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Generating actionable climate information in support of climate adaptation and mitigation

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Generating actionable climate information in support of climate adaptation and mitigation

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Editorial: Generating actionable climate information in support of climate adaptation and mitigation

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Editorial on the Research Topic
Generating actionable climate information in support of climate adaptation and mitigation

Introduction

Climate change is exerting widespread impacts on nature, society, and economies across the globe necessitating careful consideration of climate monitoring, predictions and projections as decision support for effective medium- and long-term adaptation planning (Hewitt and Stone, 2021; IPCC, 2023). In this respect, the relevance of information at the local scale, tailored to users, is paramount in addressing potential multi-sectoral climate impacts. Recognizing this, numerous countries and organizations have instituted climate services addressing these topics in the form of national climate scenarios and climate assessments such as KNMI'23 in the Netherlands (Van der Wiel et al., 2024), UKCP18 in the UK (Lowe et al., 2018), CH2018 in Switzerland (NCCS, 2018; Fischer et al., 2022), and NCA-5 in the US (USGCRP, 2023). Such services aim to serve as a bedrock for decision support in climate action planning and to facilitate downstream applications.

Despite the shared urgency, the extent and configuration of the value chain in processing from raw climate data to the dissemination of actionable climate information as a service diverge from country to country. This divergence encompasses overarching goals (Skelton et al., 2017), scientific methodologies, specific workflow choices, integration of user needs, governance structures under institutional and political frameworks, modes of dissemination and communication, resources available and how feedback is re-integrated to adjust the production processes. The purpose of this Research Topic was to stimulate an international exchange centered on these nuanced aspects. The eleven articles that are appearing in this Research Topic of Frontiers in Climate Predictions and Projections have together shown the diversity in region-specific experiences, lessons learned, and best practices when distilling actionable climate information. They cluster around aspects of (1) distilling actionable information from climate data, (2) elaborating local-to-regional climate assessments for adaptation planning, (3) evaluating user-needs in co-production and (4) supporting climate mitigation.

Distilling actionable information from climate data

O'Brien and Nolan outline the principles and methodological chain applied to generate a set of standardized climate projections for Ireland until the 21st century assuming three emission scenarios. The projections are based on regional climate model ensembles driven by CMIP5 global climate models. In their dedicated TRANSLATE project, initiated in 2021 by the Irish Meteorological Service, two distinct ensembles of detrended, bias-corrected and downscaled simulations are inter-compared showing consistent results, enhancing confidence, and robustness. Model uncertainty is hence addressed by merging the two model ensembles into a larger sample directed toward users.

Similar to Ireland, the methodological chain to produce future local-scale climate and hydrological projections is presented by Brox-Nilsen et al.. These projections are also based on downscaled and bias-corrected CMIP5 simulations. Beyond the methodological setup, the authors report on their way of disseminating the comprehensive and complex information. With the aim to increase uptake of information, one of their most promising dissemination channels has been the publication of county-wide factsheets. In terms of uncertainty, they conclude that the tradeoff between robustness and precision should guide the dissemination of climate information and that this information should ideally be co-produced with users.

This discrepancy between robustness and precision is also addressed by Hübener et al. for the use of spatial climate data, as there exists a significant gap between the spatial resolution requested by climate impact experts and policymakers for local adaptation planning and the resolution climate data providers typically offer to ensure robustness. The authors suggest to aggregate climate data at the level of natural units maintaining the physical geographic structures. This enables use of single grid cells within that unit for local studies as exemplified in the case study of the federal state Hesse in Germany. To be applied in downstream applications, the disseminated data should further be easily accessible and easy-to-understand for non-experts.

In another case study for western Germany (Wupper catchment) climate model data from the global decadal prediction system MPI-ESM-LR is post-processed by applying a statistical downscaling step to consider the specific local characteristics for the water catchment. In this way, actionable information is distilled to optimize flood protection and water distribution management of the catchment. While the downscaling step preserves the global prediction skill, Paxian et al. found that the application of a recalibration step clearly improved the prediction skill in Germany. In particular, the 3-year mean and seasonal probabilistic SPI (standardized precipitation index) predictions showed promising results, demonstrating potential skill for use in water management needs. To optimally reach users in this field, a user-oriented product sheet was disseminated on the Copernicus Climate Change Service website.

Local-to-regional climate assessments for adaptation planning

While national and international climate assessments are nowadays an established climate service in many countries, similar assessments on a sub-national level that support concrete adaptation planning are less established and hence their role, function and added value needs to be evaluated.

Keener et al. report on lessons learnt and the added value from the Pacific Islands Regional Climate Assessment (PIRCA), exemplifying the pressing need for nuanced, collaborative climate assessments tailored to local decision-making. Over a decade, PIRCA addressed gaps in detailed climate projections for the US-Affiliated Pacific Islands, emphasizing actionable, and culturally cognizant information. External evaluations also highlight PIRCA's role in enhancing regional adaptive capacity and accelerating climate adaptation. Key components of its effectiveness include framing climate information using human- and decision-centric methods, inclusive methods, flexibility to meet stakeholder objectives, leveraging regional organizations, building relationships, and sustaining collaborations. PIRCA's success suggests transferable lessons for other regions, emphasizing the role of collaborative regional assessments in supporting local climate adaptation and policymaking—thereby complementing national and international assessments.

In a community case study Barnes and Dow present the factors that led to a hazard bias in climate adaptation planning, using the example of the city of Charleston in South Carolina (US) and how this bias was overcome. The hazard bias materialized in that adaptation planning and funding solely focused on flooding and water management, thereby overlooking other hazards—in particular heat health risks and costs of reduced labor productivity—despite being identified in the National Climate Assessment. In the absence of investments, Charleston lacked key urban heat data and technical expertise, but also motivation to develop a prioritization approach in favor of heat risk. To increase compound risk awareness and adjust investments to be inclusive of heat risk management a new coalition of researchers, practitioners, and health experts launched a heat-health research program and initiated a new heat network that significantly helped to broaden the climate resilience agenda.

Geiger et al. go beyond the pure analysis of weather and climate hazards. To render climate information actionable for adaptation purposes, they advocate for a more holistic risk approach by assessing hazard impacts together with their societal and environmental settings in a comprehensive risk approach. The authors emphasize that in particular, National Meteorological and Hydrological Services (NMHSs) are in an excellent position to foster the implementation of such an integrated risk framework into their operational routines that incorporates hazard-exposure-vulnerability models, expanding existing forecast, and impact services. This unified approach aims to create synergies within and across NMHSs, fostering collaboration with partners, stakeholders, and users for more effective risk-based services in the face of climate change.

User needs and co-production

Three studies exemplify the indispensable role of co-production between providers of climate services and their users to render climate information and climate services actionable.

Friedman et al. show that the tailoring of climate information services toward users is of utmost importance to increase the uptake of information as evidenced in the example of farmers in Papua New Guinea. Climatic changes threaten farming practices and reduce productivity. While climate information, tools, and practices exist to address climate variability, they often lack contextualization for equitable decision-making. One-size-fits-all information services don't consider regional, social, or local differences. To understand farmers' needs, a Papua New Guinea survey identified key design considerations for seasonal climate forecasts. The authors identified information content profiles, revealing gender and geographic differences. Tailoring weather and climate information services for specific farmer groups promotes equitable access, enhancing smallholders' capacity to adapt strategically to climate change while suggesting avenues for efficient scaling.

A second article takes on the tailoring of climate information to be used by farmers in the case of the horticulture sector in Kenya, East Africa. This sector is heavily affected by climate change, yet local adaptation efforts are strongly limited. Van der Horst et al. present the development of an agricultural climate atlas for two counties in the South of Kenya, aiming to bridge the gap between climate research and farmer uptake. Adopting a bottom-up approach, the atlas is tailored to local needs, focusing on specific crops but it also has the potential to be scalable to other counties and other crops. The co-created atlas demonstrates the significance of user engagement, flexibility and adaptability in climate information services for effective local adaptation. Reported challenges in this development include sustaining engagement beyond the project duration.

Figus et al. present a 24-month case study of knowledge co-production with an indigenous community and tribe in Southeast Alaska, US, focusing on climate services for adaptation and mitigation with priorities of food sovereignty and security. The study applies a theoretical framework for co-production among indigenous and non-indigenous partners. Results show that co-production can establish a collective vision, transforming applied climate science and shifting the researcher's focus to support local needs. Reported challenges include logistics, communication, and conducting research during a global pandemic. Similar to van der Horst et al. the authors recommend institutionalizing and maintaining long-term efforts for co-producing climate services aligned with community priorities.

Climate mitigation

The article by Cohen-Shields et al. addresses actionable climate information in support of climate mitigation. They argue for a modification of the regularly used CO_2-reporting method. This conventional method of reporting greenhouse gas emissions, using CO_2-equivalence (CO_2eq), underestimates the near-term impact of methane-dominated sectors. This is because the method calculates the warming impact over a 100-year period and therefore masks the potency of important short-lived climate forcers like methane. Simple climate modeling indicates that mid-century warming contributions from methane-dominated sectors (in particular from agriculture, fossil fuel, and waste) are twice as high as CO_2eq estimates. Relying solely on CO_2eq hence misrepresents the urgency of reducing emissions from these sectors and risks misaligning mitigation targets with desired temperature outcomes.

Conclusion

In conclusion, the articles in this Research Topic highlight the necessity to provide information on weather and climate in a way that is directly applicable to users and stakeholders and their needs. A user-centered approach with "actionable" information is of paramount importance and is urgently needed to support climate adaptation and mitigation measures worldwide. The exchange here also shows examples for other countries to stimulate and accelerate the use of scientific information and knowledge in user-tailored and actionable climate services in order to better manage risks and identify opportunities. This collective exchange might even contribute to the formulation of international guidelines and best practices, which are currently absent. The Research Topic also underscores the importance of establishing, maintaining and coordinating regional, national and international climate service centers worldwide as a facilitating mechanism and instrument to foster the implementation of adaptation and mitigation measures (e.g., WMO, 2011; Hewitt et al., 2020). Moreover, the Research Topic strives to delve into future challenges, the sustainability of climate services, and the exploration of long-term strategies to establish these services as indispensable sources for decision-making, akin to the commonplace reliance on weather forecasts today.

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PERSPECTIVE
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Co-creation of a Scalable Climate Service for Kenyan Smallholder Farmers

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Climate change is already impacting the horticulture sector in Kenya. Even though the effects of climate change will be severe, adaptation to climate change still has little priority at the local and county level. This paper discusses the development of the agricultural climate atlas for Kajiado and Kiambu counties in Kenya as a climate information service to support the horticulture sector. This climate service for smallholder farmers aims to bridge the gap between climate research and data provision and the uptake by farmers and farmer organizations on the ground. Rather than developing a generic service for the whole of the country, we followed a local, bottom-up approach. Working at the county level, we tried to capture local needs. The result is a co-created atlas for two counties, for specific crops. The approach can be scaled up to other counties and other crops. We elaborate on our approach, and discuss lessons learned, challenges, and future work opportunities. The development of the climate atlas shows the importance of co-creation and user engagement. In addition, flexibility in the output and process was crucial. The main challenge remains to keep engagement high after completion of the project.

Keywords: Kenya, climate services, horticulture, adaptation, smallholder farmers, climate change, climate atlas

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INTRODUCTION

Climate change presents one of the most significant challenges to Kenya's horticulture sector due to extreme events such as droughts, floods, and temperature increases (Patrick et al., 2020). The effects of climate change are already felt, with weather fluctuations impacting productivity (Omoyo et al., 2015; Chepkoech et al., 2018). Even though the effects of climate change will be severe, adaptation to climate change still has little priority at the local and county level. Integrated Development Plans hardly mention long-term climate change (Vincent et al., 2017; Patrick et al., 2020), and climate-smart technologies are promoted in a general way, but they lack a proper underpinning of what would indeed be "climate smart" at a specific location with its specific projected climate impacts (Matsaba et al., 2020). One important reason for this inaction could be the large gap between technical climate research and the usability for end-users (Findlater et al., 2021), the so-called "valley of death" (Markham, 2002). Even though information and data are available, farmers and extension workers agents are often not well informed about the effects of climate change and how to adapt because the information is not usable and understandable for them (Findlater et al., 2021).

Therefore, it is necessary to actively involve and educate farmers and their advisors to reach the "last mile" (Celliers et al., 2021).

Extensive research has been published on the development of climate services that focus on short-term weather or seasonal forecasts in Africa (Tall et al., 2014; Vaughan et al., 2019). Nevertheless, less literature is available on the development of climate services that focus on the long-term effects of climate change. We discuss the development of the agricultural climate atlas (climate-atlas.ke) for Kajiado and Kiambu counties in Kenya as a climate information service to support the horticulture sector, encompassing the production of fresh fruit and vegetables which is an important income generating sector in Kenya (Matui et al., 2016). This climate service for smallholder farmers, those in Kenya having an average landholding of 0.5 ha (Koomen et al., 2018), aims to bridge the gap between technical climate research and the usability by farmers and farmer organizations on the ground (see Matsaba et al., 2020 for a technical description). In this perspective paper, we provide insights on our methodology, lessons learned, challenges, and future work opportunities.

APPROACH

There is no one-size-fits-all when it comes to climate services. For services to be usable and to be used, they need to match the local context, inter alia in terms of planning phase, currently used knowledge, stakeholders, and capacity for using information. User knowledge and needs drive the specification of climate service requirements to enable information uptake and service utilization. However, other factors also steer the development and delivery of services. For instance, constraints emerging from available science, existing tools and available resources must be accounted for to ensure services are usable in practice. Moreover, it is often the case that stakeholders will not have well-defined information requirements and plans for service use at the outset. In a co-creation process the end-users can learn-by-doing and develop requirements in collaboration with service providers and other stakeholders (Lemos et al., 2012). This implies that identification of user needs is not a single activity but requires an iterative process in which demand and supply co-evolve through a learning process (Ziervogel et al., 2021). As such we used a bottom-up approach, which is described in the following sections, to improve the knowledge and skills of local partners and practitioners.

Needs Assessment

Previous work in Africa has also shown that user engagement is crucial to developing a successful climate service (Tall et al., 2014). Therefore, we started the project with an extensive user needs assessment. The purpose of the assessment was to find out if farmers take climate change into account, what climate information is needed by farmers, and the easiest way for them to access this information. During a 3 week field visit in September 2019, 13 smallholder farmers from Kajiado and Kiambu were visited and interviewed to get acquainted with their day-to-day work and vulnerabilities. In addition, interviews with agricultural extension officers and experts from different fields relevant to horticulture were conducted. All interviews were qualitative, with the aim to draft a general insight in the status of climate change adaptation in smallholder horticulture. Interviews during initial farm visits were informal and conversational, focused on their current agricultural practices and their perception of climate change. According to Gall et al. (2003), these interviews build "…entirely on the spontaneous generation of questions in a natural interaction, typically one that occurs as part of ongoing participant observation fieldwork" (p. 293). Later, in-depth interviews were conducted with a selected group of farmers. These interviews were focused on climate change adaptation potential and willingness to adapt. All respondents were asked exactly the same questions, but they were free to provide as much information to those questions as they personally preferred (Gall et al., 2003). Optional follow-up questions were asked if the respondent touched upon relevant issues that needed further explanation. All farmers were selected by the local extension officers. This might have influenced the representation of the farmer community in both counties. However, it was assumed that farmers represent "average" farmers from their county. The farmer interviews, which were recorded, can be found in the **Supplementary Material**.

Most farmers pointed out a growing water scarcity in critical moments in the season as major environmental struggle. The timing of rains is crucial in rainfed agriculture, but continues to become harder to predict. Besides, the overall amount of rainfall seems to have decreased. Higher temperatures were perceived by more than half of the farmers. Together with decreasing amounts of rainfall and rainfall being increasingly erratic, it has created farmer awareness of the need to adapt to climatological circumstances. Nevertheless, they focus on the coming growing season and not so much on the climate that gradually changes over decades. Most farmers have not consciously adapted to long-term changes in climate. However, some farmers did find ways to deal with current variability. For example, farmers use irrigation to prolong growing seasons. Doing so, they respond to fluctuations in market demand to get higher returns on their products.

Furthermore, results indicated that smallholder farmers are looking for crop-specific and localized information (especially in the county Kiambu, climatic conditions vary greatly over relatively small areas of land). In addition, they stressed the need for seasonal information on the start and end dates of the rainy seasons. However, it became clear that accessing this information is a challenge due to the absence of mobile devices and internet connectivity. Here, we found that the extension workers are the most important climate and weather information providers of smallholder farmers. In contrast to smallholder farmers, extension workers do have access to computers and internet connectivity. As long-term climate information has a steering function toward decision-making, rather than directly influencing decisions as is the case with short-term information (Singh et al., 2018), it would be sufficient if farmers are informed through the extension workers. As a result, the extension worker became an important target audience for the climate atlas.

User Stories

During the needs assessment, we found that it was challenging to define the main target audience. Farmers need to implement actual measures in the field, but they are not focused on changes taking place on a timescale of decades. They are more concerned about the outcome of the current or upcoming season. Extension workers would be able to guide farmers, but we also identified county officials as having an important role here. This is a barrier for effective adaptation: a complicated landscape of interests and responsibilities amongst the involved stakeholders, not fit for addressing a cross-cutting issue such as climate change.

Therefore, we developed a diagram showing the relationship between the involved stakeholders (**Figure 1**). For each stakeholder, we formulated a user story. User stories are a method, mainly used in agile software development, for representing requirements from users using a simple template such as "As a <Role>, I want <Goal>, so that <benefit>" (Lucassen et al., 2016). The role defines who will directly benefit from the climate services, the goal specifies which features the climate services should exhibit, and the benefit is the value for the user that will be obtained by implementing the user story.

Climate Data Tool

As active collaboration is important for successful co-creation (Vincent et al., 2018), users were involved during the development process where users were challenged to propose new ideas and think "outside-the-box." The basic climate data tool, the climate atlas, shows the number of days per year above/below a maximum/minimum temperature threshold for future periods (**Figure 2**). The user can manually insert the desired temperature threshold and the months of interest. Thus, users can examine the risk of temperature increases for specific crops during specific periods. We presented the first version to extension workers after which their feedback was incorporated and multiple new versions were discussed with the users. Earlier, only coarse and generic climate data was available with little information about the effects on horticulture. Including growing seasons and identifying critical parameters with our user group allowed us to make a first step and interpret the data. In order to do so, crop-specific indicators, such as temperature thresholds above which yields drop were used. These thresholds were defined by experts and the user groups. This process ultimately resulted in a climate data tool with bias-corrected ERA5 and CMIP5 temperature data from the Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S) (see Matsaba et al., 2020).

Additionally, during the user needs assessment, it became apparent that the timing of the onset of the rainy season is crucial for farmers. Therefore, the tool includes projections on the range of the start/end day of the rainy seasons. A key finding was that only looking at an "average year" provides limited information. Information on the variation between years is, therefore, a valuable and unique addition. For example, although the average onset of the long rains might be 15 March at some location, planting crops every year using that date will likely result in poor harvests. It would be better to prepare for different situations in terms of knowledge and skill (e.g., know how to handle a dry or wet year and which crops to plant). This could provide relevant climate information for strategic management of water resources.

Creating Crop-Specific Storylines Using the Tool

During our feedback sessions, we found that real-life examples would help to engage the user with the data. Therefore, based on the expert tool, we constructed two example narratives, or storylines, together with farmers. These storylines serve as an illustration for other users. For these case studies, the relevant agro-climatic indicators for two reference crops, tomato and maize, were extracted from the literature supplemented by information supplied by seed companies. Changes in climatic suitability were studied for Kiambu and Kajiado Counties, and the data was visualized to allow user-friendly exploration of the specific temperature and precipitation indicators. Finally, different adaptation options were provided. In the example storyline of tomato in Kajiado, the shift of growing tomatoes in the cooler months is explored, as maximum temperatures will exceed the harmful threshold on a regular basis during the current growing season. However, water is scarce in the cool season, thus, enhanced water retention would be required for this shift.

Capacity Development

Results have been generated for two specific counties (see www.climate-atlas.ke), and the aim is to expand and scale up the atlas to other counties as well, To increase the outreach and impact of the climate atlas, additional storylines can be developed for additional crops as well as other counties. To create this capacity in Kenya, we organized two capacity building workshops: one for technical staff at JKUAT University and one for the Kenya Meteorological Department (KMD) and local extension workers. The capacity building workshops were aimed at using the climate atlas to create storylines for new crops and for new areas. Staff from the district offices of the Kenya Meteorological Department (KMD) and local extension workers participated in these workshops. The representatives from the local meteorological offices in Kiambu, Kajiado, and Muranga provided feedback on the atlas and discussed which climate- and weather information is already available and how this relates to the climate atlas. The meteorological offices publish numerous reports and forecasts already and ideally these communication channels would be used to issue seasonal forecasts and communicate climate information to the relevant audience as well. The atlas was well-received, in particular the fact that it contains crop specific and regionalized narratives. At the same time, the tool allows users to define specific threshold values for specific periods of the year and for specific climate scenarios. The workshop also concluded that more training and capacity building activities were needed. To meet this demand, an online training module was developed (through the NUFFIC tailor made training program). This tailor-made training provides guidance on how to build and further expand the climate atlas to other crops and regions in Kenya. Participants learned more about the basics of climate change and were guided in the design of their own atlas and crop-specific story lines. They were

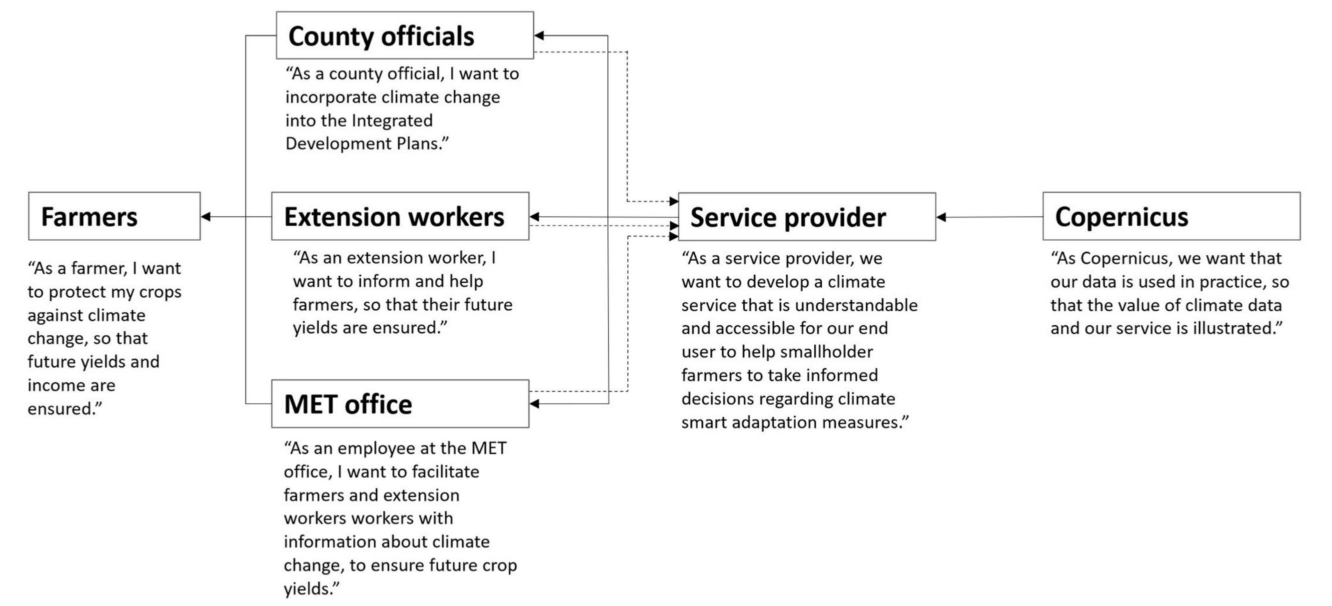

FIGURE 1 | Diagram of the stakeholders and their respective user story. The dashed lines represent feedback loops.

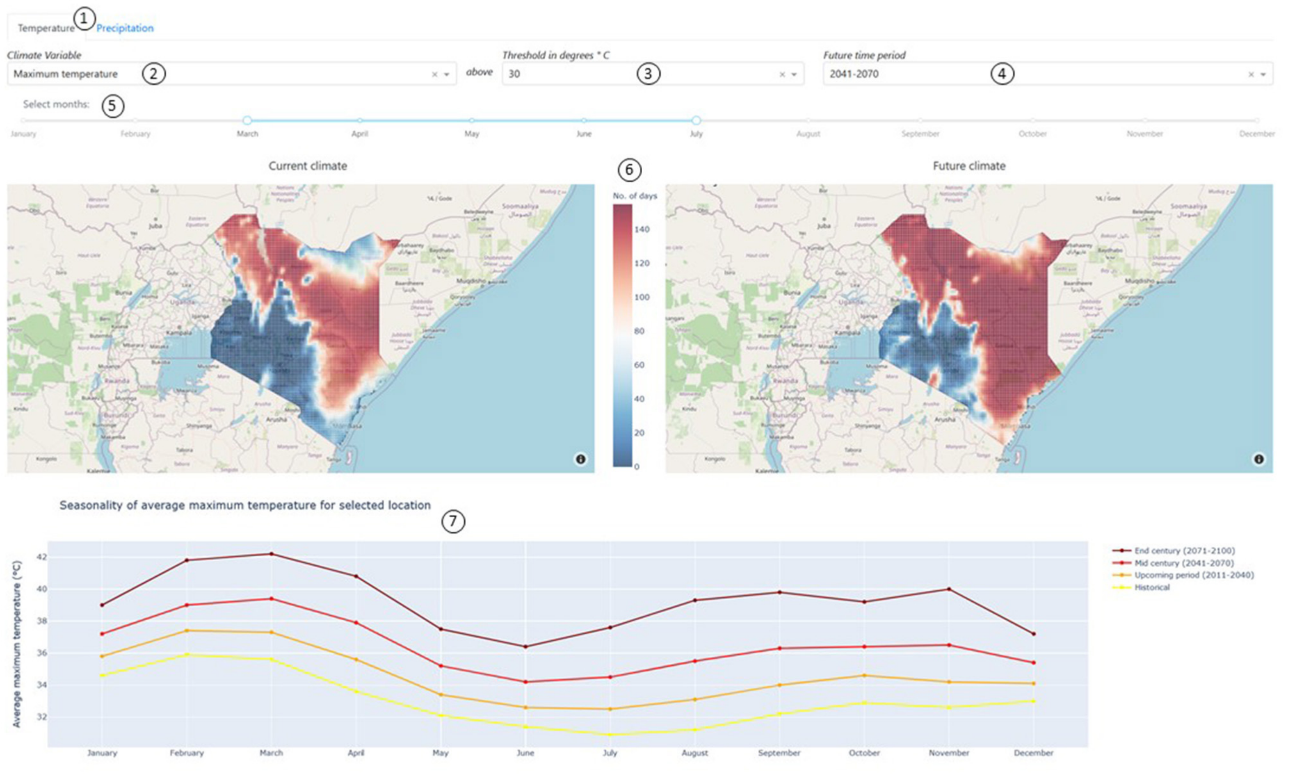

FIGURE 2 | Climate data tool with numbers explaining its function: 1. Select temperature or precipitation, 2. Select the climate variable, 3. Select the crop-specific temperature threshold, 4. Select the future period, 5. Select the growing months of the crop, 6. Clickable maps showing the number of days above the temperature threshold in the growing season, 7. Figure showing the monthly temperature variation of the selected location in the map for different periods.

encouraged to think critically about which information would be relevant in their case.

DISCUSSION

The development of the climate atlas shows the importance of co-creating a service together with the end users. We chose to work bottom-up and tried to capture local characteristics and needs. As a result the atlas is very specific for representative crops in two counties. At the start, a needs assessment has proven crucial to identify the extension workers as our main target user through which we could reach the smallholder farmers. However, they were not our only target group and the roadmap (**Figure 1**) shows that the climate atlas is not a simple tool that passes ready-made information to the end-users, but rather plays an important role in bringing the issue of climate impacts on horticulture to light in an iterative process. As a result, the atlas contains different information levels: stories to engage policy makers and other non-experts, and a deeper dive with more technical information for experts/practitioners.

Not only was the user involvement at the start important, throughout the process, users remained involved and the outputs were tested and evaluated on their usability. These moments of feedback were extremely valuable as users learned more about climate change and realized they needed other services than initially expected. Even though this meant that work needed to be redone, this process resulted in a climate service that was understandable and relatable to users. Field visits and workshops in real-life enabled us to better understand and to reach out to stakeholders. This was important to understand the local context in which the service would operate. This knowledge helped us to create user stories, which is a novel approach in the development of climate services, and to guide us through the development process. In addition, with the input from many smallholder farmers, we could integrate the climate data into storylines that served as practical examples.

The development of the climate atlas showed that flexibility in the process and outputs is important. Often the concept of climate indicators is new to the users and it is difficult for them to formulate their needs at the start. In this project, at first, the demand seemed to be for maps of temperature and precipitation-related changes on a yearly basis. At second glance, however, it turned out that users had difficulty relating these annual averages to the agricultural practices in their region. For example, if the average temperature is 2°C higher in 2050, is that good or bad, and should agricultural practices be adapted or not? At this point it became clear that, in order to reach the last mile, the indicators should be entirely crop-specific, taking into account the cropping calendar and particular critical thresholds.

The importance of flexibility has been highlighted in previous literature. For example, Vincent et al. (2018) stress that flexibility is required on the part of all institutions and individuals participating in the co-creation process. In our case, we were only able to carry out this co-creation work because our commissioning party was flexible in the outcomes, as often the outcomes are more predefined at the start of a project. Besides flexibility in the process, flexibility in the design of the climate service is important (Swart et al., 2017). The climate service needs to co-evolve with the dynamic development of information supply and demand. Therefore, we designed a climate atlas that is easily expandable when more information becomes available.

The ultimate goal of the project was to transfer the outputs to institutions in Kenya so that they can manage the climate service themselves. Even though we did transfer the content of the service, active management is still limited and it is difficult to assure that the service is still used after the completion of the project. We recognize that causes earlier reported by Venäläinen et al. (2016) also apply here: limitations of resources including funding, capacity, and expertise. As many other issues have a higher prioritization, work on climate change is often neglected. Research in Burkina Faso and Ethiopia also addresses this challenge, even after considerable effort is often made to build community engagement with the services (Harvey et al., 2019). As a result, low- and middle income countries often rely on ongoing international support in order to maintain programmatic interventions. Finding a solution to this challenge is not easy. Vincent et al. (2020) developed a conceptual framework in which they include enabling factors that they found to be crucial for actually achieving practical use in climate-resilient planning in Sub-Saharan Africa. They state that a climate service will not be used unless there are supportive institutions, appropriate policy frameworks, capacity of individuals, and agency to make decisions.

The development of the climate atlas has proven the importance of co-creation and user engagement to develop locally relevant and crop-specific user-defined indicators. Translating these specific indicators in "story lines" supported by maps created a powerful communication platform. The storylines were derived from the perspective of personas, or user stories. This helps to connect to the needs and understanding of the users on the ground. The numerous field trips and workshops showed that farmers need localized and crop-specific information, which resulted in the development of a climate data tool. This tool enables users to work with crop-specific temperature thresholds and growing seasons. Besides the value of co-creation and user engagement, flexibility during the process and output of the commissioning party and service provider was of key importance. The main challenge remains to ensure usage of the climate atlas after the project. Therefore, to increase its impact, we aim to expand the atlas and implement it into educational programs.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: www.climate-atlas.ke.

AUTHOR CONTRIBUTIONS

SvH made a first draft of the article with HG, MvS, IK, EM, JW, and JK had major contributions to the project. The draft was send to them and they reviewed the manuscript. In addition, they added text, improved the content, and changed the structure of the manuscript. All authors contributed to the manuscript 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.2022.859728/full#supplementary-material

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METHODS
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From Climate Model Output to Actionable Climate Information in Norway

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The Norwegian Centre for Climate Services (NCCS) has developed a production chain for climate information with the aim of delivering a knowledge base for climate change adaptation suitable for use by planners at various administrative levels in Norway. This process consists of two main steps: First, climate and hydrological projections are produced at a local scale (1 × 1 km resolution) using available results from global and regional climate models (GCMs and RCMs). In a second step, climate factsheets with abridged information relevant for individual counties in Norway have been co-produced with users and county authorities. Projections were produced by using a climate–hydrological modeling chain driven by downscaled simulations from 10 GCM–RCM combinations and two climate scenarios in which temperature and precipitation were first downscaled and bias-adjusted to a 1 × 1 km resolution. Bias-adjustment was necessary, partly due to biases in the RCMs. These results were published in the Norwegian climate assessment report "Climate in Norway 2100." The results have then been disseminated through various formats, such as reports, dataportals, visualizations and factsheets (available at https://klimaservicesenter.no/). NCCS has issued climate factsheets for 17 counties in Norway and Svalbard. The county-wise climate factsheets have become the most extensive product issued by NCCS. A challenge when developing information about climate change for use in adaptation is the issue of uncertainty, and the trade-off between robustness vs. precision in the numerical values given should guide the dissemination of climate information. Based on our experiences, we also recommend that climate information is developed in collaboration with users because this ensures that it will be understood by a wider audience. Most climate-related challenges for infrastructure are related to extreme events. For technical applications in Norway, climate change allowances are now available for heavy precipitation, floods, and storm surges as a tool for design analyses of buildings and infrastructure. This paper describes the production chain for the presently available climate projections following the release of IPCC AR5 (CMIP5), our experiences of the dissemination process, as well as our plans for further development of the next national climate assessment report based on IPCC AR6 (CMIP6).

Keywords: climate projections, hydrological projections, climate change allowances, climate change adaptation, co-production of climate information, Norway, Svalbard

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1. INTRODUCTION TO CLIMATE CHANGE ADAPTATION IN NORWAY

The Norwegian Centre for Climate Services (NCCS) is a collaboration between the Norwegian Meteorological Institute, the Norwegian Water Resources and Energy Directorate (the national hydrological services), the Norwegian Research Centre (NORCE) and Bjerknes Centre for Climate Research. The main goal of NCCS is to provide a knowledge base for climate change adaptation to decision makers and planners at various administrative levels in Norway. Since counties and municipalities are largely responsible for climate adaptation in Norway, delivering useful information at these scales is an important part of NCCS' mandate. The three main goals of NCCS are 1) to provide climate and hydrological data for the past and future in Norway, 2) to be the preferred supplier of knowledge about climate change and hydrology and the effects of climate change on natural hazards, and 3) to be one of Europe's leading national centers for knowledge on climate and hydrology for climate adaptation and impact research. The center is funded by the Norwegian Environment Agency, the Ministry of Climate and Environment and the collaborative partners.

