---|---|---|---|
|  |  |  |  |
| **ADVISORY** of heavy rain is issued for some areas of the Northern coast of Indian Ocean (Dar es salaam, Morogoro, Tanga and Pwani (including Mafia Isles) and Lindi regions together with Unguja and Pemba Isles.<br><br>Likelihood: MEDIUM<br>Impact: MEDIUM<br><br>**Impacts expected:**<br>localized floods, travel delays and temporary disruption of economic activities.<br><br>Please **BE PREPARED** | **ADVISORY** of heavy rain is issued for some areas of the Northern coast of Indian Ocean (Dar es salaam, Morogoro, Tanga and Pwani (including Mafia Isles) and Lindi regions together with Unguja Isle.<br><br>Likelihood: MEDIUM<br>Impact: MEDIUM<br><br>**Impacts expected:**<br>localized floods, travel delays and temporary disruption of economic activities.<br><br>Please **BE PREPARED** | NO WARNING | NO WARNING |

**FIGURE 7 |** An example of day 2–5 of the TMA severe weather impact-based forecast, indicating warning of heavy rain on day 2, advisories on day 3 and 4 and no warning on day 5 (Forecasting Division, TMA).

cyclones, extreme temperatures, and high waves (**Figures 6**, **7**). The forecasts use predefined action statements, with four levels of warning: gray for no warning, yellow and amber for an advisory (be prepared and take precautions) and red for a major warning (take action). Weather advisories inform the public about the progress of a potentially dangerous weather condition while the warnings alert the public that a weather-related hazard is imminent and that immediate action should be taken to protect lives and property (WMO, 2015; Taylor et al., 2019). The forecast has a lead time of 1–5 days and includes symbols to aid visualization of expected hazards. It also has action statements with specific guidance about action to be taken, likelihood, and local impact severity. TMA also provides seasonal weather forecast with advisory to climate sensitive sectors (TMA;WAMIS, 2018).

Although this information is widely disseminated across Tanzania, the country continues to suffer disproportionally from the impact of weather-related hazards. The understanding of decision-making processes, specifically focused on how and when various types of weather and climate information are incorporated in decision making process is key to disaster risk reduction. Early warning information is a key factor in enhancing disaster preparedness for effective responses and disaster risk reduction measures (Lopez et al., 2020). Lack of policy may hinder advances or cause barriers to the identification of user needs, use of weather and climate information in decision making and impacts of climate change adaptation initiatives and climate-resilient development planning (Vincent et al., 2017). As recent research suggested that a changing climate is likely to lead to an increase in heavy rains in Tanzania (Chang'a et al., 2017) this is important information for providers of weather and climate services, as well as the disaster risk management sector. Having a sector policy will allow the use of short-term and long-term precipitation forecasts for planning, strengthen community preparedness, and implementation of actions to reduce risks during the years when enhanced rainfall is expected. These findings are important in improving the transport sector policy on enhancing the use of weather and climate services to the widest range of users.

## CONCLUSION AND RECOMMENDATIONS

This paper uses disaster data from the Tanzanian Government's Disaster Management Department office to assess the cost and impacts of weather-related disasters in Tanzania from 2000 to 2019. The findings show that Tanzania continues to suffer from the impacts of severe weather events, causing injuries and deaths of people and livestock, infrastructure damage, loss of crops, and arable land for farming despite the availability of warnings for potential weather hazards. The observed association between observed rainfall and the total number of weather-related disaster events provides an opportunity for guiding decision-makers in terms of setting out mitigation measures for disaster risk reduction and preparedness planning. It also provides inputs to policy makers so set out priorities and mechanisms to attain the Sendai Seven Campaign which aims in lowering the mortality, reduce the number of people affected and direct disaster economic loss in relation to the GDP by 2030.

The current lack of an explicit meteorological policy (as found in many other African countries) limits the application and setting of priorities in wider range of use and implementation of various initiatives in climate sensitive sectors. This highlights the importance of: (i) Policy review to enhance uptake of weather and climate information to climate sensitive sectors. (ii) Assessing the entire chain of forecast generation, from an evaluation of the accuracy of the forecasts to how the end-user utilizes the forecasts for decision making. (iii) Investigating the value of the severe weather impact-based forecasts for decision making. (iv) Finding out how weather information is being used; whether the right information is being provided at each step; how much damage could be prevented with improved warning systems; how the information add value to decision-making; how weather hazards and vulnerability issues are incorporated in the warning issued to the public and other actors is key to the decision-makers, and (v) understanding the value of severe weather forecasts which are normally forecasted at a shorter time scale (1–5 days). The above needs will help to reduce the impacts of weather-related hazards will feed into the policy review process, broadens application of weather and climate services as well as setting out actions and plans at national and sub-national levels for enhancing decision making in disaster risk reduction.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

HEM collected and analyzed all the data and wrote the first draft of the paper. ALT, CEB, AJD, AH, and BJW commented on the methodology and study design. All authors have significance contributions to the manuscript.

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