Norway has a complex geography with large gradients in topography and climate, and challenges vary between regions and even within municipalities. The western parts of southern Norway receive the largest amounts of precipitation, up to 5,000 mm/year in coastal regions. In the rain shadow, approximately 100 km further inland, precipitation amounts are less than a tenth of this. Winter precipitation is commonly stored as snow, which melts in spring (in the lowlands) and early summer (at higher elevations). The country has approximately 5,400,000 inhabitants (Statistics Norway, 2021), distributed across the whole country. This decentralization policy results in a sparse population distributed over many small municipalities.

Although challenges resulting from climate change differ across the country, the most common natural hazards are related to water: an increase in heavy rainfall, rainfall-generated floods and rainfall-induced landslides, and for coastal regions: an increase in storm surges. It should be noted, however, that because land masses are still rising after the last ice age, the relative sea level rise is largest in the southwestern regions of Norway. The above-mentioned hazards impact different sectors and communities in various ways. In 2018, a national climate adaptation conference summarized central topics into four conference sessions: i) water and more water; ii) nature, land-use and cultural heritage; iii) civil protection in a changed climate; iv) holistic management. These topics are regarded as relevant climate adaptation challenges across Norway (Neby, 2019).

1.1. Climate Change Adaptation Policy and Guidelines

The White Paper on Climate Change Adaptation in Norway (Norwegian Government, 2012) states that all sectors have a responsibility for climate adaptation in their respective sectors, and further that municipalities carry the main responsibility for adaptation, for example through local land use planning. The Norwegian Planning and Building Act (Norwegian Government, 2013), requires that municipalities perform a risk and vulnerability assessment (RVA) for development plans. National authorities facilitate and guide the climate adaptation work undertaken by the municipalities. In 2018, the Norwegian government adopted new guidelines on climate change adaptation (Norwegian Government, 2018). These new guidelines impose heavier responsibilities on municipalities than before, for example through explicit requirements to take climate change into account in planning and to consult and take into use existing knowledge on climate change. Climate factsheets (Hisdal et al., 2021) issued by NCCS have been a core reference for climate adaptation in these governmental guidelines. They are discussed more thoroughly in section "Step 2." A survey by Klemetsen and Dahl (2020) found that 91% of municipalities in Norway have started work on climate change adaptation. The awareness of climate-related hazards is high; among the respondents, 97% expected the occurrence of an extreme weather event in their area. They further found that 76% of municipalities that have developed risk and vulnerability assesments (RVA) used a knowledge base on climate change. Of those, 61% responded that they used climate factsheets from NCCS (Klemetsen and Dahl, 2020). More details on how climate adaptation is coordinated in Norway can be found in e.g., Hanssen et al. (2013), Wejs et al. (2014), and Hauge et al. (2020).

As recommended in the White Paper on Climate Change Adaptation for Norway (Norwegian Government, 2012), a high emission scenario should be considered when assessing consequences of climate change, in line with the precautionary principle. Risk levels for riverine flooding, storm surges, landslides and avalanches are defined in the Norwegian Planning and Building Act and the associated technical regulations (Norwegian Government, 2017). Buildings in safety class 2 (e.g., a residential area) must be sited, designed or protected against the 200-year flood and the 200-year storm surge height. For the highest safety class, the 1,000-year return interval applies. Four principles for climate change adaptation have been formulated in Hamarsland (2015, our translation):

i) Buildings and infrastructure with a short lifespan (10–20 years) are designed on the basis of the current climate.
ii) Buildings and infrastructure with a long lifespan are either built to withstand projected climate change or designed based on the current climate, but which are also suitable for reinforcement at a later date.
iii) Measures should be climate-resilient, that is, they should function as intended even if the climate develops differently from what is projected.
iv) Climate adaptations contributing to achieving several goals are considered win-win adaptations and should be given a high priority."

Extreme events pose challenges for infrastructure and the built environment in Norway. To cope with the expected changes, climate change adaptation can be set into practice by making allowances for climate change in risk assessments and planning. Such climate change allowances have therefore been developed from climate projections for heavy precipitation, floods and storm surges for use in the design of buildings and infrastructure with a long lifespan, and in hazard mapping. These climate change allowances, requested by users and developed in collaboration between researchers and public management, recommend a buffer to account for increases in heavy rainfall, floods and storm surges. The Norwegian Water Resources and Energy Directorate issued the first generation of climate change allowances for floods in Lawrence and Hisdal (2011), and have refined the recommendations since then. NCCS have formulated these recommendations in general as follows: "To increase resilience to climate change, it is recommended to make allowances for climate change in risk assessments of heavy rainfall, floods and storm surges when planning long-term infrastructure and residential areas. A climate change allowance states how much the current design value (that is, an extreme value such as the 200-year value) should be increased to account for future climate change, specifically: at the end of this century, under the high emission scenario." The allowances are also used as a basis for the design of protection measures related to existing infrastructure and buildings, although additional cost-benefit considerations need to be made before making a decision. Specific formulations for heavy rainfall, floods and storm surges, respectively, are given under the relevant sections below, and in the climate factsheets.

1.2. Interacting With Users

Climate change adaptation needs to be integrated into all relevant policy fields and planning, according to the White Paper on Climate Change Adaptation (Norwegian Government, 2012), which broadens the potential user group of NCCS from scientists, via the private and public sector to the general public. NCCS has defined the prioritized user groups as listed in **Table 1**. Users are engaged through meetings and workshops initiated by both NCCS and other organizations. NCCS has been invited by intermediaries, such as the Norwegian Environment Agency and the Norwegian Association of Local and Regional Authorities (KS), to present information at courses and webinars, most of them aimed at municipal officers and consultants who implement climate change adaptation into municipal plans. In total, researchers affiliated to NCCS gave 340 presentations from 2015 to 2021. Web site statistics and participant lists at seminars NCCS have attended indicate that NCCS have also reached users ranging from international climate researchers, educational institutions, the energy sector, municipal engineers, consultants, municipal planners, and the general public. Spatial planning plays a critical role in climate adaptation and municipalities are therefore one of the main target groups. Municipalities best know their local situation and needs, and therefore, the White Paper on Climate Change Adaptation points them out as being the most appropriate authority level to develop adaptation policies (Hanssen et al., 2013). Land use plans represent an important part of climate change adaptation through their ability to shift new developments away from vulnerable, hazard-prone regions. Robust and climate-adapted spatial plans thus require information about future climate and further effects on e.g., natural disasters. In addition, several impacts of climate change depend on responses in e.g., ecological systems, or factors affecting human health. Providing useful climate datasets for scientists studying such impacts is therefore an important task for NCCS, in addition to providing municipalities with refined end products. During the past 10–15 years, the government has developed learning networks related to climate change. Two such networks, "Framtidens byer" ("Cities of the future") and iFront ("aHead") have been established between the largest cities. The mandate of iFront has been to facilitate the "tricle down" of knowledge from national networks to the networks that participating cities were encouraged to form with their neighboring municipalities, and in turn, that participating regional municipalities were encouraged to form with their neighboring municipalities and so on. The Norwegian Environment Agency and the Norwegian Association of Local and Regional Authorities initiated the first climate network in 2015 and now organizes the 4th generation climate network (Wang and Grann, 2019). A series of novel problem-oriented collaborative workshops, Klimathon (Kolstad et al., 2019; Neby, 2019; Kvamsås et al., 2021), can also be considered to be a type of learning network. These hackathon-inspired seminars gather planners from the municipal and county levels, intermediaries and knowledge providers with the aim of co-producing knowledge for use in climate change adaptation. Through dialogue, different practitioners create a common understanding of a case. Although the questions discussed are not real-life problems, the participants build on experience from local, regional and national adaptation work (Neby, 2019).

TABLE 1 | Prioritized user groups.

Government agencies responsible for infrastructure	Counties
	County municipalities, country governors
Municipalities	Departments for land-use planning, water management and emergency preparedness
Consultancies used by municipalities	
Industries/sectors	Land use and the built environment
Impact research	Ecology, floods and landslides and social sciences.

2. STEP 1: CLIMATE PROJECTIONS FOR NORWAY

The climate assessment report "Klima i Norge 2100" (Hanssen-Bauer et al., 2015; hereafter abbreviated KiN), and the shorter English version "Climate in Norway 2100" (Hanssen-Bauer et al., 2017a), present historical climate change and climate projections toward the end of this century. The Arctic islands of Svalbard were not included in the national Norwegian report, as they lie outside the EURO-CORDEX domain (Jacob et al., 2014). Therefore, a special assessment report "Climate in Svalbard 2100" (Hanssen-Bauer et al., 2019; hereafter abbreviated CiS) was published in 2019. Here, we describe the climate–hydrological modeling chain used in the 2015 version of

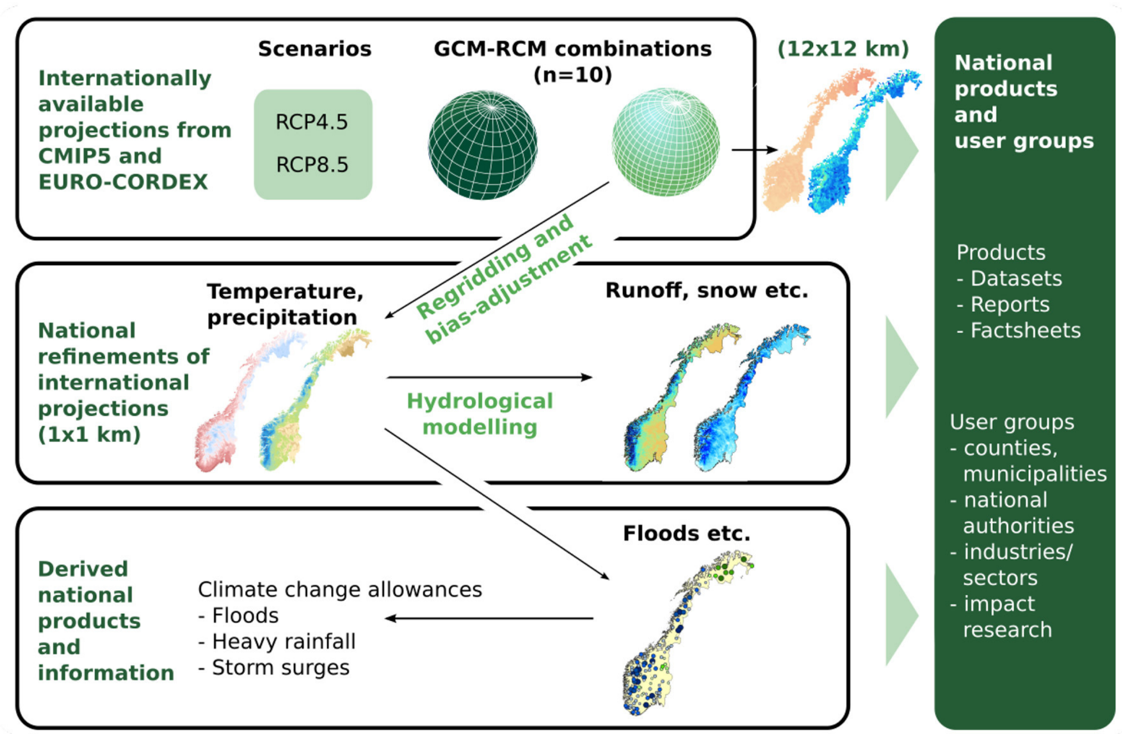

FIGURE 1 | Modeling chain from climate model output to climate information.

KiN. An update of the report "Climate in Norway 2100," planned to be issued in 2024, is briefly described under "Future work."

The climate assessment reports KiN and CiS were based on coupled atmosphere–ocean general circulation models (GCMs) from phase 5 of the Coupled Model Intercomparison Project (CMIP5). Atmospheric variables were downscaled to Norway from the output of the World Climate Research Programme (WCRP) Coordinated Downscaling Experiment-European Domain (CORDEX), see **Figure 1**. Projected temperature and precipitation were computed from regional climate models (RCMs) directly, i.e., without further downscaling or bias-adjustment, at a spatial resolution of 12 × 12 km (2071–2100 relative to the reference period (1971–2000). These data were used to estimate projected changes for counties (**Figure 2**) and as spatially distributed, gridded maps. All projections were produced from ten GCM–RCM combinations from CMIP5 (**Table 2**), downscaled for EURO-CORDEX, i.e., CORDEX models for the European domain. At the time the selection of EURO-CORDEX models were done, these ten GCM–RCM combinations consisted of all EURO-CORDEX at a 0.11 ° resolution, EUR-11, that were available at the time for two emission scenarios (RCP4.5 and RCP8.5), see **Table 2**. These simulations were later re-gridded and bias-adjusted into 1 × 1 km resolution. In addition, empirical-statistical downscaling was used to produce temperature projections for the full multi-model ensemble of GCMs from CMIP5.

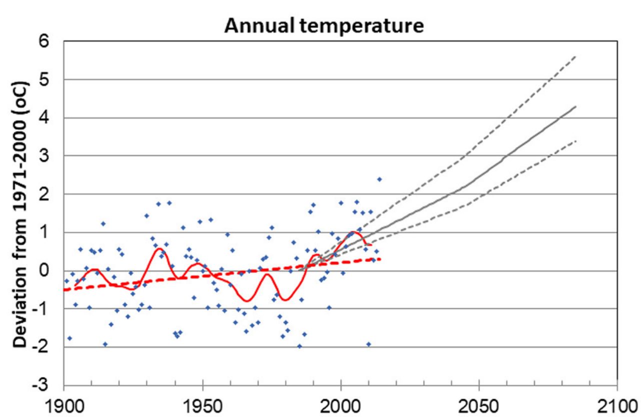

FIGURE 2 | Historical and projected annual mean temperature for one county, Hedmark. The historical development is shown as single years (blue dots), smoothed 10-year variations (full red line), trends (dotted red line). The future development is shown for the high emission scenario, RCP8.5, as the median of the model ensemble (full gray line) and low and high model simulations (dotted gray lines), for the middle of this century (the period 2031–2060 is plotted at 2045) and the end of this century (the period 2071–2100 is plotted at 2085).

In addition to climate model simulations for historical and future projections, observation-based datasets were used to present the development of the climate in the historical period, as

TABLE 2 | GCM–RCM combinations used in KiN from the EURO-CORDEX ensemble and CiS for the Arctic-CORDEX ensemble (see page 144 in KiN and page 192 in CiS for references and details).

	KiN: GCM–RCM realization	CiS: GCM–RCM realization
1	CNRM-CERFACS-CM5-CCLM4-8-17	CCCma-CanESM2-SMHI-RCA4
2	CNRM-CERFACS-CM5-SMHI-RCA4	ICHEC-EC-EARTH-SMHI-RCA4-SN*
3	ICHEC-EC-EARTH-CCLM4-8-17	ICHEC-EC-EARTH-SMHI-RCA4
4	ICHEC-EC-EARTH-HIRHAM5	ICHEC-EC-EARTH-DMI-HIRHAM5
5	ICHEC-EC-EARTH-RACMO22E	MPI-M-ESM-LR-MGO-RRCM*
6	ICHEC-EC-EARTH-SMHI-RCA4	MPI-M-ESM-LR-SMHI-RCA4-SN*
7	MOCH-HadGEM2-ES-SMHI-RCA4	MPI-M-ESM-LR-SMHI-RCA4
8	IPSL-CM5A-MR-SMHI-RCA4	NCC-NorESM1-M-SMHI-RCA4
9	MPI-ESM-LR-CCLM4-8-17	COSMO-CLM**
10	MPI-ESM-LR-SMHI-RCA4	

Stars indicate models that were not available for RCP4.5, only RCP8.5. The double star indicates that a dynamical downscaling was performed with COSMO-CLM for Svalbard.

well as for bias-adjustment and for calibrating and validating the hydrological models. The main historical meteorological dataset used was a gridded dataset from the web portal http://senorge.no/ (hereafter senorge v.1.1; Tveito et al., 2005; Mohr, 2008), with a daily temporal resolution, and a spatial resolution of 1 × 1 km. Senorge v.1.1 interpolates temperature and precipitation from observation stations, using various geographical information (e.g., longitude, latitude, altitude, distance from coast; see Mohr, 2008 for details).

2.1. Climate–Hydrological Modeling Chain

Projections of hydrological variables (runoff, snow, groundwater, evapotranspiration and soil moisture deficit) were simulated with hydrological models, taking temperature and precipitation as input. Simulations were driven by bias-adjusted temperature and precipitation from the 10 EURO-CORDEX simulations. This approach consisting of using downscaled, bias-adjusted climate data to simulate hydrological variables is often referred to as the climate–hydrological modeling chain.

Ideally, climate model output should be used directly in hydrological models. However, the spatial resolution of regional climate model ensembles, such as the EURO-CORDEX simulations, is still too coarse for local assessments, especially in a country with rugged topography, such as Norway. In addition, global and regional climate models can produce somewhat biased output (e.g., Frei et al., 2003), which unfortunately prevents their direct use in impact studies. As a result, bias-adjustment of climate model output variables has become a fairly standard procedure in climate change impact studies (e.g., Hempel et al., 2013; Dankers and Kundzewicz, 2020), despite its limitations and the additional challenges it can introduce (see for example the discussion in Ehret et al., 2012). For this work, the main challenges were related to the volume of data (10 models × 320 000 grid cells × 130 years), which favored a computationally efficient method. Temperature and precipitation were regridded from approximately 12 × 12 km to 1 × 1 km and thereafter bias-adjusted for each grid cell separately, using senorge v.1.1 as the reference dataset, see Wong et al., 2016) for details. Wong et al. (2016) also presents some reasons for bias-adjustment, e.g., cold biases for Norway in the historical period leading to an unrealistic prolonged snow season if bias-adjustment was not implemented. For a more detailed discussion of the trade-offs please see Section Discussion.

2.1.1. Hydrological Modeling

For the hydrological simulations, the HBV hydrological model (Bergström, 1995; Sælthun, 1996; Beldring et al., 2003) was selected. This model has been widely used for hydrological simulations in the Nordic region (Bergström, 2006), and is used both operationally and for research (e.g., Lawrence and Haddeland, 2011; Wong et al., 2011; Huang et al., 2019). The HBV model is a conceptual hydrological model that computes the water balance in response to hydro-meteorological forcing, including storages and depletion in snow, soil moisture and groundwater, and simulates the associated runoff. Two versions of the HBV model were used: a) a catchment-based version with height zones for snow modeling (Sælthun, 1996); and b) the gridded HBV model developed by Beldring et al. (2003). Both versions employ temperature-index methods for snow accumulation and melting and for evapotranspiration. Thus, the model can be run with temperature and precipitation time series as the only driving variables. The hydrological model includes different land cover types, e.g., lake, forest, bedrock, and urban, which specifies the percentage of the given land cover type within the gridcell.

The catchment-based HBV model was calibrated and validated for 115 unregulated catchments for use in generating hydrological projections suitable for flood analyses in these catchments (Lawrence et al., 2009; Lawrence, 2016). Multiple parameter sets were calibrated for each catchment to quantify the uncertainty in HBV model parameterization (Lawrence and Haddeland, 2011; Lawrence, 2020). Bias-adjusted precipitation and temperature time series were created for each catchment for each of the 10 EURO-CORDEX RCMs by applying two bias-adjustment methods. The bias-adjusted time series were used as forcing data to run multiple hydrological simulations for each catchment, and this was also done for each of the 25 parameter sets for each catchment. The annual maximum flood series was extracted from each simulation for 30-year time slices for estimating changes in the average annual flood, the 200- and 1,000-year floods and the predominant flood season. Due to the relatively short time periods for analyses (annual maximum series consisting of 30 years for the reference and future periods), a two-parameter Gumbel distribution was used for estimating flood return levels. Percentage future change in flood discharge was calculated by comparing estimates for the flood quantiles for the reference and future periods.

A gridded version of the HBV model was implemented with a daily time step and 1 × 1 km spatial resolution for mainland Norway (Beldring et al., 2003) to study changes in hydrological variables. The model was calibrated using precipitation and temperature from senorge v1.1 as forcing data. The results from this historical run represents the reference data for the hydrological variables at 1 × 1 km. The model was thereafter run using downscaled and bias-adjusted climate model data from the ten EURO-CORDEX models, resulting in daily gridded hydrological time series spanning the period 1971–2100. Svalbard was not included in the national Norwegian report KiN, as it is outside the EURO-CORDEX domain. A special assessment report "Climate in Svalbard 2100" (CiS) was published in 2019, based on downscaled and bias-adjusted models from the Arctic-CORDEX ensemble treated in a similar way as described for KiN. Eight models were available for RCP8.5, five for RCP4.5, all with a 50 km resolution. Because of the coarse spatial resolution in Arctic-CORDEX, an additional regional downscaling to 2.5 km resolution was performed using one model, COSMO-CLM.

3. RESULTING PROJECTIONS AND ALLOWANCES

In the KiN and CiS reports, results are computed for two emission scenarios, for the mid-century period (2031–2060) and the end-century period (2071–2100) relative to the reference period (1971–2000). To satisfy the precautionary principle, the high emission scenario at the end-century period is most often used as a basis for climate adaptation in Norway. The summary of results below are valid for mainland Norway for the end-century period compared to the reference period, under the high emission scenario RCP8.5, unless otherwise stated. Model spread in the KiN report is presented as the 10 percentile, median and 90 percentile of the model ensemble. In this paper as well as in the climate factsheets, the ensemble median is presented, in some cases with the 10 percentile and 90 percentile in parentheses.

3.1. Temperature

The mean temperature for mainland Norway has increased by approximately 1°C in the period 1900–2014. The projections toward the end-century for high emissions show a 4.5°C warming for mainland Norway (3.4–6.0°C). **Figure 2** shows how this information is conveyed graphically through a climate factsheet. For the intermediate emission scenario, RCP4.5, the temperature increase is estimated to be 2.7°C (1.6–3.7°C). As expected from Arctic amplification, the projected warming is larger for the northernmost counties (Finnmark: 5.5°C), and especially for Svalbard: 9.8°C, according to the report CiS. The projected warming in winter exceeds that of the other seasons.

3.2. Precipitation, Including Climate Change Allowance

Historically, the mean annual precipitation has increased by approximately 18% in the period 1900–2014. Annual precipitation is in general projected to increase at high latitudes. By the end of this century, annual precipitation is estimated to increase by 18% (7–23%) for the high emission scenario and by 8% (3–14%) for the intermediate emission scenario. Precipitation intensities during short-term heavy showers increase more than daily values because air has the capacity to hold more precipitable water when it is warmer. Heavy rainfall may lead to widespread stormwater runoff with traffic disruptions and material damage. Climate change allowances have therefore been developed to mitigate damages from increases in precipitation intensity during heavy rainfall. A climate change allowance for heavy rainfall states by which factor or percentage the current design rainfall (taken from an IDF curve NCCS, 2022b) should be increased to account for future climate change. The resulting climate-adjusted value is used to design infrastructure on a local, urban scale. These climate change allowances are not themselves climate projections, but are derived from climate projections of precipitation. The climate change allowance for heavy rainfall was defined on the basis of projected precipitation amounts for the end of this century (2071–2100) relative to the reference under the assumption of a high emission scenario. Initially, the allowance was formulated as "at least 40% increase," independent of storm duration or return period. In the current version of the climate factsheets (Hisdal et al., 2021), this is expanded: "If a more refined approach is desired for different durations and return values, the climate change allowance as shown in the table below (**Table 3**) may be used."

TABLE 3 | Recommended climate change allowance for heavy rainfall (modified from Dyrrdal and Førland, 2019).

	Return period < 50 years	Return period ≥ 50 years
≤ 1 h	40%	50%
> 1–3 h	40%	40%
> 3–24 h	30%	30%

At Svalbard, the relative increase in annual precipitation is projected to be larger than that for mainland Norway, i.e., approximately a 65% increase; however, the absolute values of precipitation are low (approximately 400 mm/year at Ny Ålesund) (CiS).

3.3. Snow

Changes in temperature and precipitation influence snow coverage. Higher temperatures in autumn and spring lead to a shorter snow season. A shorter snow season does not necessarily mean less snow, however. For regions with sufficiently low temperatures in a future climate (at elevations exceeding 1000 m a.s.l.; Skaugen et al., 2012), snow amounts are expected to increase due to an increase in precipitation, at least toward the middle of this century. The cryosphere is an important part of nature at Svalbard, with almost 60% of the land area of Svalbard covered by glaciers. The snow season is expected to become shorter, and the loss of glacier mass will change the landscape (CiS).

3.4. Runoff

Changes in precipitation and snow regimes will alter runoff in different ways for the different seasons. In winter, runoff is projected to increase (substantially for relative values but only modestly for absolute values) due to a smaller fraction of the precipitation being stored as snow. The timing of snowmelt is shifted to earlier in the year. In spring, this shift toward earlier snowmelt leads to a diverse picture, with an increase in runoff at high altitudes, where snowmelt continues into summer months

(June–July) in the present climate. In the same season, a decrease in runoff is projected in the lowlands, where snowmelt ends during April–May in the present climate. In summer, runoff in general is projected to decrease. This expected decrease is mainly due to an increase in evapotranspiration outweighing the increase in rainfall. In autumn, runoff is projected to increase at most locations due to an increase in rainfall. An exception are the lowlands of South Norway where higher evapotranspiration may even reduce autumn runoff.

For Svalbard as a whole, runoff is expected to increase in summer as a response to glacier melt, and in the other seasons as a response of more precipitation falling as rain rather than snow.

3.5. Floods, Including Climate Change Allowance

Although rainfall is projected to increase, flood risk depends on several factors in addition to rainfall (see Hodgkins et al., 2017; Sharma et al., 2018). In Norway, rainfall floods are projected to increase, but snowmelt floods are not (Vormoor et al., 2015, 2016; Lawrence, 2016, 2020). This difference depends on the characteristics of the river catchment, particularly related to the potential for snow accumulation. **Figure 3** shows changes in the 200-year flood by the end of the century under high emissions. The green dots correspond to catchments that are dominated by a snowmelt flood in today's climate, where the flood magnitude is projected to be unchanged or reduced. Blue dots correspond to catchments that are dominated by a rainfall flood or a combination of rainfall and snowmelt floods in today's climate, where the flood magnitude is projected to increase. The daily (24 h) time step does not allow resolving the flood peak in catchments that respond quickly to rainfall; however, more recent studies with 3-h input have shown that the flood magnitude in these catchments have larger increases (Lawrence, 2018). The largest increases in flood magnitude are expected in small, steep catchments and in other catchments in which excess rainfall accumulates and is transferred rapidly through the catchment. In larger catchments, snowmelt and evapotranspiration occurring over longer timescales (i.e., days rather than hours) have a greater effect in mitigating the impact of increases in short-term precipitation intensities as compared with smaller catchments (Sharma et al., 2018).

Recommendations for a climate change allowance for floods were developed based on the median projections illustrated in **Figure 3** for the projected change in 200-year flood values by the end of this century (2071–2100) under the assumption of a high emission scenario. For this purpose, three classes are distinguished: 1) no change or an expected decrease in flood hazard (0%); 2) an expected moderate increase in flood hazard (20%); and 3) an expected large increase in flood hazard (40%). Individual catchments are placed in one of these classes based on catchment characteristics, particularly related to location, potential for snow accumulation and the dominant flood season in the current climate. Due to the high degree of uncertainty in projected flood magnitudes and the large spread in the ensemble projections for each catchment, these three classes are used (rather than more precise values) to ensure robustness

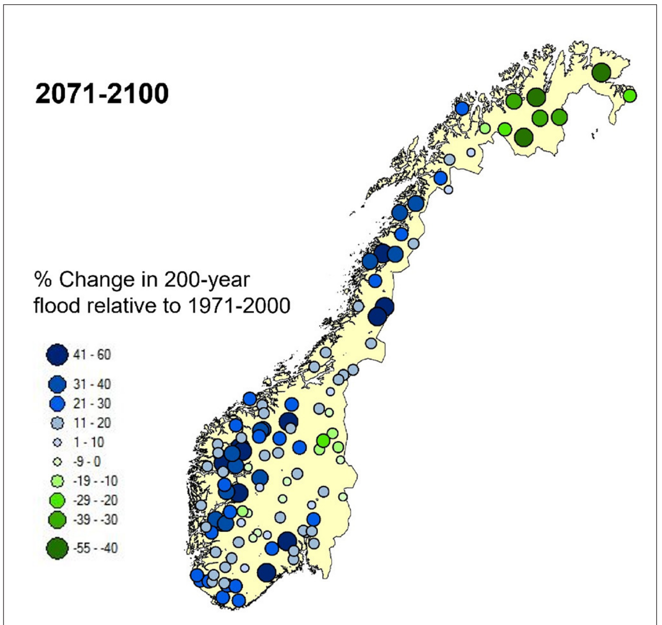

FIGURE 3 | Percentage change in the 200-year flood between the reference period 1971–2000 and projection period 2071–2100 for RCP8.5. The estimates are based on the ensemble median of 500 simulations for each of the two emission scenarios (RCP 4.5 og 8.5). For each of 115 catchments, 10 climate models (see **Table 2**) have been downscaled and bias-adjusted using two methods. In addition, the 25 best parameter sets calibrated for each catchment were used in successive runs of the hydrological model for that catchment (From Lawrence, 2016).

in the recommendations. At present, a hydrological assessment is performed for each catchment where a climate change allowance is required. However, a national map illustrating the recommended climate change allowance for all river reaches in Norway will be published in 2022. This allowance is particularly used in design flood analyses and in flood hazard mapping throughout Norway, i.e., they are targeted for the more advanced users of climate change information. Mapping of flood hazard is performed by the Norwegian Water Resources and Energy Directorate for some exposed river reaches, and these mapped river reaches are listed in the climate factsheets, together with the recommended climate change allowance for the reaches. At Svalbard, flood magnitudes are expected to increase, both as a response to increasing rainfall amounts and snowmelt and glacier melt (CiS).

3.6. Landslides and Avalanches

Landslides and snow avalanches cover many types of mass movements, see chapter 7.3 in CiS for an overview of types. Weather triggers certain types of slides and avalanches, and climate change may thus affect their future frequency. For mainland Norway, it is expected that in steep terrain, climate change may lead to an increase in the frequency of landslides, debris flows and slush avalanches associated with heavy rainfall (Hisdal et al., 2021). Increased erosion could trigger more quick-clay slides. The risk of dry snow avalanches is expected to decrease, while the risk of slush slides is expected to increase, and may occur in areas where they have not occurred previously. The climate factsheets describe how different types of landslides are expected to change based on changes in climate. In particular, earth slides, floodslides and slushflows are sensitive to climate change because of increased precipitation (Hisdal et al., 2021). The climate factsheets list existing hazard maps and highlight the importance of further hazard mapping because of the expected increased frequency of landslides and avalanches. Climate change allowances are, however, not used in hazard mapping and other assessment related to landslides and snow avalanches.

Landslides and avalanches can be classified according to the water content. Floodslides and earth slides are rapid mass movements in steep slopes, but the former has a higher water content than the latter. Both types of landslides are expected to become more frequent because they are triggered by rainfall. We differentiate snow avalanches into slushflows, wet snow avalanches, dry snow avalanches. A slushflow is a "mudflow-like avalanche composed of slush–very saturated snow" (European Avalanche Warning Services, 2022). Slushflows are, similar to earthslides and floodslides, triggered by precipitation, and the hazard is therefore expected to increase. The hazard of wet snow avalanches, an "avalanche of wet snow masses," is expected to increase in hazard-prone areas because the snowline will shift to higher altitudes and rain will fall on snow-covered ground more frequently. For the same reason, the occurrence of dry snow avalanches can be expected to be reduced. A quick-clay slide is a "very rapid to extremely rapid flow of liquefied sensitive clay" (Hungr et al., 2014). Quick-clay slides are often triggered by construction work, but increased erosion due to larger flood magnitudes may trigger quick-clay slides more frequently in the future. Rockfall is defined as "Detachment, fall, rolling, and bouncing of rock [...] fragments" (Hungr et al., 2014). Frost action influences rockfalls, which are often triggered by increased pore pressure during heavy rainfall. More frequent heavy rainfall events may increase the frequency of rockfall. Hungr et al. (2014) defines a rock slide (rock avalanche) as an "Extremely rapid, massive, flow-like motion of fragmented rock from a large rock slide or rock fall." This type of landslide is mainly caused by long-term, geological processes and are less influenced by weather events. Permafrost thawing may contribute to triggering rockslides; however, there is no scientific evidence that indicates that climate change will increase the frequency or magnitude of large rockslides. In addition to the above-mentioned processes, Svalbard will also experience changes related to thawing of near-surface permafrost in coastal and low altitude areas, and and increase in erosion and sediment transport. This is thoroughly described in the report CiS.

3.7. Sea Level Rise, Including Climate Change Allowance

The global mean sea level is rising as a response to thermal expansion and loss of land ice (Simpson et al., 2015). The relative sea level, that is, the sea level relative to land, will increase less for Norway than the global mean sea level rise. The reason for this is the vertical uplift of the land after the last ice age. Because the ice sheet was thickest around the Bay of Bothnia, this region experiences the strongest uplift. In coastal regions farthest from the Bay of Bothnia, i.e., the southwestern regions of Norway, the crust rebounds at a slower rate. Therefore, the relative sea level rise is largest in these regions. Storm surges are extremely high sea levels resulting from very low pressure and high winds. Simpson et al. (2015) provide projected sea level changes and estimates of projected storm surges for municipalities. They project more frequent storm surges and more frequent inundations. In planning long-term infrastructure, allowances for storm surges should be considered. The climate change allowance for storm surges is defined on the basis of the projected sea level change from 1986–2005 to 2081–2100, for RCP8.5, and the 95th percentile of the ensemble spread (see Table A.2.3 in Simpson et al., 2015). In Svalbard, the relative sea level is projected to fall because of continued loss of local ice masses. Storm surges are not expected to become worse because of sea level rise. However, thawing of permafrost makes coastal erosion more of a challenge.

4. STEP 2: DISSEMINATION OF CLIMATE INFORMATION IN NORWAY

National climate reports such as KiN are useful for documentation of knowledge status and for providing a comprehensive and consistent picture of climate developments in an area. For many users of climate information, however, the report has little practical usefulness, and NCCS has therefore developed several products aimed directly at different user groups (see examples in the bottom panel in **Figure 1**). Some climate projection products are published online through http://klimaservicesenter.no/, for visualization as well as for download. For less advanced users, summaries of the most important findings for each county have been compiled into climate factsheets, and maps of projected changes are presented on the web (30-year mean values). For more advanced users, the climate and hydrological projections at 1 × 1 km are made available as daily time series in netCDF format.

4.1. Climate Factsheets

Because scientific reports are generally not read by decision-makers and municipal planners and because key information from the reports has to be combined with legal regulations and guidelines on climate change adaptation, NCCS has issued climate factsheets for each county (Hisdal et al., 2021). They describe current conditions as well as the most important changes from the reference period to the end-century, under the high emission scenario following the precautionary principle (ref. Section Discussion). Physical climate hazards summarized in the climate factsheet include heavy rainfall and stormwater runoff; floods, droughts, landslides, avalanches and storm surges. In the summary table, relevant natural hazards are assigned to one of four categories: "Increased probability" (red), "Possible increased probability" (orange), "No change or less probability" (green) and "uncertain" (blue) (**Figure 4**). In addition to presenting projections and climate change allowances, the climate factsheets

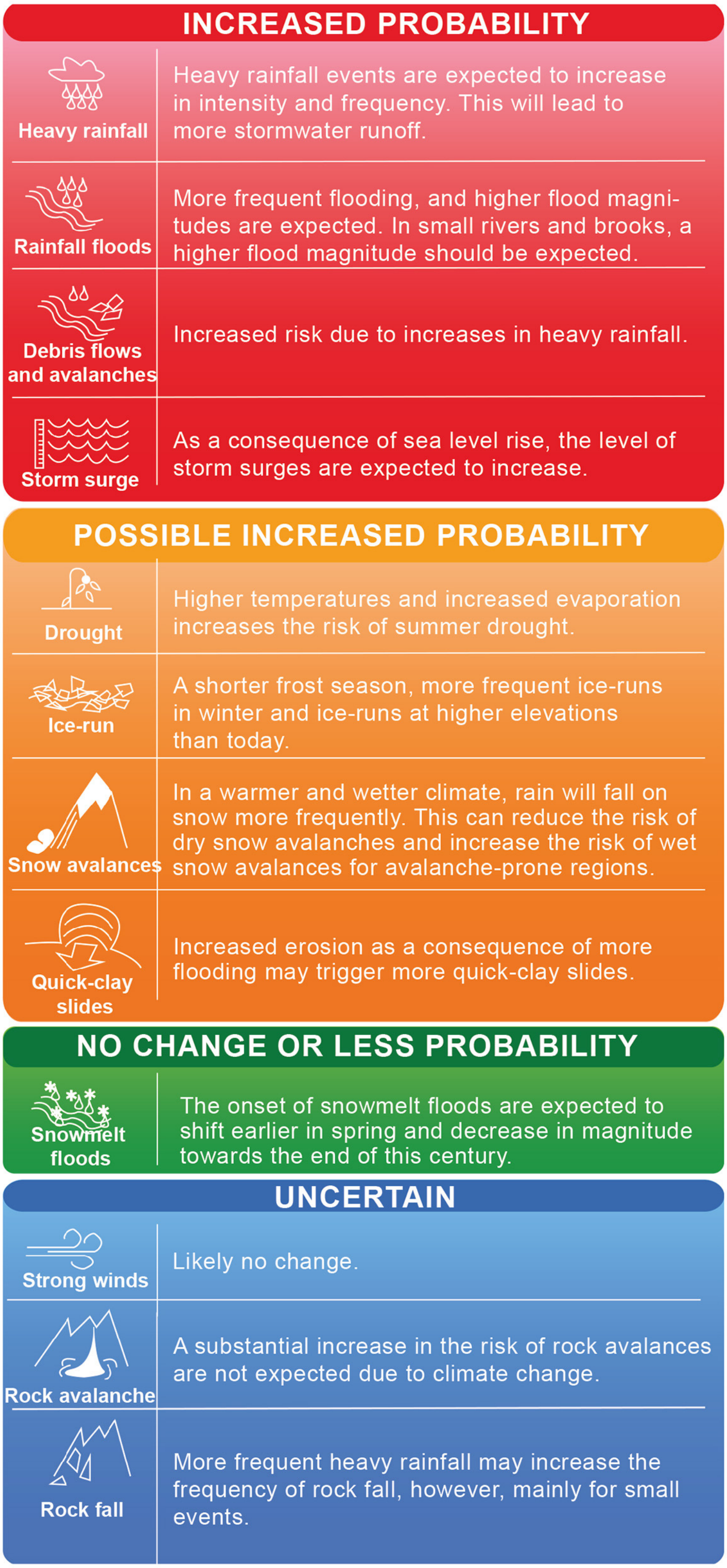

FIGURE 4 | Example factsheet for one county. The factsheet shows a summary of projected changes in hydrological conditions and natural hazards relevant to the county for the period from 1971–2000 to 2071–2100.

list climate adaptation regulations, outline natural climate risks for the county and give links to hazard maps for floods and landslides produced by the Norwegian Water Resources and Energy Directorate. The climate factsheets were updated in February 2021 and are now available both online and as printable PDF documents.

The idea of a climate factsheet was conceived during a multi-level governance network project, "Climate project Troms" (Hanssen et al., 2015), where the goal was to integrate climate change adaptation into municipal planning according to the Planning and Building Act and the associated technical regulations. The project involved participation from multiple governance levels, from the local level to the national. The county of Troms led the project, which also involved selected municipalities, the county authority, the Norwegian Directorate for Civil Protection (DSB) and NCCS. The county authorities and municipalities requested a short summary of climate change information relevant for various planning processes in the municipalities. A prototype 8-page, condensed climate factsheet for Troms county was developed and issued in January 2015, and was intended to be used alongside a report describing how to integrate climate change adaptation into municipal plans (Norwegian Directorate for Civil Protection, 2015).

After this pilot project, climate factsheets have been published for all counties in mainland Norway as well as Longyearbyen, Svalbard on request from local authorities. This co-production, where practitioners were heavily involved in developing the climate factsheet Troms, continued during work with the other counties. The content was inspired by the factsheet for Troms, but was adjusted in dialogue with county authorities. Local representatives were given the opportunity to comment and make suggestions to early drafts of the factsheet. For example, a coastal municipality in Nordland requested information about wave action, which was included in later factsheets for coastal counties. Further, the county authorities in Sogn og Fjordane, who had built up competence on climate change adaptation, asked for uncertainty ranges, whereas other county representatives did not prefer that such information be included. Prior to publication, NCCS asked county authorities to promote the climate factsheet at political meetings at the county level in order to obtain political anchoring among local politicians. Decisions on e.g., which scenario to use for climate change allowances and planning is a political question. The municipal practitioners in the pilot project stressed that political anchoring was necessary to get political support for the adaptation measures they suggested. Through dissemination on websites and in seminars and later via the implementation of governmental regulations, the public gradually became familiar with the factsheets, both their availability and their use. In addition, government organizations and county administrations have distributed the factsheets locally.

4.2. Use of Climate Factsheets

Climate factsheets are a core reference in the government guidelines on climate change adaptation (Norwegian Government, 2018) and are widely used in RVAs by municipalities (Klemetsen and Dahl, 2020). Some municipalities have developed a climate adaptation strategy (Handberg and Pedersen, 2018), where background information on local climate change was based on the factsheet for the given county, among other sources. A few municipalities have in addition developed climate vulnerability analyses. County municipalities, such as Vestland, used climate factsheets as a knowledge base when developing their adaptation planning strategy. The Norwegian Agency for Local governments has developed a portal for local climate risk in each municipality which presents **Table 1** from the factsheets. An example can be seen for e.g. Lillestrøm (The Norwegian Agency for Local Governments, 2022).

According to a survey by KS (Wang, 2018), climate factsheets are the most frequently applied service provided by NCCS. Comments on climate factsheets in such surveys point to too general information (Rusdal and Aall, 2019; Hauge et al., 2020), a need to translate knowledge on climate change into climate change adaptation (Rusdal and Aall, 2019) and a lack of capacity to use the information (Wang and Grann, 2019). Published surveys of climate change adaptation are discussed more thoroughly in Section Discussion.

4.2.1. Evaluation of the Climate Factsheets

NCCS has evaluated the use of climate factsheets and other products through a survey and workshops described in the following paragraphs. This section illustrates how NCCS use the results of the evaluation to define new user needs and inform future development of our services.

During two workshops in November 2019, NCCS gathered comments on climate factsheets. The first workshop was co-arranged with a research project, and aimed at collecting user suggestions for future climate factsheets (unpublished internal notes). Here, specific indices for the land use sector were suggested. The second workshop was co-arranged with the Norwegian Association of Local and Regional Authorities (KS) and was aimed at collecting user comments on the climate factsheets (unpublished internal notes). The comments about the climate factsheets can be summarized as follows:

- The factsheets raise awareness about climate change adaptation.
- The factsheets are too general to be used for local decisions, such as detailed land use planning. Translation of technical knowledge to the downstream user is required, in particular from recommended climate change allowances to design in practice. Examples are requested.
- Municipal officers use other data formats than researchers. They requested data as maps.
- Which status do the recommendations have? Are they legally binding?

Some of the municipalities had not used climate factsheets in their planning strategies, and they explained that their planning strategy is changed every 4th year such that the climate factsheet was not published in time to incorporate it into the planning strategy. One participant had not heard about the climate factsheets before the workshop.

In one survey of the NCCS website, it was requested that NCCS make projections available through existing web portals such as http://senorge.no/ (unpublished, internal notes). A user from the hydropower sector requested projections aggregated for catchments, similar to the Swedish Meteorological and Hydrological Institute's portal Hypeweb (SMHI Hypeweb, 2022).

4.2.1.1. Klimathon

The climate factsheets from NCCS were a topic for discussions at a so-called Klimathon events targeting a variety of practitioners, aiming in particular at municipal planners (Neby, 2019; Kvamsås et al., 2021). Discussions were prepared as group posters and presented in a common poster session, in addition to reflective notes and evaluations. One group working on "Nature, land-use and cultural heritage" devoted their time to addressing how the climate factsheets could be used in conjunction with other knowledge bases, and listed the following possible solutions: check lists, local knowledge in map formats, political anchoring in land use plans and a database of example measures (Neby, 2019). The authors point out that challenges and barriers were addressed rather than solutions. Although most participants knew about the climate factsheets and/or used them regularly, some participants did not know where to find local climate information (Neby, 2019). The numbers given by Klemetsen and Dahl (2020) in the introduction to this paper can therefore be interpreted as follows: 24% of the municipalities that have developed RVA analyses have not used a knowledge base about climate change. The potential for disseminating climate factsheets to a wider audience is therefore present.

4.3. Dissemination of NCCS Data on the Web

Maps of 30-year means are presented on the NCCS web portal https://klimaservicesenter.no/climateprojections. Web portals allow for displaying additional information (e.g., more maps) than that which is presented as figures in the KiN report. This web portal displays projected changes for the mid-century period (2031–2060) and end-century period (2071–2100) relative to the reference period (1971–2000) for two emission scenarios (RCP4.5 and RCP8.5) as well as the reference period average. It also contains a few variables that have been computed after the report was issued: projected changes in days with snow depth exceeding 30 cm, and zero-degree crossings. The latter was calculated from bias-adjusted maximum and minimum temperatures (Nilsen et al., 2021). On the web, only the ensemble median is shown, whereas in the KiN report, model spread is shown using the 10 percentile, median and 90 percentile.

The bias-adjusted climate variables and hydrological simulation results (mean temperature, maximum temperature, minimum temperature, precipitaton, runoff, snow, groundwater, evapotranspiration and soil moisture deficit) for 101 GCM–RCM combinations are available as daily values for the period 1971–2100 at the 1×1 km spatial resolution. They can be downloaded from the NCCS website (nedlasting.nve.no/klimadata/kss), for two emission scenarios (RCP4.5 and RCP8.5). These data are freely available for research and other purposes in accordance with the Norwegian Licence for Open Government Data (NLOD). The whole or parts of the dataset has been downloaded by e.g., students, scientists, consulting companies and energy companies. The dataset has been applied in research projects to estimate impacts of climate change for agriculture (e.g., Haugen et al., 2019) and for societal risks (e.g., the project Klima 2050 Klima 2050, 2022).

Based on requests from users, NCCS recently created maps of projected changes that can be accessed from the web portal through an application programming interface (API). More specifically, these maps are available as figure files, through the Web Map Service (WMS) standard. This standardized technical solution has the advantage of providing the most updated version of a map automatically, without having to actively search for updates. Users such as the Norwegian Environment Agency and the Norwegian Directorate for Civil Protection can display these WMS maps on their websites. Metadata will be searchable through Geonorge, Norway's national website for map data and location information (Geonorge, 2022).

On the web portal for climate scenarios, maps of 30-year means are not presented as zoomable, interactive maps. Instead of developing yet another web portal that contributes to the abundance of information, maps will be presented on an existing web portal, http://senorge.no/, that contains state-of-the-art functionality for map presentations and data download. The senorge web portal displays gridded maps of weather and water conditions at a daily resolution and lower. This open portal is widely used by the general public and media. The web portal has been user-tested for user groups ranging from ski tourists, hydropower companies and emergency preparedness institutions as well as students and the media (unpublished internal notes). Recent developments in senorge include webpages adapted for use on mobile phones, and the availability of a subset of 30-year means (temperature, precipitation, runoff and snow). All maps are accessed from the API described above.

4.3.1. Dissemination in Collaboration With the Media (NRK)

NCCS have recently disseminated climate projections for each municipality in Norway through a collaboration with the Norwegian Broadcasting Corporation (Norwegian Broadcasting Corporation, 2020). The feature article has reached 900 000 page views and has been used as reference for reader's letters to local newspapers confronting local politicians (personal communication with the journalist, Mads Støstad, 4. November 2021). There are several examples of Norwegian climate projection being used in outreach through the media. The TV meteorologists from Norwegian Meteorological Institute have successfully communicated climate information on national television, in association with the weather forecast, where climate projections are one source of information (European Meteorological Society, 2022).

5. DISCUSSION

Here we discuss what NCCS can improve to assist in overcoming some common barriers for implementing climate change adaptation measures. We first explain how uncertainty is considered, and second, how the trade-off between robustness and precision guides the dissemination. This second point is relevant when providing more local products on a gridded or averaged scale, when allowing users to zoom in to the actual numbers in the 1 x 1 grid cell, and when giving more detailed climate change allowances. This discussion is structured around a few core requests from Norwegian climate data users and barriers that are documented as hindrances to climate change adaptation (e.g., Hauge et al., 2020; Klemetsen and Dahl, 2020). Through presentations at meetings and workshops, climate factsheets have been promoted to widely different sectors, ranging from land use planning, sewage/stormwater management, and emergency preparedness to agriculture. Whereas, advanced users often request direct access to data in formats that comply with the existing workflow of the user (e.g., time series and map formats made available through API), the non-technical audience tends to prefer simple visualizations, zoomable maps and guidance (Hanssen-Bauer et al., 2017b). When issuing data to a wider audience, NCCS has considered the trade-off between robustness and precision: a robust estimate takes uncertainties into account, e.g., by including an uncertainty range or by rounding, whereas a seemingly precise estimate under-communicates the underlying uncertainties. Advanced users request uncertainty estimates to a larger degree than less advanced users and it remains a challenge to present these uncertainties in a clear manner that can be understood by the various user groups. Uncertainties in the climate projections can be separated into i) uncertainty related to natural variability, ii) uncertainties related to future emission scenarios, i.e., which is most likely, and iii) model uncertainty related to global and regional climate models and hydrological models.

In most climate factsheets, point i) is explicitly addressed, by presenting changes between two 30-year means and smoothing decadal variations in plots. Further, climate factsheets present time series and numbers aggregated for counties. On the web portal https://klimaservicesenter.no/climateprojections, point ii) are shown by presenting the intermediate, RCP4.5, as well as the high, RCP8.5, emission scenario, while point iii) is illustrated by showing not only the ensemble median, but also the 10 and 90 percentiles. The report KiN describes these uncertainties and states that we partly cope with the uncertainties by presenting median values, for different emission scenarios, as well as intervals including 10 to 90 percentile model spread for various climate variables. In KiN, point iii) was addressed further by downscaling temperature from all available CMIP5 models by empirical statistical methods (ESD; Benestad, 2021). The median of the annual temperature projections were rather similar, and the 10 to 90 percentile spread for the most only slightly higher in the large ensemble ESD projections than in the EURO-CORDEX-based projections. This adds credit to the temperature projections. Regretfully, the ESD models for precipitation were not very skillful at the time. The KiN report states that the illustration of the uncertainty maps only parts of the total uncertainty, and that the results therefore need to be considered in relation to their application. The climate factsheets also discuss uncertainty, and recommend the use of the median model result as this is the most robust estimate given the available ensemble. Only the factsheet for Sogn og Fjordane states the model spread (point iii). On that portal, gridded precipitation and temperature is shown at a 12 × 12 km resolution.

Ideally, the climate–hydrological modeling chain should include multiple bias adjustment methods and multiple hydrological models, in addition to a large GCM–RCM ensemble. Previous studies have shown that the bias adjustment has an impact on the climate change signal (e.g., Hagemann et al., 2011), as does the choice of climate model and hydrological model (e.g., Schewe et al., 2014). The results by Schewe et al. (2014) and Hagemann et al. (2013) indicate that the choice of hydrological model impacts the results the most in water-scarce areas. This knowledge is behind the motivation of including an additional bias-adjustment method and two evapotranspiration parameterizations in the distributed hydrological model in ongoing research projects (see Section 6). However, difficult decisions have to be made regarding feasibility when it comes to the number of model setups and simulations.

Reaching out to practitioners in the target groups in a comprehensible, but non-technical manner is crucial for an effective climate adaptation because these practitioners are responsible for implementing climate adaptation measures in practice. Handling uncertainties becomes even more important when presenting results for less advanced users. Feedback from these users reveals a wish for even more tailored information, either directed toward a specific sector or with a higher spatial resolution. Surveys of climate change adaptation have found that respondents request more local and specific information than what is given in e.g., the climate factsheets (Hauge et al., 2017; Rusdal and Aall, 2019; Kvamsås et al., 2021). At a meeting with NCCS, a representative for the county governor Agder requested information for the town hall entrance, which illustrates what Neby (2019) call a seemingly "insatiable need for local information." Maps of gridded climate projections at a 1 × 1 km grid (Wong et al., 2016) are usually sufficiently detailed for research purposes, but not necessarily for local planning. In its current form, the uncertainty inherent in the climate and hydrological projections, make them unsuitable for literal interpretation when zooming to the nearest 1 × 1 km. This issue has become relevant because gridded maps will be published at http://senorge.no, which allows zooming to very fine detail. On senorge.no, precipitation and temperature is shown at a 1 × 1 km resolution. Currently, users are prevented from zooming too much, but in the future, NCCS will strive to prepare local information that will be sufficiently robust to be presented at fine resolutions.

5.1. From Regional to Local Information

Many tools and web portals present Europe-wide climate information, e.g., Copernicus Climate Change Service (C3S) Copernicus Climate Change Service, 2022), IMPACT2C (IMPACT2C, 2022), and Climate-ADAPT (Climate-ADAPT, 2022). Although they provide very comprehensive information, they are likely not being used by local practitioners in Norway, who prefer information in Norwegian (Copernicus Climate Change Service, 2017; Hanssen-Bauer et al., 2017b). Further, regional climate projections are too coarse-scaled to be used for local climate adaptation, which makes downscaling necessary.

The complex topography of Norway makes this point very relevant. For example, the highest mountain of Norway is 2469 m a.s.l. At a 1 × 1 km grid resolution, this mountain is represented with a grid cell of elevation 2260 m a.s.l. At 12 × 12 km resolution, however, the highest grid cell in the CORDEX EC-SMHI model is 1646 m a.s.l. Temperature, precipitation and thus climate variables derived from these variables are sensitive to altitude. Even though relative changes may not be sensitive to altitude, relative changes are influenced by thresholds such as the 0°C threshold. We therefore stress the need for bias-adjustment, in addition to downscaling, before hydrological modeling (Wong et al., 2016) and when analyzing absolute values (e.g., Nilsen et al., 2021). Limitations of bias-adjustment methods are being discussed in the scientific community (e.g., Ehret et al., 2012; Maraun and Widmann, 2018). Since the bias-adjustment procedure is applied to each 1 × 1 km^2 grid cell (over 320 000 in total) and to ten precipitation and temperature projections, each containing over 130 years of data, the chosen method must be computationally efficient. Empirical quantile mapping method (Gudmundsson et al., 2012) was selected because this is a method that does not assume a theoretical distribution and that corrects each variable individually. However, this type of univariate bias-adjustment method cannot correct potential biases in precipitation-temperature dependency in climate model data. In addition, the bias-adjusted datasets basically reproduce the spatial correlation structure of the climate model, and this can differ significantly from the observed one. Similar concerns can also be raised about the temporal biases that exist in the climate model outputs, such as the length of wet and dry spells.

Bias-adjustment was performed e.g., for the Swiss climate assessments (National Centre for Climate Services, 2018). Not all national climate assessments contain bias-adjusted output, however. NCCS' advice to practitioners who want to download climate projections in order to do their own calculations, depends on their application. If absolute temperature and precipitation is essential, our advice is to use our post-processed datasets; if not, our advice is to use the projections without bias-adjustment. For the interested reader, the British climate assessment provides guidance on bias-adjustment (Fung, 2018).

5.2. Municipal Averages

Norwegian counties are diverse, most counties span from coastal to high-elevation regions, which introduces a need to specify local data. Information on a municipal level has been requested and generated as average values. This local dataset provides data tailored toward a smaller area, for example, municipalities inland will not be presented with information on sea level rise. However, municipalities are also diverse; therefore, a municipal average does not necessarily solve the problem of too general information. After NCCS provided climate projections aggregated to municipalities for the feature article written by the Norwegian Broadcasting Corporation, representatives from two municipalities on the west coast of Norway commented that the information given for the historical climate did not align with their experience. The west coast of Norway is characterized by steep topographical gradients from the coast to the mountains, with most of the population located in the lowlands. An average value of all grid cells within the municipality therefore corresponds to an average altitude, and is not representative for the altitude where people reside. No inhabitant or decision-maker feels the average of a grid cell or a municipal average. One municipality having a relatively dry local microclimate objected that they were presented as being among the third wettest municipalities in Norway. When including higher altitudes into the averaging, however, this municipality does not come out as a particularly dry one. The higher altitudes within the municipality in fact include glacierized areas. When these higher altitudes are weighted in the municipal average without further comment, the result seems counterintuitive. In retrospect, an explanation of the discrepancies between what is experienced locally and simulations aggregated for a larger area would have been helpful. For the next generation of climate projections, NCCS considers aggregating results based on e.g., catchments or altitude zones. Aggregation of climate information within representative altitude zones (e.g., 0–400 m a.s.l., 400–800 m a.s.l., and above 800 m a.s.l.) is a possible way of post-processing data to provide robust estimates, not necessarily precise estimates. In addition to local information, users request more specific and detailed information (Hauge et al., 2020), e.g., tailored products and indices such as indices for heatwaves, frost in the growing season and drought. Klemetsen and Dahl (2020), however, found this barrier to be ranked as the least important among 10 barriers to climate change adaptation. Municipalities that have more experience with climate change adaptation, and thus know what to look for, ranked it higher than those with little experience. More specific information can be provided through guidance on translating climate information into action. Still, many questions from practitioners remain unanswered, for example: "What does a 4 degree warming within this century mean for ecology? How does it influence construction standards (e.g., choice of material, air conditioning) or agriculture (e.g., harvesting time, crop yield)"? Assessing the impact of a warmer, wetter climate is an active field of research, and NCCS strives to provide relevant datasets for impact research (e.g., Haugen et al., 2019 and the project Klima 2050).

5.3. Barriers to Uptake and Use of the Climate Information

5.3.1. Capacity and Resources

One of the most commonly cited barriers for climate change adaptation in Norway is a lack of capacity and resources (e.g., Rusdal and Aall, 2019; Selseng et al., 2019; Wang and Grann, 2019; Hauge et al., 2020; Klemetsen and Dahl, 2020). This is particularly true for small and medium-sized municipalities, that is, municipalities with fewer than 50 000 inhabitants (Rusdal and Aall, 2019; Klemetsen and Dahl, 2020). Since many municipalities are small, there are limited possibilities to form robust professional environments outside of the networks described above. It is commonly stated that municipal planners do not have the time or capacity to read reports, nor even to search for such literature. Providers of climate information can alleviate these challenges in capacity by providing data in a format that can be readily used in e.g., Geographic Information Systems or other planning systems, ranging from text-based to map-based and numerical services. Until now, NCCS has provided maps as .png figures on web platforms and as WMS, but plan to extend this service for the next round of KiN through co-production with users. The aim is to design a map service based on user needs and requirements.

5.3.2. Detailing of Allowances

The use of three classes for a climate change allowance for flooding (i.e., 0, 20 and 40%) rather than more precise estimates represents a strategy for simplifying recommendations for climate change adaptation. At present, guidance for the use of the classes is available on a regional basis and requires an assessment by a practitioner as to which class is most suitable for a given catchment. Amongst practitioners, there is a clear wish for a more detailed approach. NCCS are aware that more guidance is needed, and this is being addressed in other projects involving the NCCS consortium. In addition, the current recommendations do not distinguish return periods although recent work has shown this to be relevant (Lawrence, 2020), and further work is also in progress on this issue.

5.3.3. Abundance of Information

Much guidance material for climate change adaptation is available nationally and internationally. Whereas, national climate services tend to concentrate on a few climate variables (Samaniego et al., 2019), NCCS combines climate and hydrological projections, including snow, runoff and floods, with information on e.g., landslides and avalanches. Other services are more comprehensive. C3S presents an impressive web portal, visualization tool and guidance. The abundance of information can make it hard to navigate through the various alternative sources of information. In a study of guidance material for climate change adaptation in Norway, Hauge et al. (2017) evaluated 84 guidance reports and web portals. They concluded that information in the form of reports, websites and tools is abundant, but to a large degree is not used by practitioners. Having an abundance of information seems to be an advantage, but can also become a barrier when users do not know where to begin reading.

This problem can be alleviated by making the information available in formats and workflows already used by the practitioners (e.g., in APIs and Geographic Information Systems). Municipalities access public maps from the map catalog geonorge.no. WMS maps from NCCS will therefore be searchable on Geonorge when they become available. Another way of reaching the practitioner in their workflows is to continue disseminating information through popular web portals, such as http://temakart.nve.no/ and http://senorge.no/. Finally, the Norwegian Directorate for Civil Protection has developed a one-stop shop for public data on risk and vulnerability for natural hazards (https://kunnskapsbanken.dsb.no/). Ephemeral services are not of much use for long-term municipal planning. For climate services developed through short-term research projects, it would be particularly relevant to collaborate on transferring the ownership to a national database when the research project is completed. There are a few examples that short-term projects have been given a longer life time and granted long-term support and continuity by being transferred to governmental agencies (e.g., www.ovase.no). Overlapping information from different sources can result in contradictory results. Different authorities such as the public road authorities and Oslo municipality issue their own recommendations for a climate change allowance (The Norwegian Public Roads Administration, 2018). In some cases, the assumptions underlying the information and the areas for their use differ between sources, but if this is not clearly specified it can be a source of both confusion and frustration amongst practitioners. In other cases, multiple sources for information on projected climate change impacts can mislead practitioners to take into use erroneous results. For example, when studies of future changes in flood hazard are undertaken in large-scale projects (e.g., European-wide or larger), the resulting projections often indicate a future reduction in flooding throughout the country. This can result from a variety of factors, but is generally related to the simulation of snow accumulation, melting and their consequences for flood generation. This can be due to, for example, scale issues, the need for bias correction or simply the performance of the chosen hydrological model. For example, EDgE, a prototype project related to C3S, simulated too much snow under the current climate in many catchments in Norway, with the consequence that simulated flood magnitudes decrease in the future in those catchments (Samaniego et al., 2019). This resulted from a "cold" bias in the model ensemble and confirms a need for local analyses (Vormoor et al., 2015, 2016; Lawrence, 2016, 2020) and local verification, also in larger-scale projects. The web portal Climate information (Swedish Meteorological and Hydrological Institute, 2020) also disseminates information regarding projected changes in flood hazard in Norway that do not agree with local analyses. For example, if one enters the coordinates for a point located in a catchment in the northernmost region of Norway (Karasjok in Finnmark "69.47 / 25.51") the portal states an increase in the 50-year return value of annual maximum discharge. This point is an area with a significant seasonal snow cover, for which ensemble projections developed by the Norwegian Water Resources and Energy Directorate (Lawrence, 2016, 2020) clearly indicate a decreased flood hazard by the end of the century. The differences again can be due to a range of differences in the modeling and analysis setups. Nevertheless, such obvious contradictions in projections can both lead to confusion and undermine the credibility of information generated by climate services.

We therefore stress the need for national and international collaboration to avoid creating conflicting results and/or guidance as to which results are most trustworthy and reliable for different regions or sectors. We have no clear vision of this collaboration, but a few ideas are put forward here. When developing guidance material, there is much to learn from best practices and standards (e.g., ISO-14091, 2021). Different user needs range from the large-scale to local. International climate service providers (C3S) fulfill a Europe-wide need, but to fulfill a local need, these providers could benefit from a collaboration with national climate services. Norwegian users have the advantage that the Norwegian Environment Agency systematically collects and disseminates sector-specific information on their web pages (NEA, 2022). In particular, national and international climate service providers can benefit from a closer collaboration, both regarding data products and translation into local languages.

6. FUTURE WORK

An update of the report "Climate in Norway 2100" has been ordered by the Norwegian Environment Agency to ensure that the national knowledge base on climate adaptation is updated based on the most recent global and regional climate projections. Even though climate projections from the new CMIP6 ensemble are available on the global scale, NCCS requires a sufficient number of downscaled simulations from EURO-CORDEX (Gutowski et al., 2016; Jacob et al., 2020) to be available before CMIP6-based simulations can be used for new analyses. The updated report will therefore be issued in 2024. The climate community has delivered many new developments during the years since KiN was issued in 2015. In CMIP6, new Shared Socio-Economic Pathways (SSPs) replace RCPs as emission scenarios driving the GCMs. Several novel datasets will be used to describe the historical development of atmospheric variables, including a gridded dataset for wind, and an homogenized gridded dataset developed for trend studies. In addition to RCMs at the 12 × 12 km scale, simulations from a convective-permitting model will be run at finer spatial and temporal scales. These simulations are expected to increase our knowledge of climate change effects on heavy rainfall, stormwater runoff and rapid flooding in small catchments. The complexity of the modeling chain has increased since the production of the previous generation of hydrological simulations. Previously, gridded hydrological variables were simulated using temperature index methods for calculating evapotranspiration.The new generation of hydrological projections will be simulated using an updated version of the gridded HBV model, which allows for two alternate evapotranspiration schemes: the traditional temperature index method and the Penman-Monteith method (Huang et al., 2019). Hence, more climate variables need to be bias-adjusted. The bias-adjustment method is also improved, both by introducing a second bias-adjustment method, and by introducing a post-processing technique (Mehrotra and Sharma, 2019). Catchment-based simulations will apply both the HBV model used for previous work and the DDD model (Skaugen and Onof, 2014). The DDD model uses simplified energy balance methods for evapotranspiration (Skaugen et al., 2020) and snow modeling (Skaugen et al., 2018). In addition, it will be used for simulations with a 3-h timestep, with the aim of improving our estimates for climate change effects in catchments that respond quickly to rainfall (e.g., Lawrence, 2021).

New climate projections may differ from previous projections, which can pose challenges when communicating updated results. For example, the reference period has changed from 1971–2000 in KiN to 1991–2020 in the updated report, whereas the end period is 2071–2100 in both cases. The absolute value of changes can seem smaller than in KiN, because an 80-year period is used instead of a 100-year period, and the standard normal period 1971–2020 is warmer and wetter than the reference period 1971–2000 (NCCS, 2022a). Further, different emission scenarios in CMIP5 and CMIP6 are not necessarily comparable. The model ensemble in KiN had a cold and wet bias (Wong et al., 2016), and the ensembles are based on relatively few global models (both in the new and previous projections). Thus, there are reasons to believe that new climate projections may differ from the previous projections.

A separate report for sea level rise will be updated based on Simpson et al. (2015). The report is planned to be issued in 2023, and will focus on sea level, wave action, and storm surges. No new simulations are planned for Svalbard because Arctic-CORDEX simulations are not available for CMIP6 yet, and this would require a parallel production line for a different domain. Instead, a summary of CiS and a literature review of recent research will be included.

7. CONCLUSIONS AND ACTIONABLE RECOMMENDATIONS

This paper describes the production of climate factsheets in two steps, step 1: the production of background information through a climate–hydrological modeling chain used in the reports Climate in Norway 2100 (KiN) and Climate in Svalbard (CiS) and step 2: co-production of knowledge leading to the continual development of climate factsheets and dissemination of climate data from NCCS.

- NCCS' experiences in developing and disseminating climate and hydrological projections are valid for Norway, however, many experiences may be relevant for climate service providers in other countries. We propose the following recommendations:
- The trade-off between robustness and precision should guide the dissemination of climate information. Both the climate information and recommendations for their use should be understandable by a wide audience, preferably available in the local language.
- We recommend collaborating with users on developing the climate service. The first climate factsheets were developed through a multi-level governance network, and all subsequent climate factsheets have been reviewed by local representatives and later discussed in fora such as a Klimathon. If possible, coordination of the long-term operation of a service should be done in partnership with national authorities.
- Downscaling of regional climate model data for use in local climate change adaptation, as well as bias-adjustment of the climate output variables is often necessary. We recommend a strategy that involves both providing as local information as possible, but at the same time ensuring the quality of the information relative to the downscaled model simulations it is derived from. This involves considering the trade-off between robustness and precision, such as given by the example of a climate change allowance that differentiates between a small number of distinct classes, rather than detailed values which individually are highly uncertain.
- An abundance of climate information is available, which can make the climate change adaptation landscape hard to navigate between alternatives to find the most relevant and reliable sources. To guide users to the appropriate information,

it is helpful to provide data in established web portals and APIs in formats that comply with the existing workflow of the user, preferably in the user's mother tongue. We stress the need for national and international collaboration to avoid creating conflicting results and to provide guidance as to which results are most trustworthy and reliable for different regions or sectors.

Climate change adaptation measures should be implemented for buildings and infrastructure with a long lifespan. This is formulated into the following climate change principles: For buildings and infrastructure with a short lifespan, the design can be assessed on the basis of the current climate. Buildings and infrastructure that have a long lifespan are either built to withstand projected climate change or designed based on the current climate, but prepared for reinforcements later.

DATA AVAILABILITY STATEMENT

The datasets generated and analyzed for the report KiN can be downloaded from NCCS' download portal: https://nedlasting.nve.no/klimadata/kss. Results can be viewed at https://klimaservicesenter.no/climateprojections. Data for Svalbard can be provided on request.

AUTHOR CONTRIBUTIONS

HH, IN, and IH-B have authored the climate factsheets. IH-B was the main editor for both reports KiN and CiS. AD produced climate change allowances for heavy rainfall and is leading the work on updating the report KiN. WW downscaled and bias-adjusted the climate variables. IH produced gridded hydrological simulations. DL produced flood simulations and climate change allowances for floods. IN wrote the manuscript. All authors have contributed substantially to the manuscript.

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Accelerating Climate Change Adaptive Capacity Through Regional Sustained Assessment and Evaluation in Hawai'i and the U.S. Affiliated Pacific Islands

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As the impacts and risks from climate change increase, the climate assessment landscape has expanded in scope and application, resulting in the desire for more information relevant to local decision-making. Some regions lack detailed climate projections and a body of consensus findings about sector-specific impacts, and there is a need for actionable, culturally cognizant, translated climate information suitable for integration into operations and management, budgeting, funding proposals, and domestic and international policy. The Pacific Islands Regional Climate Assessment, or PIRCA, is the subject of this decade-long case study illustrating the need, development, and benefit of creating and sustaining a nuanced, collaborative, and deliberately inclusive climate assessment effort among researchers and practitioners in Hawai'i and the US-Affiliated Pacific Islands (USAPI). Using external evaluations done in 2013 and 2021, and our observations as participants in the process, we describe regional adaptive capacity challenges—an important component of the decision context for PIRCA stakeholders—and analyze the role of the PIRCA network in accelerating climate adaptation. We also examine how regional and national assessments complement each other, and how assessment processes can aid in translation to sub-national decision making across the climate science-policy interface. Results reveal components of the PIRCA that are foundational to its effectiveness: framing climate information in human and decision-centric ways; use of inclusive and non-extractive methods; willingness to shift approaches to meet stakeholder objectives; leveraging the resources of the Pacific Regional Integrated Sciences and Assessments (RISA) and other boundary organizations; taking the time to build relationships; and creating a dedicated position to sustain collaborations and relationships within the region and at larger assessment scales. Our experience and the feedback received through the evaluation suggest that these lessons are transferable to other regions and scales, and that sustained and collaborative regional climate assessments can serve a key function in complementing major national and international assessments, by translating and more effectively

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targeting information to meet local needs in support of regional climate adaptation and policymaking.

Keywords: Pacific Islands, evaluation, adaptation, acceleration, climate change assessment, co-production

INTRODUCTION

The Role of Actionable Climate Assessments in Shaping Policy, Funding Priorities, and International Negotiations

Actionable climate assessments such as the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports and the U.S. National Climate Assessments (NCA) have been critical in characterizing past climate trends and future projections and their impacts (e.g., USGCRP, 2017, 2018; IPCC, 2021, 2022), shaping emission mitigation goals (e.g., IPCC, 2014; UNFCCC Glasgow Climate Pact[1]; Hawaiʻi Act 234 and 15[2]) and setting broad research and adaptation funding priorities (e.g., USGCRP., 2012; Green Climate Fund (GCF), 2020) at global and national scales. Over the last several decades, the climate assessment landscape has evolved from mainly global and large-scale syntheses of physical mechanisms of change like those in the early IPCC and NCA products, to integrated analysis and special reports including social science and decision contexts (e.g., New et al., 2022), sectoral and regional impacts (e.g., USGCRP., 2016; USGCRP, 2018), evaluation of progress on adaptation planning and policy (e.g., Halofsky et al., 2015), mitigation pathways (IPCC, 2018), and extreme event attribution (e.g., Seneviratne et al., 2021) at smaller spatial scales (e.g., Bedsworth et al., 2018; MCC STS, 2020). There are benefits and challenges in increasing the scope and reach of climate assessments for use by regional and local decision-makers who need climate information to guide adaptation and mitigation to address rapidly emerging impacts on their communities. With the mounting financial and societal costs and risks associated with climate change, information such as climate trends and projections at finer spatial and temporal resolutions, the interactions of impacts across key sectors, and adaptation options are needed more quickly at sub-regional and sub-national, policy-relevant scales to support planning.

To accelerate the transformation of climate change science into knowledge that is useful and usable at sub-national planning scales, critical analyses of existing assessment frameworks recommend expanding cross-disciplinary collaboration, increasing the frequency of ancillary assessment products, co-developing information and tools by including information users in the assessment process, and sustaining the process using networks of both government and civil society (Lemos and Morehouse, 2005; Raes and Swart, 2007; Dilling and Lemos, 2011; Moss et al., 2019). Sustained interaction between scientists and information users, at local and regional scales, in informal networks and through climate boundary organizations can especially build trust in climate products and counterbalance misunderstanding and the perceived irrelevance of scientific information, as well as focus outputs to be stakeholder relevant (Dilling and Lemos, 2011; Wall et al., 2017; Ziaja, 2019).

Going beyond these well-established and broadly applicable recommendations, there are several unique challenges and needs in the Hawaiʻi and U.S. Affiliated Pacific Islands (USAPI) region that make effective local and regional climate assessments essential foundations for accelerated adaptation planning and implementation and for negotiations and global advocacy. Chief among them are widespread climate data scarcity, varied political classifications (**Figure 1**), spatial isolation, and the colonialism that burdens self-reliant populations and creates persistent funding inequities.

Need for Co-produced Climate Information and Translated Research to Strengthen Community Resilience and Adaptation Efforts

At an organizational level, the process of collaborating to develop "actionable" or "useful" climate research and information with regional and local managers and decision-makers has matured since the late 1990's (Pulwarty and Redmond, 1997; McNie, 2008; Prokopy and Power, 2015). As a framework, the co-production process emphasizes principles of stakeholder participation, interdisciplinarity, active communication, and relationship-building among project partners to foster trust in researchers and salience of scientific products for decision making and related social impact (Cash et al., 2003; Jacobs et al., 2005; Lemos and Morehouse, 2005; Moser, 2016). This process of scientific co-production can be used to lay the foundation for sustaining a robust assessment process (Lemos and Morehouse, 2005) that is applicable to adaptation planning in locations with differing geographies, demographics, climate impacts, decision-making needs, and sources of funding or available data. Co-production of research and assessments is becoming widely accepted—even demanded—as a methodological framework for increasing trust and use of scientific information in planning and management across different sectors (Lemos and Morehouse, 2005; Lemos et al., 2012; Meadow et al., 2015). Benefits of co-production include: integrated decision-relevant contexts from the conceptualization phase; increased representation and diversity of affected stakeholders; and creating credible policy-researcher networks that can accelerate actionable science (Dilling and Lemos, 2011; Ziaja, 2019). Co-production is useful in building a sustained local and regional climate assessment process by increasing bottom-up participation from diverse sectors of society, increasing climate literacy

[1]Advance text of the UNFCCC Glasgow Climate Pact https://unfccc.int/sites/default/files/resource/cma2021_L16_adv.pdf.

[2]HI Act 234, 2007 https://health.hawaii.gov/cab/files/2014/07/GM1005_.pdf; and Act 15 https://www.capitol.hawaii.gov/session2018/bills/GM1115_.PDF.

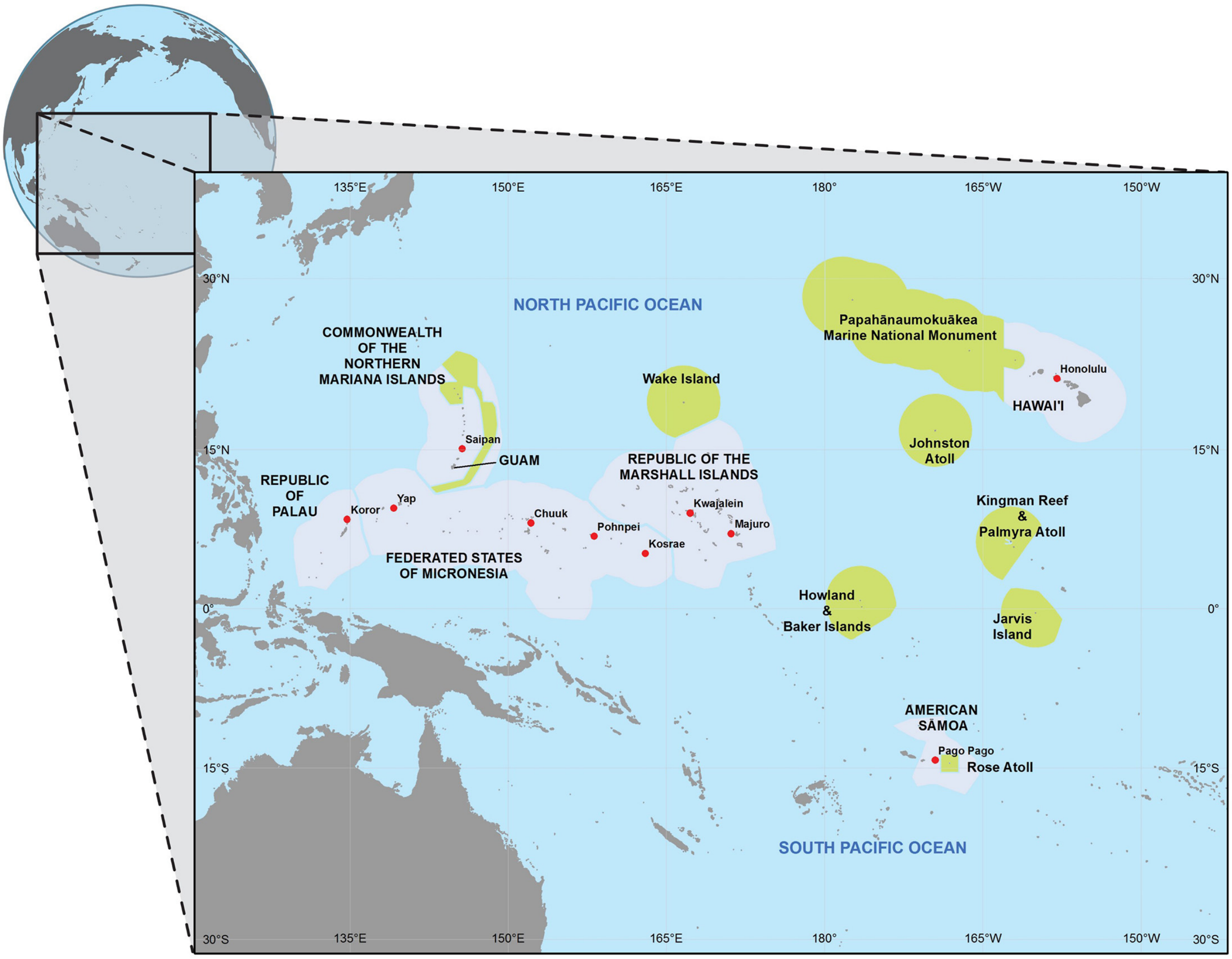

FIGURE 1 | The Pacific Islands region includes the State of Hawai'i, as well as the U.S. Affiliated Pacific Islands (USAPI): the territories of American Sāmoa and Guam; the Commonwealth of the Northern Mariana Islands (CNMI); the Republic of Palau; the Federated States of Micronesia (FSM); and the Republic of the Marshall Islands (RMI). Residents of Guam and the CNMI are U.S. citizens; those from American Sāmoa are U.S. nationals[4]. Under the Compact of Free Association (COFA), citizens of the FSM, Palau, and the RMI can live and work in the U.S. without visas, and the U.S. is obliged to provide economic assistance to COFA nations. On this map, shaded areas indicate the exclusive economic zone of each island, including Marine National Monuments (in green). [Figure from Keener et al., 2018].

and capacity in decision making contexts, establishing trust and transparency through relationship-building, and framing findings to directly address stakeholders' needs (Lemos and Morehouse, 2005; Moser, 2016; Moss et al., 2019). There are, however, also documented challenges. For instance, building such interdisciplinary science-practice relationships and networks takes time, significant human and financial resources, requires scientific data and models that match the complexity of users' environments, and is often not weighted favorably toward professional advancement in academic institutions (although this is starting to change, e.g., Purdue University tenure[3]) or in rankings of traditional research grant proposals, hindering sustaining these projects (Agrawala et al., 2001; Lemos and Morehouse, 2005; Bolson and Broad, 2013; Lemos et al., 2018; Moss et al., 2019; Meadow and Owen, 2021).

Challenges in Building Inclusive, Regionally Representative, and Sustained Assessments

There are several examples of national organizations with regional programs that utilize concepts of co-production of academic science and stakeholder participation to produce

[3]https://www.purdue.edu/provost/faculty/promotion/criteria-tenure-procedures.html

[4]Rights related to citizenship vary in the Pacific Islands. Those born in American Sāmoa and Swains Island are classified as U.S. non-citizen nationals and are not legally able to vote in federal elections or hold federal office, although they can serve in the military, have a U.S. passport, and can live and work freely in the country. U.S. citizens are also considered U.S. nationals.

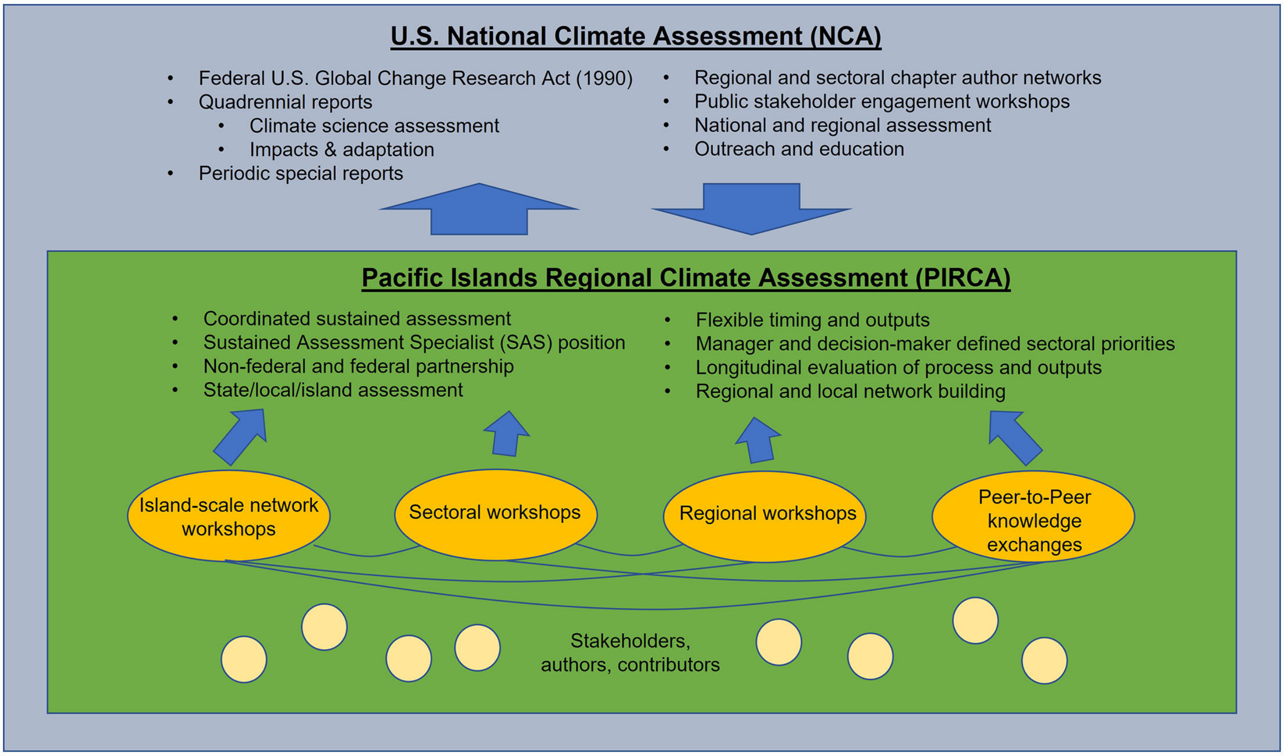

FIGURE 2 | The conceptual structure, functions, and stakeholders of the Pacific Islands Regional Climate Assessment in relationship to the U.S. National Climate Assessment (NCA), coordinated by the U.S. Global Change Research Program (USGCRP).

"actionable" environmental science, including the NOAA Regional Integrated Sciences and Assessments (RISA), Hawai'i Sea Grant, He'eia National Estuarine Research Reserve (NERR), Pacific Islands Climate Change Cooperative (PICCC, now defunct), Pacific Islands-Climate Adaptation Science Center (PI-CASC), Pacific Islands Water Science Center (PIWSC), and the Hawai'i Cooperative Extension Service, many of which have contributed significantly to Pacific Islands climate assessment products. The NOAA RISA program has been a pioneer in developing, documenting, and implementing the co-development process in climate research and assessment (McNie, 2008, 2013; Lemos et al., 2014; Parris et al., 2016; Meadow, 2017). Regionally focused and stakeholder-driven, RISAs are competitive interdisciplinary climate research programs that function as boundary organizations and span the science-policy interface. The Pacific RISA, based on the island of O'ahu, Hawai'i, serves the greater USAPI region and coordinates the Pacific Islands Regional Climate Assessment (PIRCA). The PIRCA is a collaboration of scientists, businesses, governments, and communities in Hawai'i and the USAPI founded in 2011 to inform the regional chapter for the Third NCA and create a process to exchange climate information (**Figure 2**). The PIRCA process and outputs used principles of co-production to form an inclusive network of contributors and a reliable assessment of climate knowledge for the region (Keener et al., 2012; Moser, 2013), and addressed the barriers mentioned above by leveraging coordination and human and financial resources from the Pacific RISA program, the USGCRP, the PI-CASC, the PICCC, and others, to establish a sustained assessment process. An external evaluation of the 2012 PIRCA revealed that while regional stakeholders found the network's first collaborative report highly credible and the process trustworthy, the information did not fully meet their needs, particularly in assessing sectoral impacts in the USAPI that were not addressed in-depth in the first PIRCA report (Moser, 2013).

This case study discusses the creation and ongoing activities of the PIRCA and documents its evolution through time with longitudinal external evaluations done in 2013 and 2021 (Moser, 2013, 2022 *in progress*). We analyze the climate impacts and information needs for the USAPI region, the decision context in which the PIRCA functions for a variety of regional stakeholders across different islands, the potential role the PIRCA network and reports serve in accelerating the creation of regional and local climate policy, the ways in which regional and national assessments complement each other, and identify transferable process characteristics that could be utilized to aid in translation across the climate science-policy interface.

CONTEXT: CLIMATE AND CAPACITY CHALLENGES IN HAWAIʻI AND THE U.S. AFFILIATED PACIFIC ISLANDS

The USAPI region encompasses thousands of islands, more than 300,000 square miles of land, and millions of square miles of ocean, including 50% of the U.S. Exclusive Economic Zone (**Figure 1**). The island region contains diverse geographies, climates, political classifications, cultures, languages, histories, and ecosystems that require different assessment foci and approaches that resonate with the needs of stakeholders in each location. As described eloquently in the introduction of *Indigenous Literatures from Micronesia* (Flores and Kihleng, 2019), the Pacific Islands have a complex 400-year colonial history with impacts that persist today. Starting in the 16th century, European and Asian countries and the United States successively occupied, exploited, and colonized the lands of the Indigenous peoples of Micronesia, Polynesia, and Melanesia. Hawaiʻi and Micronesia were used as important transit points, military hubs, sources of natural resources, and opportunities for European and U.S. missionaries. During these several hundred years, islands across the region were sequentially colonized by Spain, Germany, Britain, France, the United States (after the Spanish-American War), Australia, and Japan. As a consequence of colonization, the lands, waters, and people of the Pacific Islands were involved significantly in the Pacific Theater during World War II (Poyer, 1991), with resulting widespread environmental devastation and displacement of Indigenous people due to region-wide warfare and nuclear weapons testing in the Republic of the Marshall Islands (RMI) (Simon, 1997; Cocklin, 1999; Yamada and Akiyama, 2013). Following the war, American Sāmoa and much of Micronesia—as the Trust Territory of the Pacific Islands—came under U.S. administration. In the 1970's—90's, USAPI districts achieved independence with special U.S. political affiliations or became U.S. territories, ensuring U.S. military access through the present-day and economies dependent on international aid and military spending (Friedman, 1997; Overton et al., 2018). U.S. military presence in the region continues and has included construction of a missile defense system in Kwajalein, RMI, and multiple major installations in Hawaiʻi and Guam. In recent decades, Pacific Islands have been discussed in global media about climate change, with the dominant portrayal of islanders as vulnerable, frontline populations on "sinking islands" (Shea et al., 2020; Aguon, 2021) experiencing some of the most severe physical and socioeconomic impacts from anthropogenic climate change for which they bear little to no responsibility for causing. Very recently, islander-informed media narratives may be shifting toward a focus on the resilience of communities, adaptation solutions, and climate justice (Shea et al., 2020; Aguon, 2021).

Existing governance and social systems can hinder climate adaptation—planning, funding, and implementation. For example, the Commonwealth of the Northern Mariana Islands (CNMI), American Sāmoa, and Guam are ineligible for bilateral and multilateral climate finance and are excluded from UN agencies, programs, and adaptation funds (e.g., the Green Climate Fund). Meanwhile, the Freely-Associated States of the Republic of Palau, the RMI, and the Federated States of Micronesia (FSM) are systemically under-represented in regional island governance councils and are currently ineligible for U.S. Federal Emergency Management Agency (FEMA) funding. The physical realities of living on small, remote islands exacerbate vulnerabilities. For instance, Hawaiʻi has the most expensive electricity rate in the United States, and more than 85% of food is imported on most islands (Leung and Loke, 2008; Asifoa-Lagai, 2012; Keener et al., 2018). Political leaders in the Pacific Islands consistently classify climate change as their primary existential threat and advocate for aggressive mitigation policies and adaptation investment to improve regional environmental security, through, for example, the *Majuro Declaration for Climate Leadership*[5], the *Boe Declaration for Regional Security*[6], and recently, the *Kainaki II Declaration for Urgent Climate Change Action Now*[7], the strongest collective advocacy instrument issued by Pacific Islands to date to support their position at the UN Secretary-General's Climate Action Summit.

The region has historically experienced a high burden of climate disasters, sometimes resulting in wide ranging impacts to food and water security, human health, infrastructure, ecosystems, and geopolitical stability. The direct and indirect burdens of these events are often underestimated and are projected to increase with climate change (The World Bank., 2013; Keener et al., 2018). The damages resulting from weather and climate-related extremes are rarely the result of an isolated event. Rather, they are typically "compound" events, occurring in combination (Raymond et al., 2020), and with ongoing environmental, historical, and societal stresses. Recent (spatial or temporal) compound events include extreme rainfall, flooding and wildfire (Nugent et al., 2020); a particularly destructive 2018 typhoon season; land and ocean heatwaves and coral bleaching and death (Couch et al., 2017; NOAA National Centers for Environmental Information., 2020); El Niño and drought (Annamalai et al., 2015); and wave, tide, and surge events with rising sea levels (Vitousek et al., 2017). While the need for cross-sectoral climate adaptation is great, the Pacific Islands are relatively data-scarce compared to the Continental United States, and IPCC and NCA assessments are insufficient to inform island-scale policy (Keener et al., 2012; Moser, 2013; National Academies of Sciences Engineering Medicine, 2021). Although multiple international aid organizations operate within the region, there has been

[5]Pacific Islands Forum Secretariat, 5 September 2013. *Majuro Declaration for Climate Leadership*. Majuro, The Republic of the Marshall Islands. https://www.forumsec.org/wp-content/uploads/2017/11/2013-Majuro-Declaration-for-Climate-Leadership.pdf.

[6]Pacific Islands Forum Secretariat, 5 September 2018. *Boe Declaration Action Plan*. Boe, Nauru. https://www.forumsec.org/wp-content/uploads/2019/03/Updated-Brief-on-Boe-Declaration-Action-Plan-1.pdf.

[7]Pacific Islands Forum Secretariat, 11 December 2020. *Kainaki II Declaration for Urgent Climate Change Action Now: Securing the Future of our Blue Pacific*. Funafuti, Tuvalu. https://www.forumsec.org/2020/11/11/kainaki/.

limited relationship building with in-country subject matter experts, resulting in products that have not always met the climate needs of local policymakers and resource managers (Moser, 2013).

The adaptive capacity of islands when faced with increasing climate shocks and stressors is negatively affected by regional issues such as limited capacity-building, underinvestment in infrastructure, social inequality, and multiple colonial histories. In the CNMI, improper military and industrial waste disposal resulted in contaminated drinking water (Denton et al., 2014; Grecni et al., 2021). Following contamination after the impact of Super Typhoon Yutu in the CNMI in 2018, residents relied on desalinized ocean water (Gilbert, 2018). After World War II, most of Guam's population shifted from subsistence farming to a reliance on imported food (Marutani et al., 1997), which has negatively affected food security and human health. Climate impacts such as changing rainfall, higher temperatures, and more intense storms compound and hasten the decline of local crop production (Taylor et al., 2016; Grecni et al., 2020). In November 2021 on the island of O'ahu, Hawai'i, it was revealed that tens of thousands of gallons of jet fuel had leaked from the World War II-era U.S. Navy Red Hill Bulk Fuel Storage Facility's underground storage tanks into the largest aquifer supplying drinking water on the island, sickening and displacing thousands of families (Jedra, 2022). As this example shows, even in the most prosperous place in the USAPI, historical impacts decreased O'ahu's freshwater resilience in the face of continuing drought (Frazier and Giambelluca, 2017) and reduced Hawai'i's future ability to provide freshwater in an emergency and protect water resources—as mandated in the State Constitution—for domestic and Native Hawaiian traditional and customary uses. While downscaled climate projections and other data are needed for adaptation projects, science and data alone do not address the systemic and structural dimensions needed to successfully adapt (Finucane, 2009), and some normative co-production processes can reaffirm traditional boundaries when actors assert the dominance of Western science and reinforce notions that it is superior to other forms of knowledge (Daly and Dilling, 2019). Four-hundred years of colonialism in the region that exploited the islands for their strategic military value, resources, trade location, and other extractive purposes resulted in communities with limited capacity and a culture of drop-in consultants and researchers (Finau et al., 2000; Braun, 2021; Lett et al., 2022). These complex issues require a different approach to co-producing useable climate information that is non-extractive, culturally cognizant, flexible enough to incorporate different modes of interaction, centered around relationships and storytelling, transparent, iterative, and inclusively co-developed with resource managers and local governments to foster collective ownership and shared understanding (Amitage et al., 2011; Daly and Dilling, 2019; Aguon, 2021). In fact, assessments anywhere must consider the unique geographical, historical, and cultural contexts if they are to make useful contributions to decision making.

THE PIRCA, KEY PROGRAMMATIC ELEMENTS, AND RESULTS

The Second PIRCA: Key Elements of Assessment Co-development

Since its inception more than a decade ago, the PIRCA has incorporated feedback obtained from external evaluation to shape the ongoing assessment process and network's growth and inclusion of new expertise and areas of focus. As a result, the expertise and topic areas that the PIRCA includes were diversified in the most recent round of assessments. A frequent appeal by those interviewed and surveyed in the 2013 evaluation was to update the PIRCA regularly, incorporating new topics, including identifiable trends in top priority impacts on key economic sectors and human security, adaptation options and costs, and cultural impacts (Moser, 2013). Moreover, respondents to the first PIRCA, which was still Hawai'i-centric, wished for jurisdiction-specific assessments. The PIRCA coordination team recognized that to fulfill these needs, a new full-time "Sustained Assessment Specialist" (SAS) within the region was crucial, and found financial resources from multiple partners to fund the position through the Pacific RISA.

As a result of this feedback, the foci, author structure, and processes for assessment development have evolved. The most recent round of PIRCA assessments produced the Hawai'i and U.S. Affiliated Pacific Islands regional chapter of the Fourth NCA (Keener et al., 2018), as well as island-specific assessments for Palau (Miles et al., 2020), Guam (Grecni et al., 2020), the CNMI (Grecni et al., 2021) and American Sāmoa (Keener et al., 2021). Other reports for the RMI, the FSM, as well as the initial work for the regional chapter of the Fifth NCA are in progress as of this writing. While technical writing teams for the 2012 PIRCA were mainly subject matter experts from Hawai'i-based academic and federal government institutions, the 2020–2021 PIRCA authorship varied by jurisdictional report and was split between Hawai'i-based academics and specialists in local NGOs and governments residing in each jurisdiction. Additionally, between 25 and 50 practitioners from a wide range of management sectors were credited as Technical Contributors for each assessment. The changes in assessment characteristics in response to feedback between the first and second PIRCA, and the status of those same elements in regional contributions to recent U.S. NCAs, are presented in **Table 1**. Authors and Technical Contributors attended a workshop in their jurisdiction, which the PIRCA coordination team planned and organized in partnership with local co-authors and key points of contact from government, higher education, and NGOs (**Figure 3**). In proximity to the workshops, members of the PIRCA coordination team met with a few Technical Contributors for more in-depth conversation on key topic areas for which they had unique expertise. These meetings were *ad-hoc* or opportunistic and were arranged in connection with planning for or facilitating the local workshops (**Table 2**). Following those workshops or meetings, Technical Contributors were invited to continue refining the PIRCA report for their jurisdiction in an iterative process of reviewing drafts of

TABLE 1 | Key differences in characteristics of the first and second PIRCA, and the status of the same elements in regional contributions to recent U.S. NCAs.

Assessment	Author structure and composition	Main foci or topics	Development process (key elements)
First PIRCA (2012)	Hawai'i- and U.S. Continent-based authors and contributors (academic and federal roles)	Physical impacts (e.g., freshwater and drought, sea-level rise and coastal inundation, ecosystem impacts)	Workshops in Hawai'i, involving authors and technical experts; author drafting; review by science advisory committee
Second PIRCA (2020–2021)	USAPI- and Hawai'i-based authors (academic, USAPI government, and NGO roles); 25–50 locally based contributors per assessment	Human- and decision-centric topics (e.g., climate indicators; climate-risk management; considerations for households, families, and vulnerable populations; considerations for key sectors; research and information needs)	Workshops and meetings in USAPI, involving stakeholders in variety of sectors and roles (govenment, NGO, business, and academic/research); iteravite draft development among authors and technical contributors; review by advisory committee with diverse expertise
Third NCA, Hawai'i and Pacific Islands chapter (2014)	Hawai'i-based lead and convening authors; 7 contributing authors	Ocean changes, coral reefs, and fisheries; freshwater supplies; terrestrial ecosystems; sea-level rise and coastal infrastructure; human migration	Technical input report development (PIRCA 2012) and workshops; Author chapter drafting; advisory committee review; pubic and expert review; federal agency and White House review
Fourth NCA, Hawai'i and USAPI chapter (2018)	Hawai'i-based authors; 77 technical contributors, majoirty Hawai'i-based, and a small number from USAPI	Water supplies; ecosystems and biodiversity; coastal communities; marine resources; Indigenous peoples; cumulative impacts and adaptation	Public engagement workshops (1 in Hawai'i; 1 in Guam); sectoral workshops hosted by author team; author drafting; federal agency, public, and expert review
Fifth NCA, Hawai'i and USAPI chapter (forthcoming)	USAPI-, U.S. Continent-, and Hawai'i-based authors; USAPI and Hawai'i-based technical contributors (TBD)	TBD	Regional Engagement Workshop (1 for Hawai'i and USAPI); sectoral workshops hosted by author team; author drafting; federal agency, public, and expert review

the assessment, and the PIRCA coordination team tracking and responding to all comments.

The PIRCA workshops were structured to be accessible to managers and decision-makers across a range of sectors, and to elicit feedback on an early draft of the PIRCA report to further develop the content. The PIRCA workshops linked participants to the U.S. NCA process by presenting findings from the Fourth NCA and describing a sustained assessment process in which local and regional assessments gather and synthesize climate knowledge and inform the national assessment.

Evaluation Methods

To assess how the ongoing PIRCA process is evolving and responding to expressed stakeholder needs, we conducted an evaluation between Fall 2021 and January 2022. It involved data collection from two principal sources: a survey and interviews with assessment participants and beneficiaries.

The survey was sent to a database of 222 individuals across Hawai'i and the USAPI. Respondents were approached by email; 22 of those emails were no longer functional (resulting in an actual n=200). The 29-question survey was open between October 13 and November 30, 2021 and received 60 responses—an excellent response rate of 30% in an email- and social-media saturated world during the COVID-19 pandemic. The majority of respondents were based in Hawai'i, but all jurisdictions for which the Fourth NCA chapter and PIRCA reports had been prepared were represented, as well as a few Continental U.S. respondents.

The survey questions were prepared by Moser in collaboration with the Pacific RISA team (inluding Keener and Grecni) (see survey instrument in **Appendix 1**) and focused on the Fourth NCA chapter and the jurisdictional PIRCAs, inquiring about people's involvement and contributions, their perceptions of the report's relevance, usefulness, legitimacy and credibility; the uses of the report; future assessment needs; and for respondents who knew of the first PIRCA, about improvements made based on the feedback received from the evaluation conducted in 2012–13.

Following the survey, the evaluation also involved in-depth interviews (conducted by Moser) with selected assessment contributors and observers. The Pacific RISA team provided a prioritized list of 38 potential interviewees, including representatives from all jurisdictions and the Fourth NCA chapter[8]. Of these, all the "very high" and "high" priority interview candidates (28 individuals) were approached and 21 individuals representing all PIRCA jurisdictions and the Fourth NCA chapter responded favorably and were interviewed. One interview was discontinued (due to an inability to address interview questions during a local crisis). The remaining 20 interviews were completed, with interviews lasting on average 56 min (range 27–92 min). Given the time since some portions

[8]Prioritization was done by Keener and Grecni and was based on factors such as individual's (1) direct involvement in either the Fourth NCA chapter or regional assessments as an author, contributor or reviewer; (2) direct involvement in an assessment-related workshop or event; (3) position in local government or other key decision-making bodies that is likely to have knowledge of the assessment; or (4) position in the federal government with direct knowledge of the PIRCA contribution to the NCA.

FIGURE 3 | The 2019–21 PIRCA workshops and reports explored climate change impacts and responses in U.S. Affiliated Pacific Islands. Photos on the left illustrate example climate-related impacts: **(A)** Heavy rains that produce flooding, as pictured here in Nu'uuli, American Sāmoa, become more likely as the climate warms (Photo courtesy of Valentine Vaeoso). **(B)** Human-ignited wildfires burn a sizable portion Guam's land each year. Dry conditions increase the potential for wildfire on tropical Pacific Islands, and total acres burned tends to be higher in the year following an El Niño event (Photo courtesy of Guam Department of Agriculture, Forestry Division). Pictured on the right are PIRCA workshops and events: **(C)** participants of the CNMI workshop; **(D)** participants of the Palau workshop; and **(E)** members of the PIRCA team with Guam's Lieutenant Governor and Co-Chairs of the Guam Climate Change Resiliency Commission (photo courtesy of the Pacific Islands Climate Adaptation Science Center).

of the the assessment were completed, the consistency of insights gained, and based on responses from those who were approached but declined to be interviewed suggested that additional interviews would likely not yield more useful information. Thus, the lower-priority individuals were not approached. Interviews were semi-structured, recorded, and detailed notes were taken, then analyzed for themes. Recordings were destroyed after the analysis. Some interviewees also sent written follow-up notes or documents mentioned during the interviews.

The interview questions focused on nine topics (see interview protocol in **Appendix 2**), including background of the interviewee, participation in the Fourth NCA/PIRCA, uses of the Fourth NCA outputs by stakeholders/decision- and policy-makers (at local/state and federal U.S. levels), impacts of greater inclusiveness in the Fourth NCA vs. the first PIRCA, perception of the inclusive stakeholder participation at the national level, the value of the Sustained Assessment Specialist position, other information sources for decision-makers, barriers to building greater resilience through adaptation, and emerging needs. The interview protocol was reviewed and agreed to by the Pacific RISA staff. Both the survey and interviews were determined to be "exempt" human subjects research by the East-West Center's IRB.

Evaluation Results

Familiarity, Interest, and Perceived Relevance, Legitimacy, and Credibility

A very large majority of survey respondents (>90%) and all interviewees were closely familiar with the Fourth NCA Pacific Islands chapter (released in 2018) and the jurisdictional reports (released between 2020 and 2021) - a similarly high level of awareness as was found in the evaluation of the first PIRCA. At the time of the survey, respondents confirmed that they had either heard of, read, or scanned and remembered various parts of those assessments. Of greatest interest to survey respondents in the Fourth NCA chapter were the Executive Summary, the section on coastal communities, and the section on adaptation. Those familiar with the jurisdictional PIRCA reports found the sections synthesizing key issues for managers and policymakers; implications for families, households and vulnerable populations; implications for vulnerable sectors; indicators of climate change; and on managing risks in the face of uncertainty of greatest interest.

The framing of climate change challenges in human- and decision-centric ways in the jurisdictional reports is in and of itself notable. This constitutes an innovation in response to the 2012 report (and thus does not allow for a direct

TABLE 2 | PIRCA assessment workshops including dates, locations, conveners, and expertise represented held in each jurisdiction in 2019.

Date of workshop	Workshop location	Co-hosting partners	Expertise of participants (academic or practice)
June 10, 2019	American Sāmoa Community College, Pago Pago, American Sāmoa	American Sāmoa Community College	Agriculture, coastal management, coral reef research and management, education, environmental protection, historic and cultural resources, natural resources management, public works, utilities, water management, weather forecasting
July 23, 2019	Palau National Marine Sanctuary headquarters, Koror, Palau	Republic of Palau Office of Climate Change	Agriculture, coral reef research, cultural resources, disaster management, economic development, ecosystems, energy systems, fisheries, human health, infrastructure planning, tourism, utilities
July 30, 31, 2019	Saipan, CNMI	NOAA Office for Coastal Management and CNMI Bureau of Environmental and Coastal Quality	Agriculture, coastal resources management, education, extension, fish and wildlife management, public health, natural resources management, parks and recreation, planning and development, policy and governance, public works, ocean ecosystem research and management, utilities
October 29, 2019	Governor's Complex, Adelup, Guam	Guam Climate Change Resiliency Commission; Pacific Islands Climate Adaptation Science Center; Guam Bureau of Statistics and Plans; University of Guam	Climate science, climate vulnerability assessment, climate and weather forecasting, coastal and ocean resources management, cultural resources, energy systems, environmental protection, homeland security/civil defense, nature conservation, planning, public advocacy, water and environmental research, water management

comparison of different parts of the assessment between the first and second PIRCA reports). Survey respondents found the sections they reviewed "somewhat," "very," or "extremely" useful. Leading in this regard were the sections on the implications of extreme weather and climate events for key sectors (96.7%); and on families, households and vulnerable populations (90.6%); followed closely by the key issues for managers (90.3%); climate change indictors (90.3%); and managing climate risks in the face of uncertainty (87.1%).

In write-in answers, respondents hinted at why and for what the reports were useful, including having an audience-tailored, concise, peer-reviewed summary and explanation of climate change trends and impacts for funding requests, policy briefings, education, and communication/outreach. This finding is completely consistent with the first PIRCA report. However, in comparing what respondents got out of the first (less detailed) vs. the second (jurisdictionally specific) PIRCA reports, they were six times more likely to agree than to disagree that the jurisdictional PIRCA reports provided more regionally specific climate information and more specific risk information on issues relevant to their work, and 5.7 times more likely to agree than disagree that the second PIRCA provided more information on what can be done to adapt to climate change. The few who indicated that any report sections were not useful to them either were already familiar with the issue or restricted that judgment to the less relevant synthesis of global climate change.

The legitimacy of the PIRCA process appears to also have boosted the use of the reports by decision-makers in Pacific Island jurisdictions. First, interviewees appreciated the deliberate, careful and respectful approach to co-designing the assessment process. Being mindful of not overtaxing individuals, strategically timing workshop events, respecting local culture, and working closely with island points of contact to identify all relevant stakeholders was viewed as a key ingredient in people joining the effort and viewing it as "with and for them" rather than "about them" (i.e., a non-colonial, non-extractive approach to co-design). Moreover, the engagement of practitioners and climate change professionals in the development of the assessment, particularly in identifying impacts, future risks, and adaptation options, provided the structured opportunity for authors and technical contributors to review new information regarding how the changing climate is affecting, or is expected to affect, their area of purview or expertise. As a result, assessment participants were eager to apply information gleaned through the assessment even before the reports were published. Soon after the workshop in Palau, for example, the National Office of Climate Change contacted the PIRCA coordination team to request use of the draft PIRCA in a funding proposal to support the development of the National Adaptation Plan. Familiarity with the range of experts involved in informing and producing the report also appears to have driven trust in the product among participants. Interviewees, for example, thought "all the right people were at the table." But even among the broader survey population, 86.3% of respondents felt the development of the assessments was "highly," "very" or "somewhat legitimate" (this question was not asked in the 2012 survey).

The majority of survey respondents also found the Fourth NCA regional chapter and jurisdictional reports highly credible. More than 72% of respondents found them "very" or "extremely" credible, with <2% disagreeing with that judgment – a perception of credibility nearly as high as in the 2012 PIRCA report (although the question was asked slightly differently and had fewer levels to choose from, so can only be compared with caution). Representative of many study participants, one noted, "I now have [a] credible reference document I can use in my work and studies that talks about my island home." Others found it particularly important to have such a credible report in use with policymakers. That said, some 17% of respondents couldn't judge the assessment in this regard – suggesting maybe some opportunities to convey the qualifications of assessment participants more directly in the future.

Process Benefits

Survey respondents and interviewees appreciated their participation in the assessment beyond the involvement in co-designing the stakeholder workshops. Those involved in shaping the engagement opportunities felt deeply respected and were pleased with what was achieved. Noting that "many make the mistake of not connecting with local people," the fact that Pacific RISA did was considered foundational for the assessments' conduct and successful delivery. In addition, most survey respondents (71.4%) who participated in those events as contributors to the assessment found them at least "somewhat," "very," or "extremely valuable." (This is a slightly higher level of appreciation of these events compared to a similar, but not identical question asked about the outreach around the first PIRCA report, thus allowing comparison only with caution.) More than half of the respondents (57.1%) appreciated them as opportunities to learn from others what they are doing to address climate change; 53.6% found them valuable as opportunities to ask questions of experts; and 50%, respectively, also found them useful as opportunities to learn about adaptation, network with others, and simply be in dialogue with people about what to do. One interviewee found the workshop in their jurisdiction to be "one of the best we ever had." Experts involved in the process were glad to not just share knowledge, but also correct any information from the larger regional assessment that did not apply to their particular jurisdiction, while yet others were glad to have a forum for difficult but important conversations to occur. As one put it, "It's a chance to force these necessary conversations with local decision-makers."

The educational value of those stakeholder engagement events, together with the information contained in the reports, cannot be overestimated. More than 62% of survey respondents noted that they now have a better understanding of what climate change means to their region, and 26% felt they can now take climate change into account in their work. As such, the participation in the process, connecting with peers, and having jurisdiction-specific information at their fingertips, illustrates that the assessment was perceived as empowering. "I have useful recommendations to inform management and policy decision making."

Interviewees also spoke to another aspect of the assessment process, particularly those who had been involved in prior assessments and who had a keen understanding of the often-extreme capacity constraints in the USAPI. Uniformly, interviewees saw the value of having dedicated staff (a "Sustained Assessment Specialist," SAS) assigned to support the assessments as "critical." Particularly in a region that thrives on good relationships, having someone focused on building relationships was seen as foundational. Many interviewees were aware and deeply appreciative of the range of tasks undertaken by the SAS, including extensive outreach to obtain robust input, communication, "cat herding," editorial assistance "down to the semi-colon," finding needed data, identifying gaps in contents, and so on. One emphatically called the SAS "integral to the success of the Fourth NCA."

Evidence of Use of the PIRCA for Practical Decision-Making in a Changing Climate

Stakeholders have used the jurisdictional assessments when writing proposals for climate-related finance, communicating with the public and their peers, proposing and developing new law and policy, and integrating the information in management plans. We mention just a few examples here. As noted earlier, the PIRCA report for Palau serves as a technical resource in the development of the National Adaptation Plan. In Guam, meetings with legislators, legislative aids, and consultants to review NCA and PIRCA findings informed new legislation. Inspired by an adaptation option presented in the Guam PIRCA, one successful bill in the Territorial Legislature passed a statute that created the Tumon Bay Insurance Task Force, to be comprised of representatives from across the government of Guam, to examine the prospect and evaluate the feasibility of parametric insurance for the beaches and corals reefs of Guam's Tumon Bay (Kaur, 2020a; Public Law 35-107, 2020; Limtiaco, 2021). Other new laws prohibited the burning of forest land and established a task force to explore the possibility of establishing conservation areas on select Guam Government properties that overlay the Northern Guam Lens Aquifer to protect the island's main freshwater aquifer, considering future drought projections (Kaur, 2020b; The Office of Sen. Sabina Perez Bureau of Statistics Plans' Guam Coastal Management Program., 2020; Public Law 35-134, 2021; Public Law 35-141, 2021). A training for territorial government staff, held prior to the update of American Sāmoa's Hazard Mitigation Plan, highlighted the PIRCA assessment as a resource and invited a coordination team member to present on climate-sensitive hazards detailed in the assessment.

Actors in government, including Guam Governor Lou Leon Guerrero (Pacific Daily News Staff., 2020), publicly acknowledged the PIRCA's role in informing policy, revealing key climate change issues, and providing consolidated, relevant knowledge for local decision processes. Palau's National Climate Change Coordinator said of the Palau assessment, "This report provides a glimpse of key issues... it serves as a guide with suggestions to enhance our resilience to climate change" (NOAA Climate Program Office, 2020). Shortly after the release of the assessment for the CNMI, the report's lead author testified as an invited expert witness in a Full Committee Hearing of the U.S. House Committee on Natural Resources regarding the Insular Area Climate Change Act (H.R. 2780), which proposed new federal programs for climate change adaptation and mitigation for U.S. Insular Areas (U.S. Congress, House, Committee on Natural Resources, 2021).

DISCUSSION

Acceleration of Information Uptake for Adaptation Decision-Making

Recent PIRCA activities demonstrate how regional assessment efforts can accelerate the flow and application of information from larger national and international climate assessments into local-level decision-making by relating key findings to local context and consolidating relevant information. In the case of the PIRCA, jurisdiction-specific assessment co-production processes helped to counter the information-overload effect and perceived irrelevance of national and international assessments by providing structure for climate researchers (some authors of the larger assessments) and local managers to review the larger assessment findings, examine their local implications in the context of key sectors, and together distill the salient knowledge for decision-making. In workshops, participants questioned the "experts" about levels of uncertainty, leading to better understanding among the group about points of consensus and factors contributing to remaining uncertainties.

The regional assessment also strengthens national and international climate assessment processes. Resource- and place-specific details captured in the PIRCA reports make the information available to a wider decision-maker audience, and to the NCA, IPCC, and other regional and international assessments that have historically not had access to fine-grained knowledge of local climate risks and adaptations. By delivering nuanced, place-based assessments in between the NCAs, regional assessment efforts can serve a key role in an integrated and sustained national assessment program (such as envisioned and described by Buizer et al., 2016).

One value of the PIRCA products to decision-makers appears to be the ability to use a single report as a resource and reference document for climate change information. One participant summarized this valuable function, saying, "Before we had the PIRCA, we had to piece together the information from other reports... so time-consuming." While various climate reports, documents, and peer-reviewed literature exists for each place, the time and capacity required to comb through it for relevant information can represent a significant barrier to timely fundraising and addressing climate change in policy and management situations. Both interviewees and survey respondents confirmed that having a consolidated state-of-knowledge helps to facilitate and accelerate the use of climate information for planning by managers without specific expertise or extra time. Meanwhile, participatory co-development of the reports meant that some decision-makers across government and NGO sectors were already familiar with, and trusted, the basic structure and content, making fact and information-finding easier.

Working in an assessment context outside of the Continental United States necessitates a nuanced approach that differs from, and can complement, that more commonly used in the NCA and international climate assessments. As a crucial point of departure, well-established multi-state and country assessments have traditionally placed a large emphasis on the findings of peer-reviewed articles and expert consensus; however, a dearth of published data and literature in the USAPI led the PIRCA team to rely on partnerships with local researchers and practitioners, in NGOs, government, and academic institutions, to source relevant data, traditional knowledge, and recent research findings, much of it "gray literature" or not yet published. Workshop discussion sessions allowed an informal prioritization of climate issues in terms of locally perceived levels of risk and consequence, and to understand, if only anecdotally, the climate impacts and risks not yet scientifically documented. Even in regions where relatively more published literature and data exist, the inclusion of local and traditional knowledge can imbue assessments with greater legitimacy and credibility among local stakeholders and allow frontline communities to enter policy discussions by bringing their own words, experiences, and forms of knowledge into decision-making spaces where they are often absent (Daly and Dilling, 2019; Davis and Ramirez-Andreotta, 2021). The PIRCA use-cases further demonstrate that bringing together various actors who hold different knowledges can promote social learning, shared understandings, and "collective ownership" (Amitage et al., 2011). Subnational assessment efforts, in their participatory development, can foster these critical functions, which are needed across all U.S. regions if adaptation is to increase.

Interviewees pointed to an important impact of the Fourth NCA Pacific Islands chapter on the overall NCA process in this regard, which can be read as an aid in the acceleration of information provision and uptake. Following the urging of one of the Fourth NCA convening lead authors, the USGCRP formally accepted Indigenous knowledge (only available in the oral tradition) as equivalent to scientific knowledge without having to be peer-reviewed. In a scientifically data-scarce and capacity-limited region such as the small-island states in the Pacific, much long-term observational information would have to be ignored if it could only be included in an assessment once it is reflected in the peer-reviewed literature. Thus, getting local and traditional ecological knowledge accepted as valid and equivalent to scientifically acquired knowledge has helped speed up the assessment process and address issues of knowledge-equity in climate adaptation planning. Combining it with the available scientific information in one report, the time to information use is significantly reduced.

Adjusting Assessment Methods to Resonate in Different Geographical Contexts

In each of the jurisdictions, PIRCA engagement linked directly or indirectly with local governance and policy entities by, for example, aligning outreach with the launch of the Guam Climate Change Commission and co-hosting a workshop with Palau's National Office of Climate Change. The format and timing of workshops adapted to fit into partners' already planned convenings and were sometimes "nested" within broader meeting agendas. The underlying logic for the adaptable workshops approach was twofold: (1) to avoid burdening over-tapped stakeholders who participate in many, often overlapping, planning and input activities; and (2) to embed the final assessments within, or have direct relevance to, local governance frameworks and processes. This points to the notion of a "sustained assessment" that aims at building ongoing relationships between researchers/assessors and practitioners (Moss et al., 2019), rather than a "stop-and-go" approach more common in the NCAs. Ongoing relationships may limit the repeatedly needed intense ramp-up of stakeholder relationships, and also avoid drawing on the same stakeholders again and again. This is a lesson that applies widely to other NCA regions, given the frequently mentioned challenge of "stakeholder fatigue" (e.g., Cooke and Kothari, 2001; Reed, 2008; Chu et al., 2016).

That the PIRCA is a network does not imply that the engagement and co-production model is merely replicated across all jurisdictions. Interviewees repeatedly noted how the Pacific RISA team understood the need for such a nuanced approach, banking on the cognizant leadership of local contacts to frame the assessment and navigate local politics. Those relationships then enabled engagement with groups that is respectful of local culture and customs, which differ among jurisdictions. The team made decisions on the process and products that intentionally aligned with local culture, language, technology use, and values, for example translating a summary into local language (Samoan), structuring daily agendas to include cultural protocol and meetings with dignitaries or elders, and inclusion of meals with appropriate foods at workshops. A focus on key sectors, both in the structured engagement and the assessment reports, rather than the drivers of climate change impacts, further emphasized the relevance of the assessments to the stakeholders' governance and management responsibilities and purview. Regional and local climate assessment efforts that shift their methods or approach to meet the objectives and fit into the agenda of decision-making bodies may go farther in their quest for user uptake than those efforts that remain detached from local governance.

Assessment and Learning Networks as Climate Boundary Organizations

Trust in the Pacific RISA as a boundary organization and as a central player and coordinator of the PIRCA had already been built in the years leading up to the most recent round of assessments (Moser, 2013). Boundary organizations provide a distinct and helpful interface for the exchange between science and policy or practice, with accountability to both sides, and critical translating, negotiation, and interface management functions (Guston, 1999; Gustafsson and Lidskog, 2018; Ziaja, 2019). While the design of the interface varies, boundary organizations as formal networks facilitate the exchange of climate information in quickly-evolving contexts and in more informal networks (Ziaja, 2019), such as the PIRCA. The evaluation of the Fourth NCA regional chapter and jurisdictional PIRCA reports suggests that the central role of Pacific RISA has only been solidified, as the lead coordinators and authors have in many cases become the initial contacts for decision-makers seeking trusted climate information on a short timeline or interested in proposing a project to meet a local need. Pacific RISA works actively and swiftly to connect researchers with practitioners while responding to requests and questions as a trusted source of climate information. Thus its partners learn and can build up their capacity to address climate change; in turn, Pacific RISA staff learn from local partners about the realities and challenges on the ground, which informs its research agenda, and the conduct of assessments. As one interviewee concluded, "If they continue [this careful approach to assessments] with NCA5, they [Pacific RISA] will become a real flagship in the Pacific.... like SPREP for disasters"[9].

In considering the success of the Pacific RISA as a regional boundary organization effective in the NCA, a critical factor—as described above—was a dedicated and full-time science-policy boundary spanning position, the Pacific Islands SAS (NOAA Regional Integrated Science Assessments (RISA) Program, 2021). The role of the SAS was central to building relationships and maintaining the PIRCA networks in the region over years, assessment products, and as partner organizations and administrations came and went, and is a necessary role for assessment success that can be transferred across regions.

CONCLUSION

The PIRCA is a decade-long case study illustrating the need, development, and benefit of sustaining an iterative process of building trusted relationships as the all-essential foundation for a collaborative climate assessment effort with researchers and practitioners in Hawaiʻi and the U.S. Affiliated Pacific Islands. Because of the expansive area, diverse cultures and geographies, colonial histories, and variation in the availability of peer-reviewed literature and data, a nuanced approach to climate assessment was used that considered expertise, information, context, and outputs needed at different island scales. Regional and local climate assessment efforts that shift their methods or approach to meet the objectives and fit into the agendas of decision-making bodies in our experience go farther in their quest for user uptake than those efforts that remain detached from local governance and historical context.

Recent PIRCA activities demonstrate how regional assessment efforts can accelerate the flow and application of information from larger national and international climate assessments into local-level decision-making by relating key findings to local context and consolidating relevant information. In defining itself as a collaborative climate science boundary organization with a dedicated Sustained Assessment Specialist to coordinate and build relationships, the PIRCA is growing as a go-to trusted resource and as a network of actors that is essential for translating rigorous climate research and multiple forms of knowledge into relevant management and policy outcomes at local and regional levels. Our experience and the feedback received through the

[9]SPREP, the Secretariat of the Pacific Regional Environment Programme, is a well-known intergovernmental organization headquartered in Apia, Sāmoa (see: https://www.sprep.org/about-us).

evaluation suggest that sustained and collaborative regional climate assessments can serve a key function in complementing major national and international assessments, by more effectively targeting information needs at local and regional climate adaptation and policymaking.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The study involved human participants and thus were reviewed and approved by the East-West Center IRB. The study was found to be exempt, and thus participants were not required to provide their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

VK and ZG conceived of the case study presented. VK developed the initial theory and established the framework, and ZG expanded upon and coordinated the project. VK, ZG, and SM planned the evaluation approach and developed the survey and interview questions collaboratively, integrated evaluation findings into the PIRCA process and products, and co-wrote the manuscript and provided critical insight into the findings. SM collected, analyzed the survey, and interview data. 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.2022.869760/full#supplementary-material

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Water AND Heat: Intervening in Adaptation Hazard Bias

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After centuries of adapting to coastal living, increases in stormwater and tidal flooding events, along with projected sea level rise, led Charleston, South Carolina, USA to define flooding as an existential threat to the city. With billions of planned flood management projects underway, and additional billions of federal disaster flood recovery funds allocated to the State of South Carolina, the Governor's office established a South Carolina Office of Resilience in September 2020, with a focus on water management. The City of Charleston developed its own Flooding and Sea Level Rise Strategy. Simultaneously, the fourth National Climate Assessment pointed to heat health risks and projected costs of lost labor productivity concentrated in the Southeast, yet local recognition of heat as an equivalent threat to flooding was not apparent. Although Charleston's All Hazards Vulnerability Assessment included extreme heat as a significant hazard, without a group focused on heat, ongoing work in the city continued to prioritize water management as annual flood events rapidly escalated. This narrow adaptation framing was further solidified as funding focused on flood recovery and adaptation and technical experts worked within water-related boundaries. These interacting forces led to Hazard Bias, an inherent organizational process of reinforcing focus on a single hazard in the context of compound, complex hazard risks. To adapt to increasing heat, Charleston will need to raise compound risk awareness and adjust its capital investments in resilience to be inclusive of heat mitigation and adaptation as well as water. Yet in 2020 Charleston lacked basic urban heat data, technical expertise, and a strong source of motivation to develop a prioritization approach for recognizing multiple risks and complementary adaptation opportunities in those investments. Recognizing the inherent bias, a new coalition of heat researchers, practitioners, and health experts launched a tripartite heat-health research program and spurred the development of a new heat network in Charleston. The network reduced hazard bias by raising heat-health risk awareness and by intervening in adaptation planning to broaden water-only considerations to be inclusive of water AND heat. This paper provides a detailed case study how the intersections of multiple networks, messengers, and messages contributed to broadening the local resilience agenda from a "hazard bias" and how the lessons learned during this transformative process further reveal health inequities.

Keywords: hazard bias, climate adaptation, extreme heat, health inequities, flood management

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INTRODUCTION

Charleston, South Carolina, centered on a peninsula at the confluence where the Ashley and Cooper Rivers join the Atlantic Ocean, is one of the oldest cities in the USA. For its 300 plus years, the rivers and ocean have been obvious dominant physical influences in where and how the city developed. The battery walls were constructed to protect the lower part of the peninsula from the ocean waves; low-lying areas were filled to create more space to build, and a major port connected Charleston to global trade. The climate, with the exception of hurricanes, was a lesser factor. Years of drainage, pumping and piping enabled former swampland to become habitable while the wealthiest Charlestonians escaped summer heat by traveling inland to the cooler Blue Ridge mountains.

Fast forward to 2010 (or so) and after centuries of adapting to the coast, awareness of Charleston's relation to the sea was shifting to a focus on the threats posed by rising relative sea levels and the increasing frequency of tidal flooding. Tidal flooding events that had occurred an average of <1 time/year in 1920s were occurring an average of 42 times per year [National Weather Service (NWS), 2022b]. Globally, temperatures were also rising, but local temperature change did not elicit dramatic concerns. The sultry summer weather was normal. Rather, the increase in sunny day flooding and the prediction of further sea level rise motivated Mayor John Tecklenburg to consider flooding as an "existential threat to the city" and prompted the US Army Corps of Engineers to propose an estimated $1.4 billion sea wall to provide additional protection to Charleston's peninsula, the heart of its economy. Paired with nearly $2 billion of Federal Disaster Recovery funds allocated to the State of South Carolina from 2015 to 2021, much of which was directed to coastal counties, and nearly all of which focused on flood recovery, funding was clearly not the primary problem, but instead, it was recognition of heat as an significant threat.

Still, in other cities and many research fields, heat was receiving more attention with findings relevant to Charleston. The fourth National Climate Assessment [US Global Change Research Program (USGCRP), 2018] pointed to heat health risks and projected costs of lost labor productivity concentrated in the Southeast. Research in North Carolina highlighted the increased odds of pregestational births associated with days of high temperatures but less than heatwave conditions (Ward et al., 2019). Moreover, concern over energy insecurity as a dimension of poverty was rising in association with heating and with cooling (Hernández, 2016). The Union of Concerned Scientists (2019) projected that Charleston-North Charleston would go from a historical average (1971–2000) of 74 days above 90°F/year to 123 such days/year by midcentury (2016–2065) under current emissions trends. The COVID 19 pandemic was making the depth of racial health disparities associated with these hazards and exposures more visible (Phillips et al., 2021).

Situated in this context, this paper reflects our shared experiences in how the intersections of multiple networks, messengers, and messages contributed to broadening the local resilience agenda from a "hazard bias" toward flooding to be inclusive of heat and how the lessons learned during this transformative, focus widening process further reveal health inequities. Hazard bias is the inherent organizational problem of single hazard focus in the context of compound and connected hazard risks (Barnes and Temko, 2022). For Charleston, compound and connected hazard risks include the coincidence of hurricane/storm and heat seasons (Zscheischler et al., 2018; Raymond et al., 2020). Hazard bias appears to stem from the combination of (1) disparate lived experiences and their histories reinforced by (2) the focus of disaster declaration typologies and associated funding, and (3) the siloing and reinforcement of depth over breadth of technical expertise (Barnes and Temko, 2022). This paper offers an application of this new concept as a way of identifying an inherent challenge in climate adaptation planning.

While each of these factors has been identified individually as a barrier to adaptation, the reinforcing feedbacks among them have received less attention. A narrowly focused adaptation process has the potential to result in investments that neglect opportunities to address the risks to the historically underserved and socially vulnerable communities and miss chances to take advantage of complementarity and reduce competition among adaptation strategies.

In the Charleston context, being from an underserved and socially vulnerable community almost serves as a proxy to heat-health risks as census tracts with low canopy cover map closely to those with high values on the Center for Disease Control Social Vulnerability Index (City of Charleston, 2021a). Such environmental injustice amplifies inequities, including inequitable exposure to extreme heat and limited resources to deal with such exposures (Hoffman's, 2017; Hoffman et al., 2020; Hsu et al., 2021). While the body of literature on extreme heat and health continues to grow alongside global temperatures, there's more to do to raise awareness and to substantively adjust public investments to be more inclusive of heat mitigation and adaptation strategies (Keith et al., 2019).

Herein, we describe the intertwined efforts required to overcome hazard bias in Charleston, recognizing the escalating risks of heat alongside flooding, and the pathways taken to date. This case study offers concrete examples and lessons learned, including ways of seeing risks more fully, of understanding inequities as risk magnifiers, and the types of collaborations necessary to do so. While progress was made in increasing the awareness of heat threats and patterns of vulnerability, it is not yet clear if the actions taken to address the threats will focus on the needs of socially vulnerable and historically marginalized communities. Future efforts to design and implement adaptation strategies will still require distributive and procedural justice and equity as central guiding concepts.

CHARLESTON'S CLIMATE CONCERNS

Charleston's first major climate change planning effort was the "2015 Sea Level Rise Plan", followed by a second edition, titled "Flooding and Sea Level Rise" in 2019 with mentions of trees for flood and heat mitigation (City of Charleston, 2015, 2019b). In 2020, the City of Charleston completed its first City Vulnerability

Assessment (City of Charleston/Fernleaf Interactive, 2020) which identified extreme heat as a significant current and growing future climate risk consistent with the highest confidence level in IPCC Sixth Assessment Report [Intergovernmental Panel on Climate Change (IPCC), 2021]. According to the US Climate Resilience Toolkit (USCRT), the City expects to have triple its current number of extreme heat days by the end of the century [US Climate Resilience Toolkit (USCRT), 2022], but has no designated financial resources for heat adaptation as compared to its flooding and sea level rise projects [City of Charleston, 2022a,b; US Army Corps of Engineers (USACE), 2022]. While the 2022 approved General Operations Budget acknowledges the need for warming shelters, specifies funding, and identifies non-profit collaborations to provide such shelters during winter months, there are no reciprocal budget items for cooling shelters in summer months (City of Charleston, 2022a, p. 215). In fact, there are no mentions of extreme heat management in the 2022 budget.

Compounding this financial challenge, many in the South assume heat is manageable as the presumption of "it's always been hot here" may undermine the ability to meaningfully address heat. Howe et al. (2019) found that on a scale of 0–100 (low to high), residents of Charleston County, on average, reported ranking extreme heat event risks at 41, one point above the national average. At the national level, this research also reported that, consistent with differences in the vulnerability of residents, responses from poorer neighborhoods and those with larger minority populations generally have higher perception of extreme heat risks than wealthier neighborhoods with more white residents (Howe et al., 2019).

While daily heat exposures are distinct from heat waves, heat is the nation's deadliest weather-related risk (**Figure 1**). The NWS [National Centers for Environmental Information (NCEI), 2022] identified nine days with "excessive heat" events in Charleston between 1996 and 2020, defining excessive heat as a combination of high temperatures and high humidity (which together form a heat index) that can impact human health [National Weather Service (NWS), 2020]. An excessive heat event is recorded/reported when heat indices "meet or exceed locally/regionally established excessive heat warning thresholds" (Strassberg and Sowko, 2021). The recent and less publicized wet bulb globe temperature climatology for the Southeast indicates that Charleston averages between 10 and 15 days a year with at least 1 h of temperatures above the black flag level at which point, the US Army guidance indicates that heavy work be reduced to 15 min accompanied by 45 min rest.

Community members rely on air conditioning, the ability to afford it, and a stable power grid to cope. Unfortunately, those with less means struggle with energy security, including access to air conditioning or affordability of energy, increasing health disparities, and impacting heat-related co-morbidities among more vulnerable populations (Hernández, 2016; Jessel et al., 2019). Moreover, those who suffer most have the least visibility as evidenced in the documentation of energy poverty in Charleston County [CISA, Carolinas Integrated Sciences and Assessments, 2019b; Texas Energy Poverty Research Institute (TEPRI) and Southeast Energy Efficiency Alliance (SEEA), 2021]. While in recent years there have been efforts to provide some senior citizens with air conditioners, to better weatherize homes, and to help with energy bills, these short-term solutions lack comprehensiveness and do not solve Charleston's growing heat problems (City of Charleston/Fernleaf Interactive, 2020).

To stave off worsening conditions for those most vulnerable, Charleston should raise compound risk awareness and adjust its capital investments to be inclusive of heat mitigation and adaptation. Yet in 2020, Charleston lacked basic urban heat data, technical expertise, and a strong source of motivation to develop a prioritization approach recognizing multiple risks, differential susceptibility, and complementary adaptation opportunities in for those investments to serve those most vulnerable to extreme heat. Although Charleston's Vulnerability Assessment identified extreme heat as a hazard, including much of the city as medium to high impact areas, extreme heat was not the focal point of the assessment and deeper technical analyses were not included (City of Charleston/Fernleaf Interactive, 2020). The screening level GIS analysis overlaid the number of households with members over 65 and number of households living below the poverty line with percentage canopy cover at the census tract level (City of Charleston/Fernleaf Interactive, 2020). Charleston's flood-related issues were, and remain, priorities, given their growing incidences and the capital and operational costs associated with those incidences. In turn, there were no motivating programs, project proposals, or other incentives geared toward recognizing the parallel growing threat of extreme heat and the potential for co-beneficial solutions alongside water management. Without such support and incentives, there were no technical experts retained to address heat alongside flooding concerns nor inclusion of heat mitigation in proposals for water management. Instead of including heat risk considerations in ongoing discussions about water management, particularly where green infrastructure solutions might offer multi-benefit strategies and where consideration of heat vulnerability might include more socially vulnerable areas, water management was the hazard focus. Exploring the cultural, economic, and technical constructs that lead to Hazard Bias provides insights to the changes required for such prioritization to occur. Framing this exploration, **Figure 2** illustrates how the interactions among Disparate Impacts, Funding Availability, and Technical Expertise, become filters that restrict which hazards become the resultant investment priorities in cities.

Disparate Impacts

The impacts of heat and flooding are distributed differently among entities in the Charleston area. While there is little specific documentation about heat impacts in Charleston, there is considerable relevant research documenting differences in vulnerability for individuals based on health and exposure. The impacts of recurrent flooding on individuals and the City itself are much better documented locally and nationally.

For those with the means to cool their homes and businesses through air conditioning and weatherization, for whom the cost of energy is not a burden, and for those with the choice and means to relocate away from risky areas should the need arise, heat risks are less apparent. In the city's 350+ year

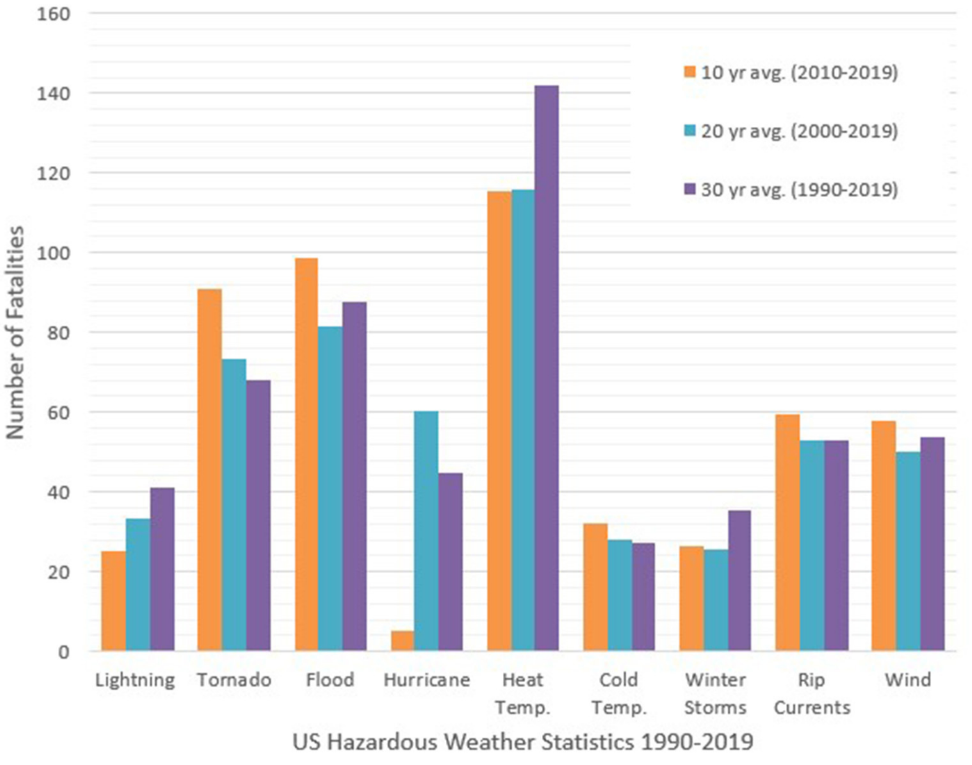

FIGURE 1 | US weather-related fatalities. Source: National Weather Service (NWS) (2022a).

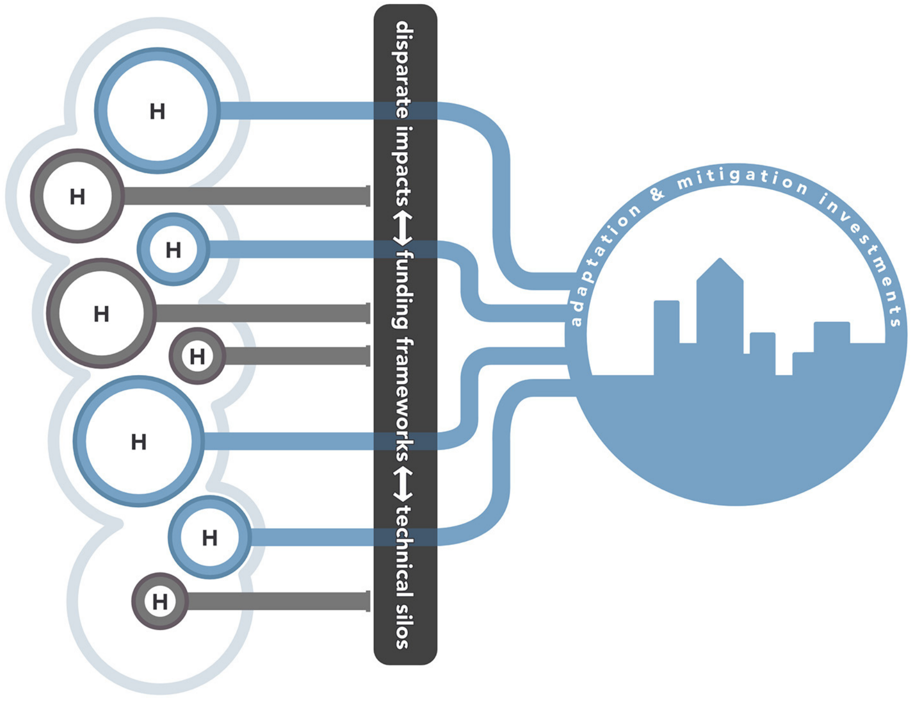

FIGURE 2 | Interacting barriers resulting in hazard Bias in adaptation and mitigation actions.

history, that has always been the case. However, for those whose daily work exposes them to extreme heat (outdoor workers, un-air-conditioned warehouse workers), whose co-morbidities exacerbate their reactions to extreme heat exposure [Global Heat Health Information Network (GHHIN), 2022], whose personal decision-making lacks informed awareness of, or choice to avoid, heat risks, extreme heat represents material risks to life and livelihood.

Exposure to extreme heat impacts people in Charleston in differing ways. For example, prior to the COVID-19 pandemic, Charleston welcomed over 7 million tourists annually (College of Charleston, 2019a). Tourists represent a vulnerable group as many are unacclimated to Charleston's warmer weather. Comparatively public transit riders are better acclimated as they are primarily local residents who rely on public transit due to limited access to personal vehicles or due to incentive programs by employers, such as the Medical University of South Carolina (MUSC), or the College of Charleston which encourage public transit ridership given their focus on emissions reductions and due to parking constraints on Charleston's peninsula (College of Charleston, 2019b; Medical University of South Carolina, n.d.). While these local groups are relatively better off than tourists, waiting at transit stops still results in additional heat exposures.

Heat health impacts, such as those captured by emergency responder data or heat-related mortality, are not yet well tracked or discussed regionally although more recent research on the public health burden of extreme heat, and on energy insecurity as a proxy for heat-health risk, continues to improve shared understanding (Burkart et al., 2021). While some local groups help senior citizens to weatherize homes and obtain air conditioners (Sustainability Institute, 2022; Project Cool Breeze, n.d.) these efforts are relatively small compared to the scale of Charleston's need and receive scant attention compared to its risks. For example, in 2016, the Post and Courier, Charleston's local newspaper, interviewed an emergency medicine physician who described child athletes dying every year from exposure to extreme heat, arguably the most understandable heat-health risk in regional discussions Johnson (2016). Yet this same article referenced research from Fisher, Sheehan, and Colton (2017) noting South Carolina's low-income families spend up to ¼ of their household income on energy. However, to date, there has been no other structured research to reveal these challenges, such as the comparison of LIHEAP (Low-Income Home Energy Assistance) recipient locations, flood-prone areas, and public transit ridership, a key set of interrelated indicators and proxies that could shed light on the compound risk areas and the opportunities for greater integration of heat into water management planning. Thus far, the research team has relied on these reports alongside the described data collection, recognizing that to truly understand the impacts of living with extreme heat, the next phases of research must delve into communities directly and learn more through their stories.

Comparatively, with chronic flooding from cloudburst events that lead to flooding of inland streets, high tides, and King Tides, storm surge flooding at the coast, and increasing sea levels and groundwater, Charlestonians' experience several types of water hazards is well documented. The City's 2015 Sea Level Strategy emphasized that "by 2045, the City is projected to face nearly 180 tidal floods a year" (City of Charleston, 2015, p. 1). The City of Charleston estimates that each flood event that affects the Hwy.17 Septima Clark Parkway—cross town highway costs $12.4 million (in 2009 dollars). The City further projects $1.53 billion in gross damages and lost wages taking into account impacts on long-term job creation; restricted access to commercial properties and medical centers; impacted tourism and business activity, lost productivity spent navigating flooded areas; and extensive police resources focused on damaged and "rescued" vehicles (City of Charleston, 2015). The report of the City of Charleston's Special Commission on Equity, Inclusion, and Racial Conciliation (2021:23b) includes a section on Health Disparities and Environmental Justice which includes multiple long-term goals to improve health and specifies, "Prioritize flood mitigation strategies that address racial equity and environmental justice" as a long-term goal but does not mention heat. These futures emphasize water priorities for the majority and the historically underserved even as a minority cannot afford to cool their homes and lack alternatives, such as cooling centers, for respite.

Unsurprisingly, as illustrated in the map comparison of Charleston's surface temperatures with life expectancy, social vulnerability, and income, Charlestonian's engrained inequities represent a chronic backdrop to the experience of extreme heat (**Figure 3**). Understanding the linkages between vulnerability and poverty, as well as individual and community capacities to cope, requires a deeper understanding of inherent societal inequities and their interrelatedness to disaster risk responses and to governance approaches lacking contextual, procedural, and distributional equity (Eriksen et al., 2007; Lavell et al., 2012; Marino and Ribot, 2012).

Disaster Declarations

As of January 2022, there have been no federally declared heat disasters anywhere in the United States or its territories even though, since 1991, heat-related fatalities far outpace those by any other disaster, sans COVID-19, in the United States [**Figure 1**; Federal Emergency Management Administration (FEMA), 2022]. Instead, drought is commonly designated, reinforcing the focus on capital loss [NOAA National Centers for Environmental Information (NCEI), 2022].

While the majority of recovery funding in the United States is federally appropriated, following the 1948 Midwest flood and the subsequent development of the Disaster Relief Fund, this is not the only source of disaster funding. States and Local governments also fund recovery. However, the Federal Disaster Declaration and associated appropriation is the modern funding mechanism for the Robert T. Stafford Disaster Relief and Emergency Assistance Act, passed in 1988, that, today, structures much of the Nation's disaster recovery and mitigation efforts (Painter, 2022). These emergency or disaster declarations, form the foundation of FEMA's disaster response programs and, as well, responses managed by the Department of Housing and Urban Development (HUD) (Robert T. Stafford Disaster Relief and Emergency Assistance Act, 1988).

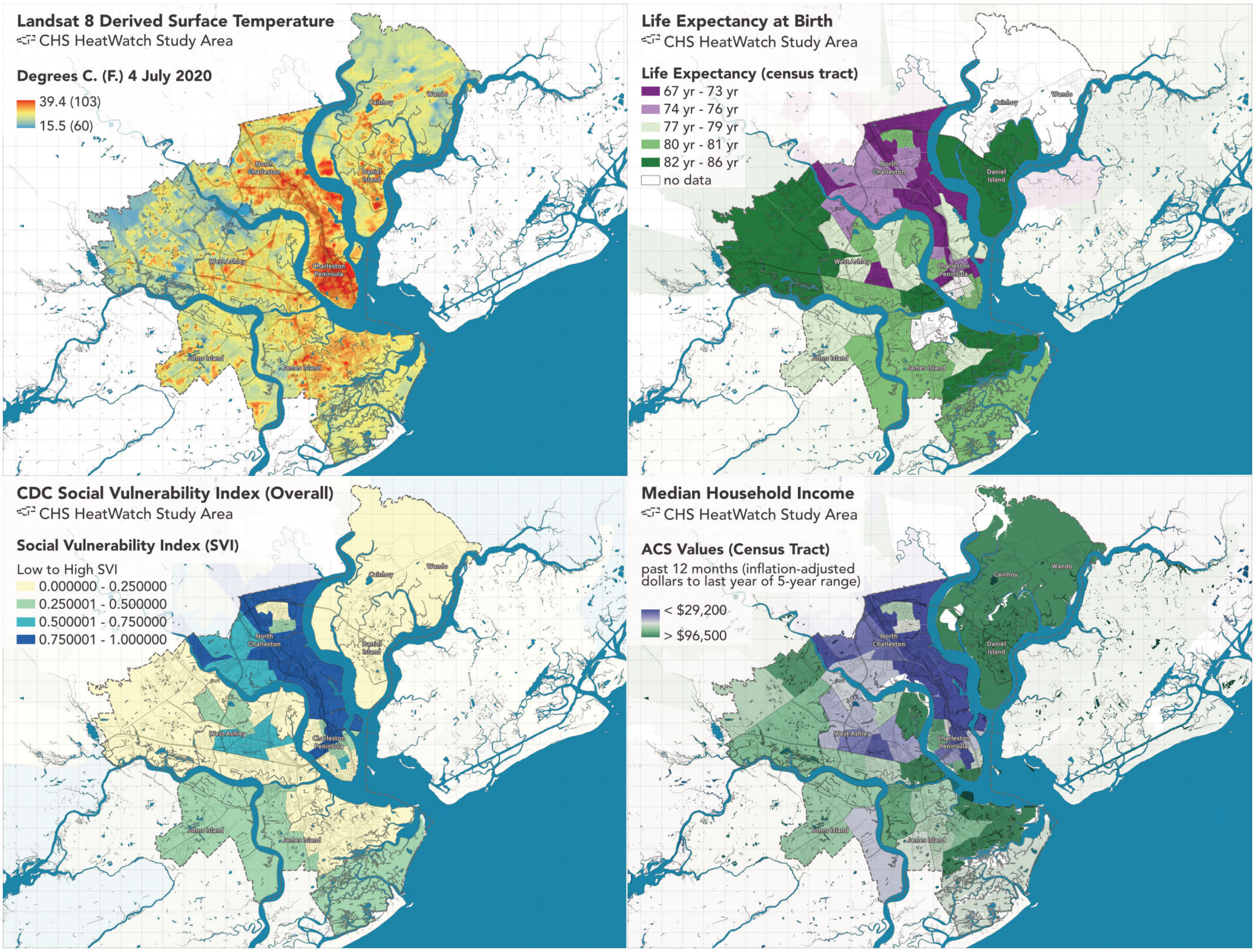

FIGURE 3 | City of Charleston Heat and social vulnerabilities comparison.

Since 1953, there have been 4,632 discrete emergency or major disaster declarations in the United States or its territories [Federal Emergency Management Administration (FEMA), 2022] and each is classified by the perceived threat causing an economic loss. Recovery and/or mitigation funds are then earmarked to address specific economic losses, typically biased toward capital asset losses, specific to the designated event. While this process makes sense in the context of Congress' role in managing the appropriation of public funds, the bias of disaster declarations toward capital loss associated with a discrete event does little to address other compounding, complex risks and their associated (not necessarily economic) costs. In the case of heat, the systemic issues here are substantive. As (Keith et al., 2019, p. 2) note, heat risks are "distinct than [sic] other climate risks for multiple reasons, including the historic lack of governance and legal regulatory structures."

In the state of South Carolina, storms, wildfires, and COVID-19 comprise all declarations in the last decade. Without a disaster declaration, there are no federal recovery funds [Federal Emergency Management Administration (FEMA), 2022]. Without recovery funds, the choice for capital project improvements relies on state and local government interests, and to date, those have not focused on heat.

The reason for alternative foci is clear as since 2015, \$1.8 billion in recovery funds followed the multiple disaster declarations for storm recovery alone in South Carolina (The Nature Conservancy Southern Environmental Law Center, 2022). In parallel, the Governor of South Carolina appointed a statewide Floodwater Commission to focus on storm-related flooding (State of South Carolina, 2021). The State of South Carolina Office of Resilience (SCOR) intends to emphasize flooding in its first statewide resilience plan as was specified in the authorizing legislation and South Carolina remains in recovery mode from 2015 storms as of January 2022 (Disaster Relief and Resilience Act, Title 48, Chapter 62, 2020, State of South Carolina, 2022). All subsequent disaster-declaration recovery works are also in process including those related to COVID-19 recovery. At this same time, the US Army Corps of Engineers is in the midst of a 3 × 3 (3 years and under \$3 million) study for a Storm Surge Barrier for Charleston [US Army Corps of Engineers (USACE), 2022]. In parallel, numerous ongoing county and city capital projects address chronic flooding. Still others are seeking grants or innovative financing to address flooding (City of Charleston, 2020b, 2022b). While these efforts are individually and collectively important for the State of South Carolina and for Charleston to manage growing flood risks, none of these efforts includes requirements to consider heat mitigation as a co-benefit, even as several encourage the use of nature-based solutions, which in turn serves to further deepen technical expertise on, and awareness of, flood management.

Technical Expertise Silos

Given these planned investments technical experts flock to flood-prone areas offering helpful contributions toward flood reduction and toward living more resiliently with water. These water experts focus on how to address inland and coastal flooding, bringing tools and frameworks to bear on the increasing problem of urban water management. The tools and trainings are frequently discipline-specific (floodplain managers, civil engineers, hydrologists, landscape architects, etc.). The deepening of such technical expertise in water management further isolates practitioners from more holistic thinking about climate change, as evidenced by the Dutch governmental priorities on flooding and their own challenges in developing a country-wide approach to extreme heat [Klok and Kluck, 2018; Amsterdam Institute of Advanced Metropolitan Solutions (AIAMS), 2020]. In Charleston this same framing reinforces a hazard bias toward water. For example, the 252-page Dutch Dialogues Charleston report (City of Charleston, 2019a) demonstrates the lesser interest in intersections between flooding and heat with only nine general mentions. Those instances are typically focused on co-benefits of water strategies, such as, "In addition to the work on slowing, storing, redirecting, and adapting to water, complementary solutions would help. Many solutions for water also help to reduce urban heat." (City of Charleston, 2019a, p. 234). Similarly, the USACE 3 × 3 focuses solely on the storm surge barrier, and even as its critics offer more inclusive nature-based solutions, those proposals lack significant emphasis on heat mitigation or adaptation (Imagine the Wall, 2020). These solutions focus on water ONLY, creating the impression there is a necessary choice between addressing flooding OR other hazards. The hazard bias and associated siloing of expertise increase the propensity to focus on technical solutions over actions that are more intertwined with societal concerns and strategies to reduce vulnerability through socio-political interventions (Kehler et al., 2021).

The one spot where *AND* holds more power than *OR* is in the South Carolina 2020 State Act 163, which requires all municipalities to address water AND other hazards in each municipal comprehensive plan update (State of South Carolina, 2020). The Act intends to motivate a more complete understanding of risks, but it faces an uphill push given the lived experience in Charleston. However, its language, while more inclusive of other hazards, also prioritizes water.

Despite the implicit hazard bias toward flooding, fortunately, there is growing concern about heat warnings in general. Under the Biden Administration, in 2021, OSHA implemented guidance for worker health as related to extreme heat (OSHA, 2021). The National Integrated Heat Health Information System (NIHHIS) team at NOAA ran its third HeatWatch campaign and hosted numerous events to generate a culture of heat research and awareness building (National Integrated Heat Health Information System (NIHHIS), 2022). The Lancet, a leading international medical journal, emphasized the importance of better heat-health risk awareness (The Lancet, 2021). Yet in Charleston, ahead of this research program, there were two public resources for heat warnings. One was the Charleston NWS Forecast Office (National Centers for Environmental Information (NCEI), 2022), which uses a heat index of 105 (well above the black flag of 92 Wet-bulb globe temperature (WBGT) (US Department of Commerce, NOAA, 2022). The second appears in Charleston's municipal code and focuses on heat risks to carriage horses used in tourism. It provides detailed practices for monitoring the heat exposure, stress, period of water availability between tours, and other working conditions (City of Charleston, 2020c, 2022b). It was within this context that our team began building its research and engagement program.

The effort to reach diverse audiences and engage the community at many levels relied on the efforts of many individual researchers, consultants, MUSC, the Charleston Medical District Advisory Group (CMDAG), Citadel, and city leadership and staff who participated in the research and promoted the importance of the research through their networks. These boundary spanners (Goodrich et al., 2020) collectively tackled, and continue to address, ways to raise heat-health awareness in Charleston. The authors, Barnes and Dow, facilitated this broad collaboration, but the emerging outcomes are a collective accomplishment. The core research team is recognized in the acknowledgments.

DETAIL TO UNDERSTAND THE KEY PROGRAMMATIC ELEMENTS

Coming to a deeper understanding of heat-health threats highlighted the significance of two processes. An established network of trusted relationships formed the core of an expanded research agenda and partnerships between the CMDAG, CISA, and the City of Charleston. At the same time, members of those networks leveraged other connections and interests, self-organizing to broaden dialogues, participants, and outreach communications. These processes drew on distinct information sources and operated at different spatial and temporal scales, with residents making daily decisions about personal exposures and the City and the CMDAG developing long-term capital investment plans intended to integrate resilience into the built environment. **Figure 4** provides a timeline of events discussed in this section as they relate to the growth of Charleston's focus on water management since 2014 as compared to the 2021 introduction of an All Hazards approach, inclusive of extreme heat. Since 2021, the network has focused on developing a shared understanding of extreme heat risks and conducting further research heat-health impacts. Next steps include the development of practical

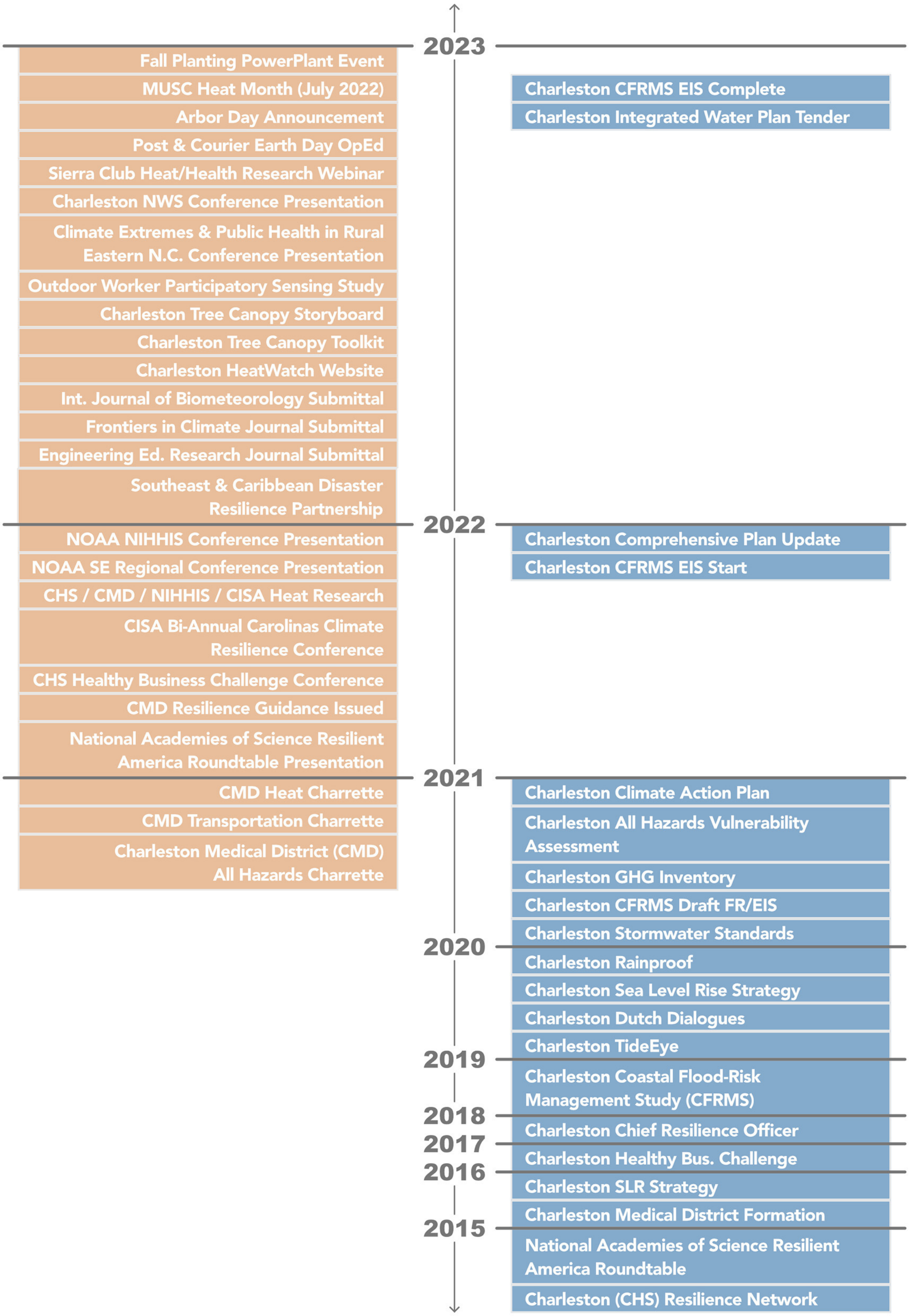

FIGURE 4 | Timeline of key programmatic events.

solutions, in concert with water management, to reduce extreme heat.

The process began from a small but significant core effort to develop an adaptation roadmap for the Charleston Medical District (CMD), a critical regional medical resource and the largest employment center in the region. Access to the CMD is frequently disrupted by flooding and given its role as a critical medical facility, securing the CMD is a priority in Charleston. With years of effort to develop near-term coping strategies, such as buying a boat to ferry patients on high tide days, and advocacy for mid-term and longer-term flood-related capital projects, extreme heat was not a priority.

Following the Charleston Dutch Dialogues in 2019, the CMDAG and Climate Adaptation Partners (CAP) began working on a district-specific resilience strategy, hosting charrettes on flooding, transportation, and funding for resilience. During early strategy meetings, initial heat risk conversations found little resonance even as the City of Charleston published its first Vulnerability Assessment, which emphasized the need for an all-hazards approach to resilience inclusive of heat, albeit not its priority (City of Charleston/Fernleaf Interactive, 2020). The everyday hazard of heat, situated across 350 years of warm, humid days, and limited heat warning systems, struggled to get attention when the direct experience of the threat was less impactful to decision-makers who lacked awareness of the relationships between heat, health, housing, and energy security, and whose daily work required immediate responses to flooding.

In the spring of 2020, one conversation became the transformative moment in heat risk perception. As part of a grant proposal development, the CAP/CDMAG team reached out to physicians who might partner on climate-related health research. During such a meeting a well-respected senior physician mentioned almost casually that several patients had passed out from heat while walking from their cars to their appointments. For those physicians in the meeting, heat-health was a known issue, but rarely were these same physicians in planning meetings for the campus. This realization of patient risk on hospital grounds moved heat from the background to become relevant to the CMD's healthcare mission. The CMDAG became more supportive of exploring heat health risks and implications for planned investments.

Next CAP prepared LandSat images of surface heat in the CMD to help illustrate the extent of the issues. The CMDAG then agreed to the conduct of a surface heat sampling pilot. Drawing from Hoffman's (2017) protocols, CAP used a FLIR ONE thermal imaging camera to capture skin surface temperatures on a typical summer day in Charleston (**Figure 5**). This sampling approach, relatively new with affordable access to thermal imaging cameras, generates useful visual representation of heat which enables community scientists and members to better understand heat in relation to various surfaces. The results showed multiple hot surfaces, including unexpected surface temperatures in areas intended for respite and in areas recently renovated to encourage greater public use. Many of these were areas where patients, faculty, staff, and visitors gather. After presenting these data to the CMDAG, the network connected CISA and CAP, launching the collaboration (the team) for Charleston's larger heat research program.

The team shared the initial skin surface heat observations in meetings with CMD master planning and operations teams to build further interest in better characterizing heat risk as related to planned capital investments, or readiness of energy resources for greater heat exposures. In parallel, as part of a heat charrette, CISA team presentations highlighted the importance of advancing the understanding of initial surface heat images by investigating highly localized WBGT to better characterize human heat stress by considering temperature, humidity, and the impact of solar radiation and winds. The team also emphasized the need to better characterize the personal exposure and stress of outdoor workers through using wearable heat and humidity sensors together with GPS-enabled heart rate trackers as they moved around the campus during the day. With this growing collaboration, the CMDAG recognized the importance—the health emphasis—of better understanding CMD exposures to extreme heat and agreed to collaborate with CAP and CISA on a more fully developed heat research program for the summer of 2021. CISA funded the research for personal monitoring and for WBGT sampling while CAP volunteered time for the coming year. With these pieces in place, in December 2021 the team then secured a NIHISS HeatWatch grant to map the urban heat island of the greater Charleston area. Building on the growing concern and commitment of the CMD to addressing heat, as part of the application, the City of Charleston committed to use the heat maps and data to inform their future actions.

In this context, the Charleston Heat Research team effort was launched, a tripartite effort to capture outdoor worker exposure at the CMD and nearby Citadel Campus, WBGT sampling in the same areas, and a city-wide HeatWatch sampling that included these same areas. This effort garnered further support and broadened a coalition of collaborators. This led to heat health risks finding an institutional home in MUSC's Office of Health Promotion, Office of Sustainability, and Arboretum, to subsequent opportunities to present these issues to the City Wellness Committee, the City Resilience and Sustainability Committee, and to numerous local organizational meetings including the Charleston Resilience Network and Charleston Healthy Business Coalition.

Conducted in the summer of 2021, the research program data analysis is still underway, but multiple outcomes are already evident. Tangible organizational outcomes increase the attention and resilience to heat risks. The CMD integrated heat into their resilience plan and the City of Charleston explicitly incorporated heat into its new comprehensive plan, which will be overseen by the City's planning director, recently relocated from Las Vegas where the Guinn Center had emphasized similar challenges (Guinn Center, 2021).

The connection of heat to health reached into city committees with the Wellness committee reviewing proposals to assure health was considered in all policies. The City Sustainability and Resilience Committee supported heat risk inclusion in its future resilience planning. The Charleston Tours Association committed to providing water and training their tour guides about heat risks for unacclimated visitors. In collaboration

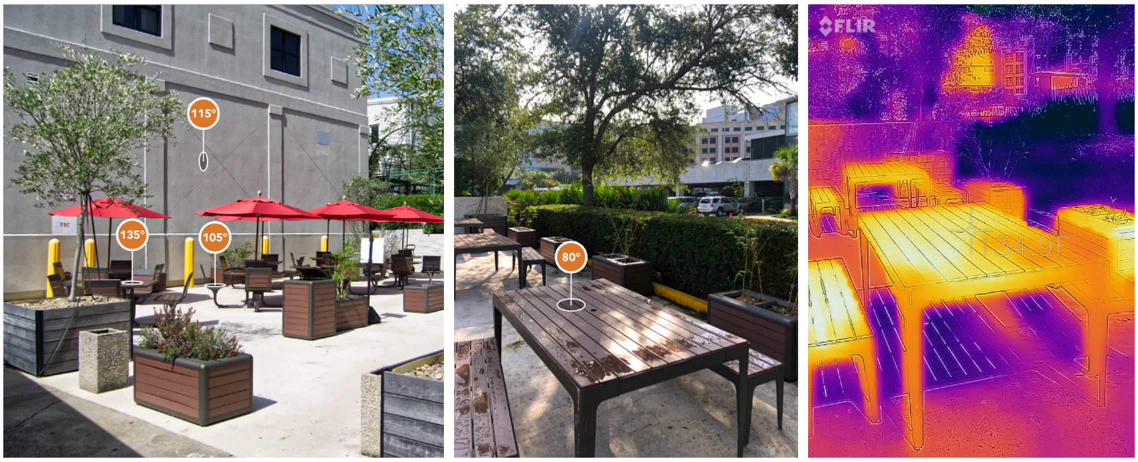

FIGURE 5 | Charleston Medical District skin surface temperature sampling.

with the city and the MUSC Office of Health Promotion, this group intends to fundraise for hydration stations for tourists and guides alike, which the City Parks Department agreed to locate in key park areas. The research using wearable sensors for outdoor workers in MUSC's Arboretum Grounds and Office of Public Safety, and in the Citadel Grounds team offered lessons that can be applied more broadly and promoted by the MUSC Office of Health Promotion. The South Carolina Department of Health and Environmental Control (SCDHEC) expressed interest in developing statewide programs on heat-health risks, coping resources and public health training, similar to the CISA Convergence of Climate-Health-Vulnerabilities web resource (CISA, Carolinas Integrated Sciences and Assessments, 2019a). Lastly, the City of Charleston is now paired with the City of Miami, the City of Phoenix, and the City of Las Vegas in a Bi-Regional Heat Research Initiative with pilot funding *via* NOAA/NIHHIS for the 2022 heat season.

Scaling up to a citywide effort fostered further connections among networks that reach around the state and connect to national efforts. These collaborations resulted in broader audiences hearing the message to consider water AND heat as the region considered climate adaptation. For example, the heat and health concerns resonated with South Carolina Interfaith Power and Light (SCIPL) already working on climate and energy poverty and brought their partners, South Carolina Chapter of Health Professionals for Climate Action (SCHPCA), into the conversation. CISA organizes the Carolinas Heat Health Coalition that includes representatives from CMD and multiple sectors and organizations around the Carolinas. The South Carolina Seven (SC7) program began addressing heat in its One Million Trees program, largely through the advocacy of the MUSC Office of Health Promotion. The MUSC Arboretum Board hosted a session to raise extreme heat awareness among its Board members and their networks. The Charleston Sierra Club invited the research team to present findings to the regional network of Sierra Club chapters. The Citadel presented the research at numerous conferences, including a student program on lessons learned about extreme heat in Charleston. The University of South Carolina in collaboration with the City of Columbia received funding for the 2022 NIHHIS Heat Watch cohort. Through targeted collaborations with the Consortium for Climate Risk in the Urban Northeast, Regional Integrated Sciences Assessment (RISA) team, the City of Philadelphia adopted similar protocols to those of the Charleston effort, applied for the NIHHIS program, and joins Columbia in the 2022 Heat Watch cohort [National Integrated Heat Health Information System (NIHHIS), 2022].

LESSONS LEARNED, OUTCOMES AND PRACTICAL IMPLICATIONS

The work on heat and health in Charleston and in the region is still very much emergent as it continues to compete with flooding, the far more visible and growing hazard. However, it is now part of the local conversation, part of local planning, and grounded in locally relevant research and practical applications. For example, while Charleston hosted a tree ordinance for many years, that ordinance focused on protection of "grand trees," not on their role in heat mitigation. It was only recently that Charleston clearly linked its work on tree canopy protection and expansion with this recent work on extreme heat by adding heat and equity considerations to their StreetTrees Storymap and in their tree canopy resources for residents (City of Charleston, 2020a, 2021a,b). Key lessons learned during this transformational process provide valuable insights for other areas where unintended hazard bias makes it exceedingly difficult to consider an all-hazards approach. These lessons illustrate multiple points to intervene in the processes reforming hazard bias.

Water AND Instead of OR

Although flooding continues to demand attention and resources due to its visibility in, and impact on, communities, and due to the inertia of systems such as disaster declarations, funding pathways and technical expertise siloes, extreme heat now has resonance due to these types of collaborations (Keith et al., 2019). The efforts to date demonstrate that cities need not choose between addressing flooding and addressing extreme heat. Water AND heat deserve attention, and in some cases, the solutions to one benefit the other, which in turn allows cities to leverage federal or local funding more fully. Consideration of all hazards is an important criterion when determining capital spending priorities and so addressing multiple hazards with shared investments is simply a smart budgeting strategy.

Health Connections

The introduction of heat as a material risk only resonated once patient health risks were recognized. In the case of Charleston, patient wellbeing was the motivating factor for a transformative change. Engaging with health professionals who understand the epidemiological evidence of health risks associated with climate change, and the impacts of energy insecurity and its inequities on vulnerable populations, warrants greater effort from those working on climate change. For Charleston, this means examining community awareness of heat risk and reconsidering whether the heat warnings from the NWS are sufficient given community exposures, coping resources, and adaptive capacities. While Charleston adopted a Health in All Policies program, the operational approach to this as related to heat health inclusion is still to be determined.

Network Amplifiers

Individual efforts to heat-health risk extend the body of knowledge, but it is in the network amplification that true engagement resides. By starting with trusted relationships and working with various organizations and institutions, momentum built along the interest pathways of the various network actors. There is value in connecting multiple agendas while not attempting to corral those agendas into a singular pathway. The work in Charleston is not a project, but a system of mutually supportive connections that continues to evolve. Encouraging such evolution along interest-area pathways builds network diversity and robustness while drawing down boundaries and technical siloes. Diversity in turn invites in various new collaborations such as SCIPL outreach *via* its many ministries, MUSC outreach through physicians and patients, as well as through the Arboretum and the Sustainability office, which in turn connected to activities such as Heat Awareness Month, Earth Day, and tree planting events. Linking energy insecurity and the interests of SCDHEC expand the reach across the state.

Event Momentum

Heat Watch was an external validation of concerns and a community event that created new types of collaborators and conversations. Media outlets participated and a series of heat-related articles made the local newspaper, a Pulitzer-recognized press that previously focused on flooding. Local meteorologists began seeking out the opinions of physicians to guide evening forecasts. Due to its tripartite research program, the team was invited to participate in a nationwide conference of heat researchers, sponsored by the NOAA NIHHIS program. Following that effort, multiple other organizers within NOAA as well as the Southeast and Caribbean Disaster Resilience Partnership connected the team to heat researchers in other parts of the world, building and deepening the network and the ability to share best practices. Most importantly, following a joint announcement by NOAA and US Department of Human Health and Services at United Nations Framework Convention on Climate Change, 26th Conference of Parties (COP26), extreme heat has a national set of collaborations on similar trajectories of heat-health interface. *Via* this connection, the team encouraged NOAA and HHS to work more closely with FEMA and HUD to integrate heat risk planning in flood recovery where possible, and to explore the opportunity for federal recovery funds for heat waves.

These activities generated interest elsewhere. By presenting this work to SCOR and SCDHEC, these offices now intend to more fully engage and to integrate heat into the state resilience plan and into the statewide planning for health outreach. As mentioned earlier, the City of Columbia intends to somewhat replicate the program from Charleston, expanding impacts even further. For South Carolina, the opportunity to amplify this work statewide, engaging less resourced communities (which may act as proxies for energy insecure areas) into this growing collaboration is an obvious next step. In concert with recent NOAA satellite imagery improvements, the set of resources to do so is growing stronger.

Given the progress in such a short time period, it is clear that Charleston has the ability to overcome Hazard Bias, and to encourage its future investments to address heat mitigation and adaptation where possible. Drawing out discussions about heat-health risks alongside multi-benefit strategies with performance criteria tied to nature-based solutions is an obvious starting point. However, even with heat on Charleston's policy agenda, and with the additional resources provided by this research, addressing entrenched inequities in vulnerability requires more than just overcoming hazard bias, even if overcoming hazard bias is a necessary step.

CHALLENGES

There are certainly challenges to this work. For example, the network benefits from the dedication of a small group of constant participants who act as keystones while the overall web of actors grows stronger. Most of these keystones volunteer their time which is an inherent fragility, recognized by the network. The future of this coalition depends on these dedicated team members even as they seek to broaden participation and in turn network robustness. As this work is in the development of a system, and not a focus on a singular project, it remains critical for the team to not consider the work "done" once research findings are published, but to continue to engage and deepen community collaboration on the issue. Situating the work within state offices focused on resilience and health will be key to that growth, necessary, but not sufficient as heat is an inherently local hazard.

The limited funding for this research is dependent on federal dollars (*via* NOAA) even as federal recovery dollars (*via* FEMA/HUD) do not prioritize it. Moreover, federal disaster declarations have yet to introduce heat. And in the sultry South, even with South Carolina State Act 163 in place, flooding remains a priority for funding, reinforcing technical siloes and sustaining hazard biases. Lastly while the SCOR intends to address heat, its legislatively mandated priorities, like its administrative oversight on recovery funding, are toward flooding.

Notably, none of these flood-related focal areas include health indicators, whether in the planning, implementation, or performance metrics. Without health as a criterion, the evaluation of success of any of these investments remains focused on capital assets, not people, and certainly not the most vulnerable.

Raising up heat health awareness and acting on it remains a challenge. While inclusion in the Comprehensive Plan is a notable step, the city lacks a Heat Adaptation Plan, offers limited awareness building and coping resources for near-term exposures (including providing no cooling centers), and struggles, like all small municipalities, with balancing budgets and needed investments. The coalition lacks the administrative powers to change this context and so continues to work at the margins, seeking collaborators with such powers to institute change.

Community members struggling the most with energy insecurity and with heat-health implications were not yet engaged in this research and so the reported disparate impacts herein lack the more nuanced understanding that a community engagement program could offer. Instead, the team reported on programs trying to provide relief services. While the patterns of vulnerability and need have become more apparent, it is not assured that resources will go to the historically marginalized and underserved communities. Achieving that goal will require design and implementation processes that focus on equity.

Lastly, while these research programs and deliberations continue, those who live with inherent risks due to energy insecurity need help now. The Southeast Energy Insecurity Stakeholder Initiative and various DHEC initiatives are seeking to address these issues (Duke University, 2022). The new federal emphasis on funding tied to heat health and environmental justice may offer the incentives to reduce/overcome hazard bias and pursue more inclusive (Water AND) strategies in adaptation (White House, 2021). Ultimately, addressing hazard bias requires those working on climate first acknowledge its pervasiveness and then act on rewiring the feedbacks that encourage such bias in pre-disaster mitigation, recovery spending, and adaptation planning.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

JB and KD made equal contributions to conceptualization and writing of this manuscript. Both authors contributed to the article and approved the submitted version.

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High-Resolution Decadal Drought Predictions for German Water Boards: A Case Study for the Wupper Catchment

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Water boards in Germany require decadal predictions to develop optimized management and adaptation strategies, especially within the claims of flood protection and water distribution management. Specifically, the Wupper catchment water board in western Germany is interested in decadal predictions of drought indices, which are correlated to dam water levels. For the management of small catchments, they need multi-year means and multi-year seasonal means of the hydrological seasons for forecast years 1–3 at high spatial resolution. Thus, the MPI-ESM-LR global decadal prediction system with 16 ensemble members at 200 km resolution was statistically downscaled with EPISODES to ∼11 km in Germany. Simulated precipitation was recalibrated, correcting model errors and adjusting the ensemble spread. We tested different recalibration settings to optimize the skill. The 3-year mean and 3-year seasonal mean SPI (Standardized Precipitation Index), indicating excess or deficit of precipitation, was calculated. We evaluated the prediction skill with HYRAS observations, applying skill scores and correlation coefficients, and tested the significance of the skill at a 95% level *via* 1,000 bootstraps. We found that the high-resolution statistical downscaling is able to preserve the skill of the global decadal predictions and that the recalibration can clearly improve the precipitation skill in Germany. Multi-year annual and August–October mean SPI predictions are promising for several regions in Germany. Additionally, there is potential for skill improvement with increasing ensemble size for all temporal aggregations, except for November–January. A user-oriented product sheet was developed and published on the Copernicus Climate Change Service website (https://climate.copernicus.eu/decadal-predictions-infrastructure). It provides 3-year mean probabilistic SPI predictions for the Wupper catchment and north-western Germany. For 2021–2023, a high probability of negative SPI (dry conditions) is predicted in most of the area. The decadal prediction skill is higher than using the observed climatology as reference prediction in several parts of the area. This case study was developed in cooperation with the Wupper catchment water board and discussed with further German water managers: The skill of high-resolution decadal drought predictions is considered to be promising to fulfill their needs. The product sheet is understandable, well-structured and can be applied to their working routines.

Keywords: decadal prediction, drought, high resolution, statistical downscaling, recalibration, water management, user co-production, case study

INTRODUCTION

Water resources and food security are strongly impacted by large-scale droughts (Benson and Clay, 1998). In spring and summer 2018, Central and Northern Europe were hit by strong drought conditions, resulting in reductions of crop yields up to 50%, which are projected to be a common occurrence in the mid of the 21st century (Toreti et al., 2019). This long-lasting and strong summer drought seems to be more extreme than the drought of 2003, resulting in larger influence on forest ecosystems in Central Europe (Schuldt et al., 2020). The combined drought and heat affected river navigation, impacting the transportation and tourism sectors (Wieland and Martinis, 2020). On the other hand, Central Europe experienced extreme rainfall and flooding in summer 2021, damaging local critical infrastructure systems, such as bridges, schools and hospitals (Koks et al., 2021). The observed heavy rainfall amounts strongly exceeded historical records in several parts of the affected area and caused over 200 fatalities (Kreienkamp et al., 2021). This catastrophe discloses the needs to decrease vulnerabilities and improve adaptive capacities in the context of future challenges of climate variations (Bosseler et al., 2021).

Such events raise the question which climate information on extreme events is needed by the German water management sector to implement appropriate actions to adapt to future climate variability (Changnon, 2003). Answers are found in intensive discussions with climate data users on workshops and individual meetings at the Deutscher Wetterdienst (DWD) and Copernicus Climate Change Service (C3S). To optimize management and adaptation plans mainly for water distribution and flood protection in the face of climate variations in the upcoming years, water boards require decadal predictions of atmospheric variables for hydrological impact modeling in Germany—since planning processes often take time. Additionally, the skill and uncertainties of the predictions need to be communicated. For instance, the Wupper catchment water board (Wupperverband) controls water level and quality of 14 dams in a catchment area of 813 km^2 in western Germany. It requires decadal predictions of the Standard Precipitation Index (SPI, McKee et al., 1993) or alternatively of the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010) for the coming 3 years, because drought indices are correlated to water levels of dams (Lorza-Villegas et al., 2021). To manage smaller dams and river catchments high spatial resolution is essential. Different temporal aggregations, such as multi-year means of the calendar year and the four hydrological seasons, are required to cover different water management and also natural processes, like the vegetation period.

These needed decadal climate predictions of the next 1–10 years lie between seasonal forecasts and climate projections and are of particular interest for mid-term water resource managers (Meehl et al., 2009). Multi-model decadal predictions were coordinated in the Coupled Model Intercomparison Project Phase 6 (CMIP6, Eyring et al., 2016), and the World Meteorological Organization (WMO) Lead Centre for Annual to Decadal Climate Predictions (ADCP) publishes a Global Annual to Decadal Climate Update (GADCU, Hermanson et al., 2022). Predictability arises from greenhouse gas and aerosol forcing (Van Oldenborgh et al., 2012) and the initialization of the ocean (Matei et al., 2012), land surface or sea ice (Bellucci et al., 2015) with observations. Thus, skill is found for ocean temperature in the North Atlantic subpolar gyre (Hermanson et al., 2014), surface temperature, precipitation and atmospheric circulation (Smith et al., 2019), such as the North Atlantic Oscillation (NAO) impacting western Europe (Athanasiadis et al., 2020; Smith et al., 2020). Statistical postprocessing procedures like recalibration (Pasternack et al., 2018, 2021) can further improve skill by adjusting model bias, drift and ensemble spread toward observed statistics.

The drought indices required by water managers compare the available water amount with a long-term climatological value (Palmer, 1965). The SPI divides the anomaly of rainfall by its standard deviation (McKee et al., 1993) but works inappropriately in dry areas because rising temperature and evapotranspiration due to climate change are not regarded (Lloyd-Hughes and Saunders, 2002). The SPEI (Vicente-Serrano et al., 2010) standardizes the difference between precipitation and potential evapotranspiration (PET), i.e., the climate water balance. If the PET is parameterized following Thornthwaite (1948), the SPEI cannot be assessed for colder regions like Germany (Paxian et al., 2019). Several recent studies analyze the prediction skill of drought indices: Paxian et al. (2019) find high 4-year mean SPEI skill in the tropics, e.g., northern Africa, and smaller SPI skill hot spots at 5° resolution. Higher 2° resolution improves spatial structures mostly without reducing skill. Solaraju-Murali et al. (2021) investigate the SPEI skill for the months before the wheat harvest and find decadal prediction skill for several global regions. Decadal predictions are feasible for soil water storage in North America, given a correct soil initialization (Chikamoto et al., 2015), and skillful for Sahel summer rainfall (Sheen et al., 2017). In Europe, Solaraju-Murali et al. (2019) detect skill for the 5-year mean summer SPI in Scandinavia and neighboring areas and for the SPEI in Southern Europe. A C3S case study for the energy sector[1] finds skillful predictions of

[1]https://climate.copernicus.eu/decadal-predictions-energy

the 10-year extended winter precipitation in Southern European river basins based on a multi-model NAO prediction.

To reach a higher resolution of climate predictions different downscaling approaches were analyzed in former studies: Dynamical downscaling has larger computational costs but reveals skill for annual and seasonal temperature means (Feldmann et al., 2019) and added values for temperature and precipitation in some European areas compared to the global model (Reyers et al., 2019). Regional prediction skill is stated for user-oriented quantities and extremes, such as frost, heat wave or growing degree days (Moemken et al., 2020). Cost-efficient statistical-dynamical downscaling reveals skill for annual mean wind speed and wind energy output, partly preserving and partly improving the global model skill (Moemken et al., 2016). For West African rainfall, dynamical downscaling of decadal predictions shows the ability to reduce bias (Paxian et al., 2016) and improve skill (Paeth et al., 2017). In the United States, statistical downscaling improves decadal rainfall predictions for impacts assessments at high resolution (Salvi et al., 2017). As to drought indices, downscaling of a multi-model seasonal SPEI prediction for 6 months in winter and spring for water management in South Korea improves skill (Sohn et al., 2013). Instead, global model skill is mostly preserved in statistical downscaling of seasonal predictions for hydropower production in Germany and Portugal (Ostermöller et al., 2021).

Given the skill of decadal predictions and their importance for society in terms of climate adaptation and resilience, first steps toward developing user-oriented decadal prediction products can be taken (Kushnir et al., 2019). The information should be tailored to user needs, paying attention to its format and its applicability in user working routines (Bruno Soares et al., 2018). The design of climate service prototypes based on seasonal forecasts in the EUPORIAS project highlights the importance of user interaction and involvement in the development of successful services (Buontempo et al., 2018). To address the needs of climate-sensitive sectors and inform decision-making in the context of climate risks the C3S offers climate datasets and sector-specific applications already (Buontempo et al., 2019). Its first step toward prototype climate services based on decadal predictions is the C3S_34c contract developing case studies for the insurance, agriculture, energy and infrastructure sectors (Dunstone et al., 2022). Both the user co-development and the exchange between scientific partners proved to be essential for developing sectoral applications for decadal predictions to be published on the C3S website[2].

Thus, this study analyzes high-resolution decadal drought predictions needed by German water boards to set up water management and flood protection plans. The Wupper catchment is chosen as case study, and its water board co-develops the C3S_34c climate service on decadal predictions for the infrastructure sector[3]. To achieve the necessary high resolution, the German decadal prediction system MPI-ESM is statistically downscaled to a resolution of ∼11 km in Germany. We chose the cost-efficient statistical downscaling due to the large decadal hindcast set. Simulated precipitation is statistically recalibrated to address model errors and standardized to calculate the SPI because it might be difficult to assess the PET for SPEI in colder regions such as Germany. The SPI prediction is estimated for 3-year means of the calendar year and four hydrological seasons, and skill is evaluated with observations. A user-oriented product sheet is developed and discussed with different German water managers. Thus, Section MATERIALS AND METHODS of the manuscript describes the model and observational data applied and the methods used: the statistical downscaling, the recalibration procedure, the calculation of the SPI, the skill assessment and the computation and display of the probabilistic prediction. Section RESULTS illustrates the impacts of downscaling and recalibration and shows the SPI skill and prediction for 2021–2023 for all temporal aggregations. In addition, the resulting product sheet is presented, and the user co-production and feedback is illuminated. Finally, Section DISCUSSION gives a summary of the major results, highlights relevant conclusions and draws a final outlook.

[2]https://climate.copernicus.eu/sectoral-applications-decadal-predictions
[3]https://climate.copernicus.eu/decadal-predictions-infrastructure

MATERIALS AND METHODS

This section presents the global decadal prediction system, the statistical downscaling for Germany and the observational dataset used in this study. Furthermore, the post-processing including the statistical recalibration and the calculation of the SPI are described. Finally, the methods to calculate probabilistic predictions and to assess prediction skill scores are explained.

Global Decadal Climate Predictions

The global decadal predictions are taken from the Max Planck Institute for Meteorology Earth System Model Low Resolution Version 1.2 (MPI-ESM-LR) which consists of the coupled atmosphere-ocean model ECHAM6/MPIOM. The atmosphere reveals a horizontal resolution of ∼200 km and 47 vertical levels, and the oceanic component features a GR15 (∼1.5°) resolution and 40 levels (Jungclaus et al., 2013; Pohlmann et al., 2013; Stevens et al., 2013). The atmosphere is initialized nudging full-fields of ERA40 reanalyses (Uppala et al., 2005) before 1978 and ERA5 reanalyses (Hersbach et al., 2020) after. The ocean initialization is based on temperature and salinity anomalies from the EN4 observations (Good et al., 2013) assimilated in the ocean *via* an Ensemble Kalman filtering method (Brune et al., 2015). This MPI-ESM-LR assimilation run is the basis for the initialization of global decadal predictions on 1st November in every year from 1960 until 2020 for a 10-year simulation period. The prediction ensemble consists of 16 members which were started from different ocean states. The external forcing was taken from CMIP6, including observed states before 2015 and the SSP245 (Shared Socioeconomic Pathways, Fricko et al., 2017) scenario after. The global decadal prediction data of MPI-ESM-LR will soon in 2022 be available on the ESGF (Earth System Grid Federation) node at DWD[4].

[4]https://esgf.dwd.de/projects/esgf-dwd/

Statistical Downscaling

To fulfill the needs of the German water management sector for high-resolution predictions the empirical–statistical downscaling method EPISODES (Kreienkamp et al., 2018, 2020) was applied to downscale the MPI-ESM-LR global predictions to ∼11 km in Germany. The other global decadal prediction systems of the C3S_34c partners, i.e., CMCC-CM2-SR5, EC-Earth3 and DePreSys4, could not provide the necessary input data for statistical downscaling. In this method, statistical relationships are searched between local HYRAS observations (Rauthe et al., 2013; Frick et al., 2014) in Germany and the large-scale atmospheric state in NCEP/NCAR reanalyses (Kalnay et al., 1996) in greater Central Europe. These relationships are then transferred to the simulated MPI-ESM-LR large-scale predictions (Kreienkamp et al., 2018):

The first step includes the detection of analog days, selecting those 35 days of the reanalysis that are most similar to a certain model day ("perfect prognosis" approach, e.g., Klein et al., 1959; San-Martín et al., 2017). This selection is based on temperature, relative humidity and geopotential height fields at different vertical levels (500, 700, 850, and 1,000 hPa) interpolated to a reduced grid of 100 km resolution. For the selected 35 analog days, linear regressions are derived between the large-scale quantities and the small-scale observations (e.g., of near surface temperature or precipitation), and then applied to the value of the respective large-scale predictor from the global prediction. This first interim prediction for each day is, however, inconsistent for the downscaled variables and grid points of the reduced 100 km grid. In the second step, the short-term precipitation and temperature variation of the interim prediction is compared to the short-term variation of all days in the observational archive, and the most similar day is selected consistently for all output variables and the entire output grid. The final synthetic time series at high resolution results from summing up this selected short-term variation and the daily climatology of observations of that day in year to be forecasted. Thus, this statistical downscaling approach provides multi-variable and multi-site consistent time series. The operationally downscaled decadal prediction dataset will be available on the ESGF node at DWD[4] during 2022 or on request before.

Observations

The precipitation observations for evaluating the skill of high-resolution decadal predictions were taken from the HYRAS observations. They provide gridded daily precipitation data for Germany and corresponding river catchments in neighboring countries at 5 km spatial resolution. The gridded fields were derived from up to 6,200 precipitation stations applying the REGNIE procedure. This method combines inverse distance weighting and multiple linear regression including orographical conditions and thus, preserves the station values in their grid boxes (Rauthe et al., 2013). The time period was extended to 1951–2020 for precipitation. The dataset also includes daily grids for mean, minimum and maximum temperature and relative humidity (Razafimaharo et al., 2020). The HYRAS precipitation dataset is available *via* the open data section of the DWD Climate Data Center (CDC)[5].

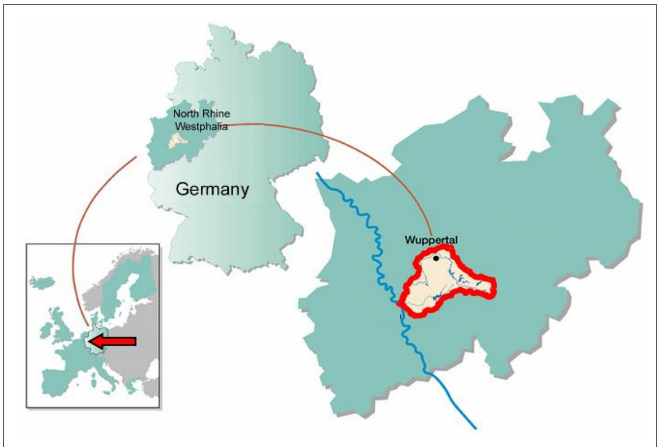


FIGURE 1 | Location of the Wupper catchment in Europe, in western Germany and in the German federal state North Rhine-Westphalia (received from Wupper catchment water board and published as part of the product sheet on https://climate.copernicus.eu/decadal-predictions-infrastructure, modified).

Hydrological Seasons and Wupper Catchment

The German water management sector is interested in decadal predictions of annual means and all four hydrological seasons for forecast years 1–3. Thus, the yearly averages of January–December, February–April (FMA), May–July (MJJ), August–October (ASO) and November–January (NDJ) were calculated for EPISODES and HYRAS precipitation data. Additionally, model and observational data were interpolated to a common regular 0.1° horizontal grid. The considered case study is located in the Wupper catchment in the German federal state North Rhine-Westphalia in western Germany. The location of this catchment in shown in **Figure 1** and marked in each plot of the results chapter. In addition, all results are also shown for whole Germany (as a second focus) to fulfill similar needs of other German water managers gathered on a user workshop (see Section User Co-production and User Feedback on the Usability of the Product Sheet).

Recalibration

The statistical downscaling EPISODES was developed for climate projections and aims at selecting the large-scale input variables with strongest relationships to the local target variables to provide high-resolution data consistent for different variables in space and revealing hardly any systematic bias. However, EPISODES does not consider to choose the large-scale variables with highest skill in reproducing the observed variability in the past. Thus, skill is preserved at high resolution but hardly enhanced (Ostermöller et al., 2021).

[5]https://opendata.dwd.de/climate_environment/CDC/grids_germany/daily/hyras_de/precipitation/

However, decadal prediction skill can be improved by post-processing techniques addressing systematic model errors, model drifts, trends and ensemble spread, like the Decadal Forecast Recalibration Strategy (DeFoReSt, Pasternack et al., 2018). This procedure uses a parametric drift correction (Kruschke et al., 2015) which applies third order polynomial parameters to correct the model drift over forecast years (Gangstø et al., 2013). A linear trend along start years is used to consider non-stationary drifts (Kharin et al., 2012). The conditional bias and the ensemble spread are adjusted by a third order and second order polynomial approach over forecast years and a linear approach over start years. The training of the recalibration parameters of a certain decadal prediction of 10 years is performed in cross validation mode omitting those decadal predictions as training data which were initialized within this prediction period. The adjustment of bias, drift, conditional bias and ensemble spread was shown to improve the skill (Pasternack et al., 2018). A more flexible improvement of DeForReSt applies a systematic model selection *via* non-homogeneous boosting to asses model orders directly from the dataset without restricting them before as well as an additive term for the ensemble spread correction (Pasternack et al., 2021). This boosted recalibration procedure was used in this study in two different settings: the first version follows the maximum orders of DeFoReSt (denoted as "standard recalibration version") and the second version applies a third order polynomial as maximum order along start years to correct the ensemble mean (denoted as "optimized recalibration version") to consider a higher interannual variability of high-resolution precipitation. In both settings, the boosting selects the best model orders of the fits only restricted by the maximum orders defined.

The annual precipitation means of January-December and the four hydrological seasons of EPISODES were recalibrated separately. All hindcast years were adjusted, whereas the training period was set to 1961–2020 (1961–2019 for NDJ) following the availability of HYRAS observations serving for both recalibration and skill assessment. This "unfair" procedure (Risbey et al., 2021) uses future data for recalibration of hindcasts in the past, which are not available for operational predictions and might include artificial skill. Thus, we performed a test of a "fair" recalibration applying only the preceding 30 years for the correction of a decadal prediction of a certain start date. The evaluation period was shortened to 1991–2020 since 1991 was the first start date of a decadal prediction to be recalibrated by 30 years from the past. However, we found major skill patterns to be robust between both approaches (not shown). Since long time periods are needed to achieve robust results when skill and recalibration vary in time, we decided to apply the original recalibration approach with cross validation (as described above).

For annual means and three of four hydrological seasons, the first year 1961 showed extremely dry conditions after optimized recalibration, identifying a clear outlier compared to the residual time series. Thus, this single year has been omitted in further SPI processing steps. Since the recalibration might destroy the standardization of the SPI (Paxian et al., 2019) it is executed before the SPI is calculated in this study [see Section Standardized Precipitation Index (SPI)]. This study applies the recalibration software tool (Pasternack et al., 2021) of the "Free Evaluation System Framework for Earth System Modeling" (FREVA, Kadow et al., 2021). Information on code availability can be found in these cited articles.

Standardized Precipitation Index (SPI)

The drought index SPI divides the anomaly of precipitation by its standard deviation (McKee et al., 1993). The parameter estimation for standardizing precipitation uses the Gamma distribution function. The resulting SPI values can be interpreted as follows (Lloyd-Hughes and Saunders, 2002): normal water availability is defined for values between −1 and 1, lower values describe dry and higher values wet conditions. The SPI calculation of this study uses the caeli package[6] of the WARSA working group at the Institute of Technology and Resources Management in the Tropics and Subtropics of the Cologne University of Applied Sciences in Germany because it is used by the Wupper catchment water board for their routine work. This assures that the resulting SPI values are comparable to their former results.

To provide proper standardized prediction products, the SPI needs to be calculated for each dataset (EPISODES ensemble members and HYRAS for different temporal aggregations) separately. The data needs to be aggregated, including temporal smoothing, spatial interpolation and ensemble averaging, before calculating the SPI. Thus, the yearly precipitation means of January-December and the four hydrological seasons of the recalibrated EPISODES hindcast set and the HYRAS observations were averaged for forecast years 1–3. The EPISODES ensemble mean was computed to calculate the SPI for EPISODES separately for the individual ensemble members and the ensemble mean. Thus, both probabilistic and ensemble mean SPI predictions can be analyzed. Since the SPI cannot be calculated for negative precipitation means, those time steps and grid boxes revealing negative means after statistical recalibration were set to zero.

The chosen time period for the standardization of HYRAS data per grid box is the evaluation period 1962–2020 (1962–2019 for NDJ), including all 3-year means within this period. The EPISODES model period is the same one but extended by the current 3-year mean forecast, i.e., 2021–2023. This is done because the chosen SPI algorithm of the WARSA working group does not allow to use a different time period for parameter estimation (needs to be equal for observations and model) and application of parameters for computing standardized time series (needs to include the current 3-year mean forecast). Thus, the period of standardization for EPISODES is only one 3-year mean longer (denoting the current 3-year mean forecast 2021–2023) than that for HYRAS, which is a marginal difference given the considered total period of almost 60 3-year means. This standardization can also be classified as "unfair" (Risbey et al., 2021) because it applies future data for standardizing past hindcasts which might produce artificial skill (see Section Recalibration). Since the caeli package does not allow computing the SPI based on a subset of the input data, we could not test

[6]http://warsa.de/caeli/

the impact of this "unfair" approach on the skill. However, this algorithm is essential for this climate service being part of the routine working environment of the Wupper catchment water board. Thus, skill results need to be interpreted with caution.

Skill Assessment

The quality of the EPISODES predictions is assessed in comparing those initialized in the past with HYRAS observations in the evaluation period 1962–2020 (1962–2019 for NDJ). The skill of the ensemble mean is evaluated by means of the Pearson (or anomaly) correlation coefficient, and the probabilistic prediction skill of the full ensemble is estimated by the Ranked Probability Skill Score (RPSS) compared to the observed climatology in the evaluation period (describing a distribution of equal weights for all categories) chosen as reference prediction.

The strength of the linear relationship between the ensemble mean prediction (X) for the selected forecast years initialized in the past and the corresponding observation (Y) along all hindcast start years (N) is assessed by the Pearson (or anomaly) correlation coefficient (r_{xy}). Predictions and observations are considered as anomalies with respect to the corresponding long-term climatological mean (μ). A correlation coefficient of zero indicates no correlation between prediction and observation, whereas values of 1 and −1 define a high positive and negative correlation, respectively (see e.g., Ernste, 2011):

$$r_{xy} = \frac{\sum_{i=1}^{N} (X_i - \mu_x)\left(Y_i - \mu_y\right)}{\sqrt{\sum_{i=1}^{N} (X_i - \mu_x)^2 \sum_{i=1}^{N} \left(Y_i - \mu_y\right)^2}}$$

The RPSS compares the probabilistic skill of a decadal prediction in reproducing the past observed variability with the skill of a reference prediction which can be used alternatively, e.g., the observed climatology in the evaluation period (defining a distribution of equal weights for all categories). Anomalies of predictions initialized in the past and observations with respect to a long-term climatology are grouped in the three categories of equal frequency "below normal", "normal," and "above normal." The limits are based on the 33rd and 66th tercile values of the predicted and observed climate characteristics of a reference period (see Section Calculation and Display of Probabilistic Predictions). Computing this separately for model and observations results in an inherent bias correction. The squared error between the cumulative probabilities of predictions $P_{j,k}$ and observations $O_{j,k}$ for n start years and K categories (here: three) is defined as ranked probability score ($RPS_{P,O}$). The predicted probability of each category is assessed empirically (as described in Siegert, 2014), following the frequency of individual ensemble members per category. The observed probability of a category is zero if the observed value is located in a higher category than selected and one if not. The RPSS relates the $RPS_{P,O}$ between predictions and observations to the $RPS_{R,O}$ between the alternative reference prediction and observations (Ferro et al., 2008; Wilks, 2011; Kruschke et al., 2014):

$$RPSS_{P,R,O} = 1 - \frac{RPS_{P,O}}{RPS_{R,O}}, with\ RPS_{P,O} = \frac{1}{n} \sum_{j=1}^{n} \sum_{k=1}^{K} \left(P_{j,k} - O_{j,k}\right)^2$$

If the decadal prediction is better than the reference prediction in reproducing past observations, the RPSS is larger than zero, if worse than smaller. If they perform equally well, it is zero. If the decadal prediction is in perfect agreement with the past observations, it is one.

However, the RPS is biased due to the finite prediction ensemble size. Thus, the ensemble-size adjusted FairRPS (Ferro, 2013; Richling et al., 2017) is estimated assuming the ensemble size grows to infinity to be able to compare predictions of different ensemble sizes. For the ensemble size M and the cumulative number of members of the prediction ensemble E corresponding to a certain category k, the $FairRPS_t$ of one forecast-event pair t can be defined as follows. The FairRPSS can be estimated based on the $FairRPS_{P,O}$ and the $FairRPS_{R,O}$ following the equation before:

$$FairRPS_t = \sum_{k=1}^{K} \left[\left(\frac{E_k}{M} - O_k \right)^2 - \frac{E_k(M - E_k)}{M^2(M-1)} \right]$$

For the (anomaly) correlation coefficient, RPSS and FairRPSS, the significance is tested to analyze if small sample sizes cause random variations influencing the skill assessment. Since the distribution of the RPSS is not known, the test applies non-parametric bootstrapping choosing randomly 1,000 samples of equal sizes from the given time period with replacement. A block bootstrapping allows for autocorrelation in decadal predictions. The random samples are analyzed using a significance level of 95%. If correlation coefficient, RPSS or FairRPSS are significantly different from zero, the skill analysis has not been impacted by random variations. Please note that such assessments of significance are subject to issues with multiple testing and should include control of the False Discovery Rate (Wilks, 2016). However, for more than 5,000 grid boxes in Germany and a significance level of 90% we would need ∼50,000 non-parametric bootstraps for this approach which is not possible due to restrictions in computing time and sample size (∼60 start years). Some tests revealed that 1,000 bootstraps clearly preserve the robust overall spatial structure of significance, but some small details might vary slightly (not shown). Thus, we highlight that one should act with caution to not over-interpret the significance of skill of single grid boxes. Only regional clusters of significant grid boxes are considered to be robust.

The correlation coefficients and (Fair)RPSS of this study were assessed based on the FREVA (Kadow et al., 2021) software tools MurCSS (Murphy-Epstein decomposition and Continuous Ranked Probability Skill Score, Illing et al., 2014) and ProblEMS (PROBabiListic Ensemble verification for MiKlip using SpecsVerification, Richling et al., 2017, based on routines from Siegert, 2014), respectively. Code is available as described in these cited articles or on request.

Calculation and Display of Probabilistic Predictions

Based on the distribution of the decadal prediction ensemble probabilistic SPI predictions are calculated. The 16 individual ensemble predictions are divided into the three categories of equal frequency "dry", "normal," and "wet," defined by low, medium and high SPI values. The groups are split by the 33rd and 66th tercile thresholds of the predicted climate characteristics of the WMO reference period 1981–2010. Finally, the predicted probability of occurrence [%] of each category is based on the frequency of ensemble members per category. However, since the number of ensemble members (16) is still restricted the estimated probability is adjusted considering the uncertainty of small sample sizes (Dirichlet-Multinomial Model, Agresti and Hitchcock, 2005). An inherent bias correction is included when the probabilistic model prediction is shown in conjunction with the tercile thresholds from observations in the reference period. The probabilistic predictions were estimated based on FREVA (Kadow et al., 2021) software tools. Original code can be accessed as pointed out in this article, and code adapted for this case study can be provided on request.

Following user needs collected on user workshops and individual user meetings prediction products should be displayed combing the prediction and its skill. Thus, the map of the final prediction product includes one dot per EPISODES grid box whose color describes the probabilistic prediction and whose size indicates the prediction skill, i.e., the RPSS compared to the reference prediction "observed climatology." Thus, a decadal prediction with a better, similar or worse skill than applying the observed climatology as prediction is represented by a dot of large, medium or small size. Many users are interested in predictions of all three levels of skill to compare the whole prediction map with real observations and understand the concept of skill. Impact modelers need the whole dataset to drive e.g., hydrological models. Both prediction and skill of the hydrological output can be compared to those of the atmospheric input to understand the connection between different variables.

RESULTS

In this chapter the impacts of statistical downscaling and recalibration on decadal prediction skill are analyzed, presenting (anomaly) correlation coefficients and the RPSS to investigate the skill of ensemble mean and probabilistic decadal predictions, respectively. Furthermore, we show the SPI prediction skill of annual means and all four hydrological seasons for forecast years 1–3 and the probabilistic prediction for 2021–2023. All results are presented for whole Germany first and then, the focus is set to the Wupper catchment area in western Germany marked in each plot. Please note that single grid boxes with significant skill should not be over-interpreted. Only regional clusters of significant grid boxes are considered to be robust (see Section Skill assessment). Finally, the product sheet of the case study published on the C3S website is presented, the user-cooperation is highlighted and the user feedback on its usability is evaluated.

Impacts of Statistical Downscaling and Recalibration

The decadal prediction skill for 3-year means of annual precipitation from MPI-ESM-LR is presented at ∼200 km horizontal resolution in Germany. Some significantly positive correlation coefficients of 0.2–0.4 can be found in northern and eastern parts and negative correlation in south-western parts (**Figure 2A**). The statistical downscaling EPISODES succeeds in preserving the prevailing skill of the global decadal prediction system at higher horizontal resolution of ∼11 km (**Figure 2B**). More local details can be seen and significantly positive correlation coefficients in several northern and eastern areas. The RPSS reveals rather similar patterns to the correlation. For MPI-ESM-LR, it is slightly negative in most regions, achieving statistical significance in the far south-western parts, except for a few positive values in some northern areas (**Figure 2C**). EPISODES again preserves the skill at higher resolution (**Figure 2D**), but more significantly negative RPSS values are stated in the southern parts. For the Wupper catchment, correlation and RPSS show slightly negative values for MPI-ESM-LR and EPISODES.

In applying the standard recalibration version with a linear trend along start years, the correlation coefficients of EPISODES clearly improve in some southern, south-western and far north-western areas (**Figure 3A**) compared to the unrecalibrated output (**Figure 2B**). However, some negative correlation remains in north-western parts and some significantly negative values in south-eastern parts. The usage of the optimized recalibration version applying a third order polynomial along start years is much more successful in adjusting the statistical properties of the high-resolution precipitation output to observations. It results in significantly positive correlation all over Germany, except for some small eastern areas (**Figure 3B**). In some regions correlations higher than 0.6 are calculated. Concerning the RPSS, the standard recalibration reveals some more significantly positive scores in the far northern parts but several more significantly negative scores in the western and south-eastern areas (**Figure 3C**) than the unrecalibrated model (**Figure 2D**). In contrast, the optimized recalibration version strongly improves RPSS values in north-western, western and southern Germany, achieving significantly positive scores in several regions (**Figure 3D**). In the Wupper catchment area, the standard recalibration degrades both scores but the optimized version results in strong improvements.

Some additional analyses showed that precipitation skill enhances from 1- to 3-up to 5-year means because small-scale unpredictable noise is reduced. Furthermore, skill remains rather constant from the beginning to the middle and then clearly drops until the end of the simulation period of the decadal prediction, denoting a clear lead-time dependency. The skill against the reference prediction "uninitialized climate projection," i.e., the same model system but without initialization, reveals that the impact of the initialization clearly remains until the mid of the predicted decade (not shown).

This analysis of precipitation is done in the full evaluation period 1961–2020 to be consistent for MPI-ESM-LR, EPISODES and both recalibration versions. Thus, the improvement of the optimized recalibration is found even when the outlier (year 1961) is included. However, in all following SPI analyses this outlier is omitted because the calculation of SPI is not possible.

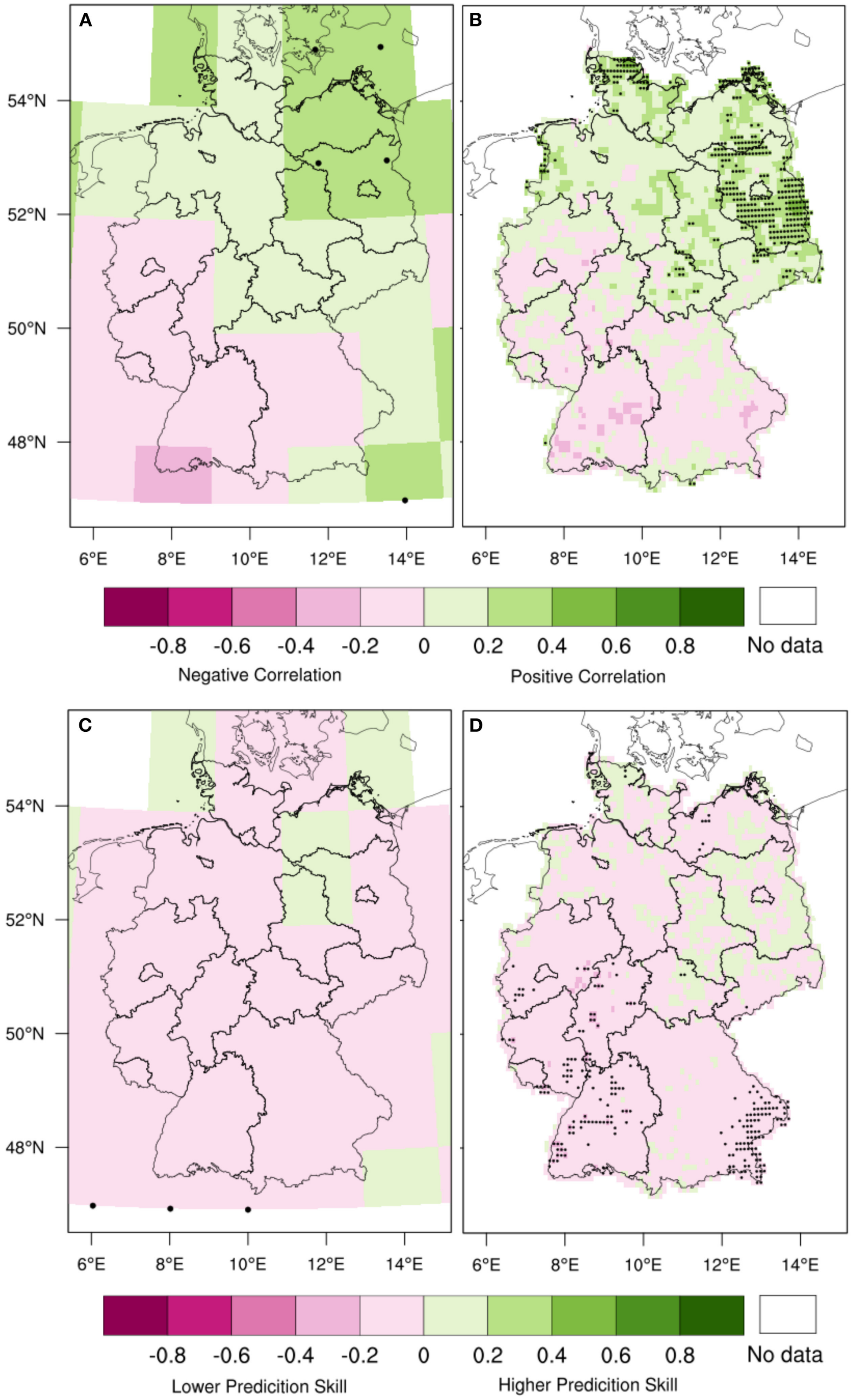


FIGURE 2 | Decadal prediction skill for 3-year means of annual precipitation for forecast years 1–3 in the evaluation period 1961–2020: (Anomaly) correlation coefficient between MPI-ESM-LR at ∼200 km **(A)** or EPISODES at ∼11 km **(B)** and HYRAS observations and RPSS of MPI-ESM-LR **(C)** or EPISODES **(D)** compared to the observed HYRAS climatology as reference prediction. Dots indicate significant skill (significance level of 95%).

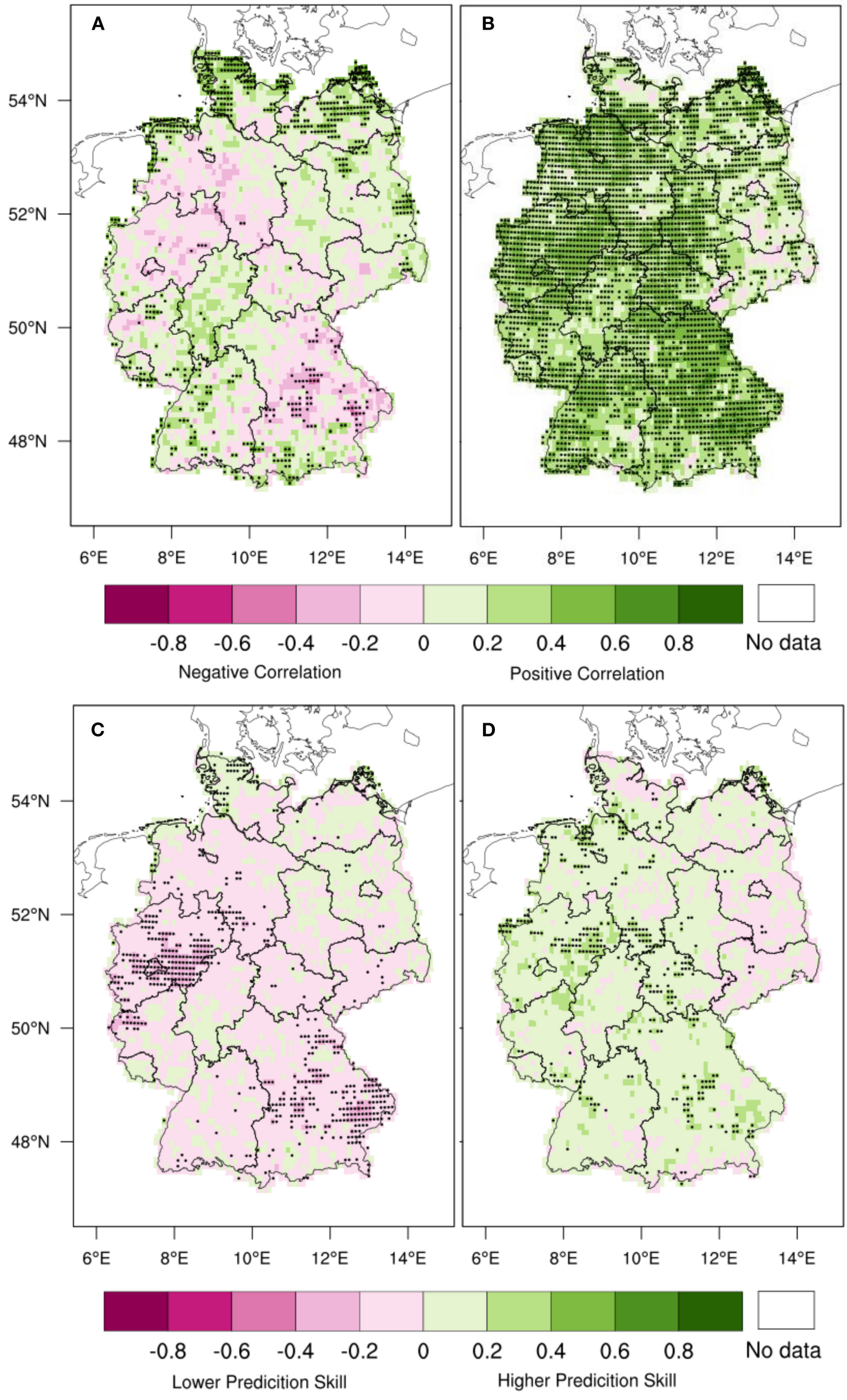


FIGURE 3 | Decadal prediction skill for 3-year means of annual precipitation for forecast years 1–3 in the evaluation period 1961–2020: (Anomaly) correlation coefficient between EPISODES at standard **(A)** or optimized recalibration **(B)** and HYRAS observations and RPSS of EPISODES at standard **(C)** or optimized recalibration **(D)** compared to the observed HYRAS climatology as reference prediction. Dots indicate significant skill (significance level of 95%).

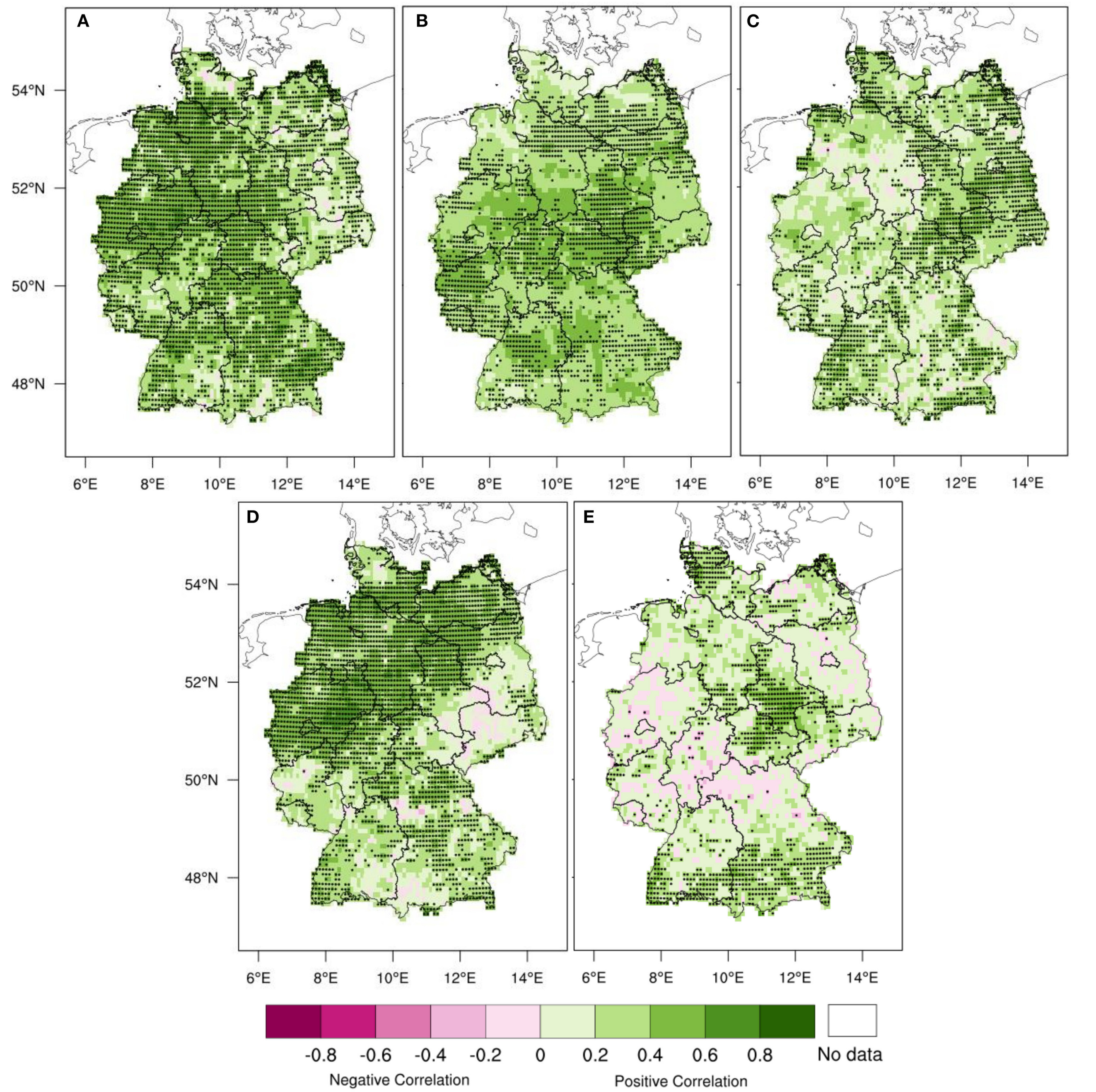


FIGURE 4 | Decadal prediction skill for 3-year SPI of January–December **(A)**, February–April **(B)**, May–July **(C)**, August–October **(D)** and November–January means **(E)** for forecast years 1–3 in the evaluation period 1962–2020 (1962–2019 for November–January): (Anomaly) correlation coefficient between EPISODES at optimized recalibration and HYRAS observations. Dots indicate significant skill (significance level of 95%).

SPI Prediction Skill

After applying the optimized recalibration version to annual precipitation means and all four hydrological seasons the corresponding SPI values and prediction skills for forecast years 1–3 are computed. The correlation coefficients of 3-year SPI of annual means (**Figure 4A**) are rather similar to those of precipitation (**Figure 3B**) in southern Germany. However, in western, central and north-western Germany the correlation is clearly improved, showing widespread areas of values between 0.4 and 0.6 and several regions exceeding a correlation of 0.6. In eastern Germany, the area of negative values is also reduced. For RPSS, similar results can be stated. Enhanced positive scores in western Germany and less negative scores in eastern Germany are shown for SPI (**Figure 5A**) compared

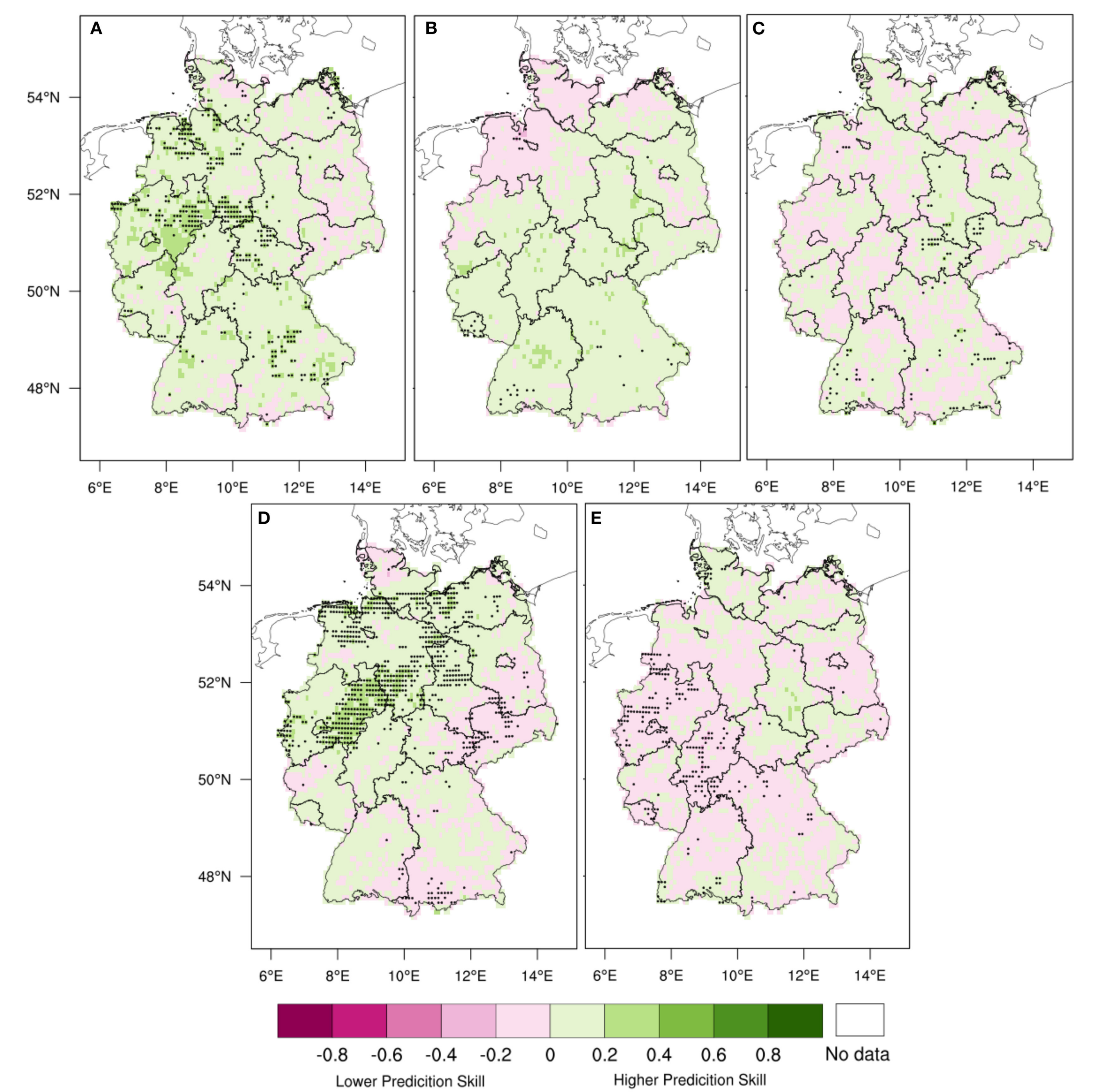


FIGURE 5 | Decadal prediction skill for 3-year SPI of January–December **(A)**, February–April **(B)**, May–July **(C)**, August–October **(D)** and November–January means **(E)** for forecast years 1–3 in the evaluation period 1962–2020 (1962–2019 for November–January): RPSS of EPISODES at optimized recalibration compared to the observed HYRAS climatology as reference prediction. Dots indicate significant skill (significance level of 95%).

to precipitation (**Figure 3D**). This also holds for the Wupper catchment area.

Concerning the 3-year means of the four hydrological seasons, FMA reveals as well significantly positive correlation coefficients over most of Germany, achieving widespread maxima of 0.4–0.6 in western, central and southern parts and minima in the far north (**Figure 4B**). Significantly positive correlations in MMJ (**Figure 4C**) and NDJ (**Figure 4E**) are restricted to some smaller regions, i.e., mainly in central-eastern and southern Germany, whereas NDJ shows even negative correlations in some western parts. Highest correlations of all seasons are found for ASO (**Figure 4D**), revealing widespread values of 0.4–0.6 in northern and western Germany and maxima of 0.6–0.8 north-east of the Wupper catchment and at the coastline of the North Sea.

Regarding the RPSS, FMA shows widespread positive scores, but significance is only found for single grid boxes in southern Germany which should not be over-interpreted (**Figure 5B**). MJJ also reveals only some significantly positive RPSS values in southern and central-eastern parts which might also be not robust (see Section Skill assessment) and even more negative scores (**Figure 5C**). As expected, worst skill results are found for NDJ with widespread negative scores and some significant ones in western parts (**Figure 5E**). Again, highest and widespread significantly positive scores are found for ASO in northern and western Germany (**Figure 5D**). However, significantly negative scores are seen in some eastern areas. The Wupper catchment area shows significantly positive correlations in ASO and partly in FMA. The RPSS is significantly positive as well in ASO but might be significantly negative in NDJ.

The FairRPSS can indicate which potential RPSS values could be achieved if the ensemble size grows further, e.g., in considering a larger multi-model ensemble. For the prevailing study, this was not possible since other decadal prediction systems did not provide necessary daily input data for statistical downscaling with EPISODES, but this might change in the future. For all temporal aggregations, the FairRPSS (**Figure 6**) shows more significantly positive scores and less significantly negative ones than the RPSS of the 16-member ensemble (**Figure 5**). Thus, a high potential for skill improvements due to a possible future enlargement of the ensemble size is found. For 3-year SPI of annual means, widespread skill over many German regions is found, except in eastern areas (**Figure 6A**). In FMA (**Figure 6B**) and MJJ (**Figure 6C**), significant skill is mainly discovered in southern and eastern parts, whereas ASO reveals widespread significantly positive scores in western and northern regions (**Figure 6D**). However, skill in NDJ remains limited to some small areas in the far north and south-west, even for larger ensemble sizes (**Figure 6E**). In the Wupper catchment area, significantly positive FairRPSS scores are computed for annual means, ASO and partly also for FMA (whereas the latter should not be over-interpreted).

Probabilistic SPI Prediction for 2021–2023

Following user needs the probabilistic SPI prediction for 2021–2023 (**Figure 7**), i.e., forecast years 1–3 initialized in November of 2020, is shown in combination with the corresponding RPSS prediction skill compared to the reference prediction "observed climatology" (cf., **Figure 5**). The color of the dots indicates the probabilistic prediction, and the size of the dots signifies the prediction skill. The 3-year SPI of annual means (**Figure 7A**) shows high probabilities of occurrence (larger than 85%) for dry conditions (negative SPI) in comparison to the characteristics of 1981–2010 in most of the area. The prediction skill is better than applying the observed climatology in several parts of north-western, central and south-eastern Germany (large dots). Again, caution needs to be taken to not over-interpret single grid boxes. The skill and the probability for dry conditions are smaller in the eastern areas and in the far south. In the far north some probability for wet conditions prevails. Dry conditions are predicted for the whole Wupper catchment area, and there might be some significantly positive skill in its eastern parts.

A widespread drying for most of Germany is also predicted for FMA, but the probability of occurrence is often smaller, and skill is rarely better than the observed climatology (**Figure 7B**). Normal conditions are forecasted for the northern parts. In MJJ, the prediction of dry conditions focusses on the north-western, eastern and south-western areas, whereas normal conditions prevail in between (**Figure 7C**). Skill is found in some central-eastern and southern regions but needs to be interpreted with caution. A stronger drying is again predicted for the whole western part of Germany in ASO with widespread significant skill in north-western areas (**Figure 7D**). The eastern and the far northern parts show normal or wet conditions but some negative skill scores prevail in the eastern areas (small dots). Finally, the predicted dry conditions are mostly limited to central Germany in NDJ (**Figure 7E**). Wet conditions are forecasted in the northern and the south-western parts and normal values in between. However, the prediction skill is worse than the observed climatology in some western regions. For the Wupper catchment area, dry conditions are predicted in FMA, MJJ and especially in ASO and rather mixed conditions in NDJ, though, robust skill is only found in ASO.

Product Sheet of the Case Study

The 3-year SPI of annual means was selected for the C3S product sheet (**Figure 8**) showing widespread high prediction skill. To comply with the limited space given in the product sheet and keep the readability of the user-oriented combined prediction and skill plot, the spatial focus of the product sheet was set on north-western Germany (50.5–53.5°N, 6.5–11°E). This area reveals highest and most significant prediction skill, includes the Wupper catchment area and further addresses similar needs of neighboring water managers as stated on a C3S_34c showcasing event (see Section User Co-production and User Feedback on the Usability of the Product Sheet). The format of the product sheet was developed in cooperation with the scientists of all four C3S_34c case studies considering intensive user feedback (see Section User Co-production and User Feedback on the Usability of the Product Sheet). The first page includes a short description of the goal of the case study and the main prediction message within a prominent red box. Below that main information the combined prediction and skill plot and a corresponding text describe the probabilistic prediction in more detail. Further background information on the needs of the Wupper catchment water board and the data and methods used to compute the prediction is given on the second page. It also includes the RPSS prediction skill, applied to define the dot sizes of the combined prediction and skill plot, and the correlation coefficients. However, please note that the C3S product sheet was published in 2021 (see below) based on 500 bootstraps, whereas the figures of this manuscript use 1,000 bootstraps which might lead to slight differences in the significance of skill.

The product sheet was published in the Section "Decadal predictions for infrastructure" (see text footnote 3) on the C3S website on "Sectoral applications of decadal predictions" together with the three other C3S_34c case studies on agriculture, energy and insurance. This website is at a pre-operational

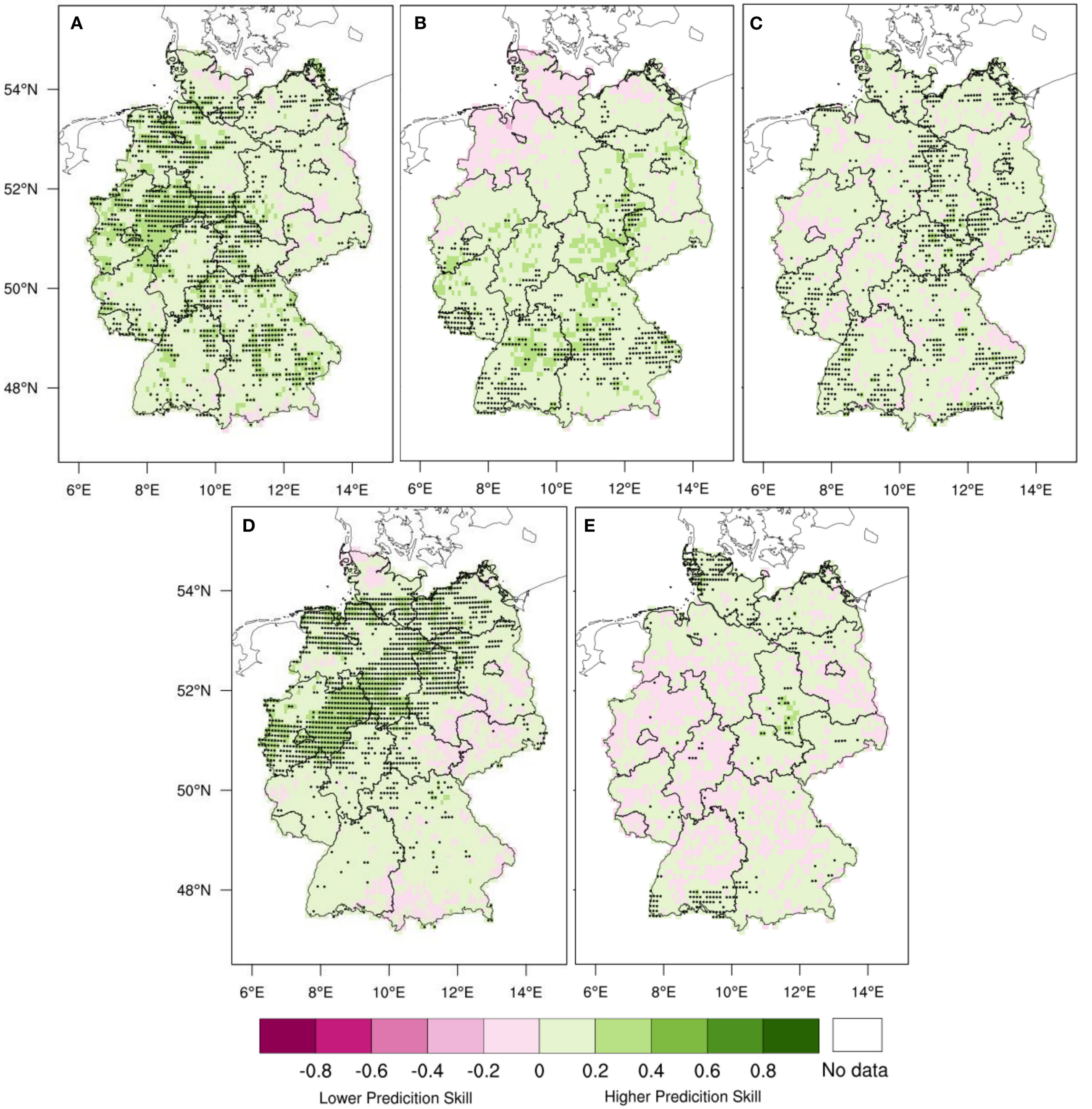


FIGURE 6 | Decadal prediction skill for 3-year SPI of January–December **(A)**, February–April **(B)**, May–July **(C)**, August–October **(D)** and November–January means **(E)** for forecast years 1–3 in the evaluation period 1962–2020 (1962–2019 for November–January): FairRPSS of EPISODES at optimized recalibration compared to the observed HYRAS climatology as reference prediction. Dots indicate significant skill (significance level of 95%).

state, offering the predictions initialized in November 2019 and 2020. This manuscript describes the case study initialized in 2020 only because that initialized in 2019 covers a shorter evaluation time period, a smaller area (only the Wupper catchment) and a different drought index (the SPEI) based on the old DWD prediction system and is less robust (see Section Conclusions). Further detailed information on model and observational data, post-processing and evaluation methods and the analysis protocol for all four case studies was published in a common technical appendix[7].

[7]https://climate.copernicus.eu/sites/default/files/2021-09/Technical_appendix_2020.pdf

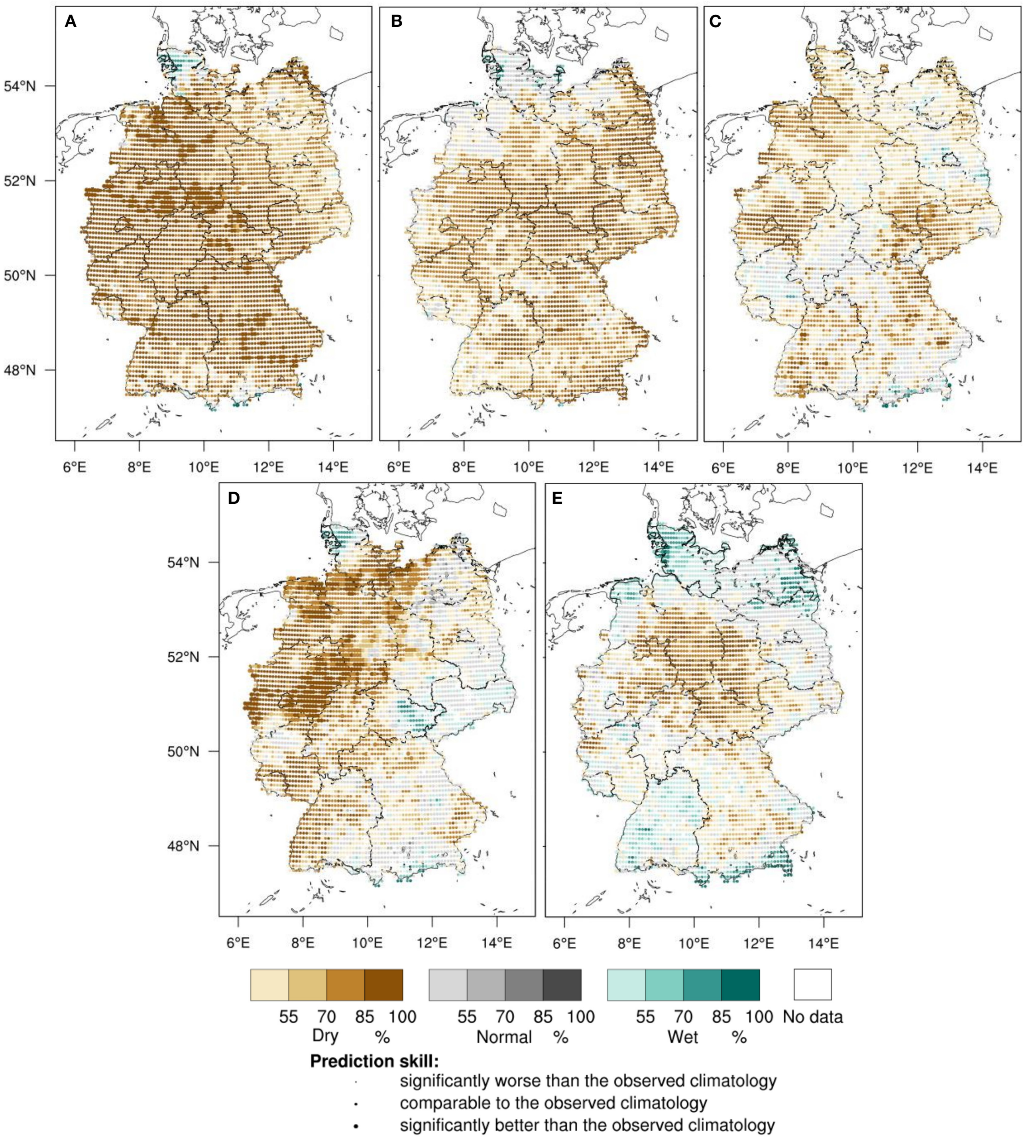
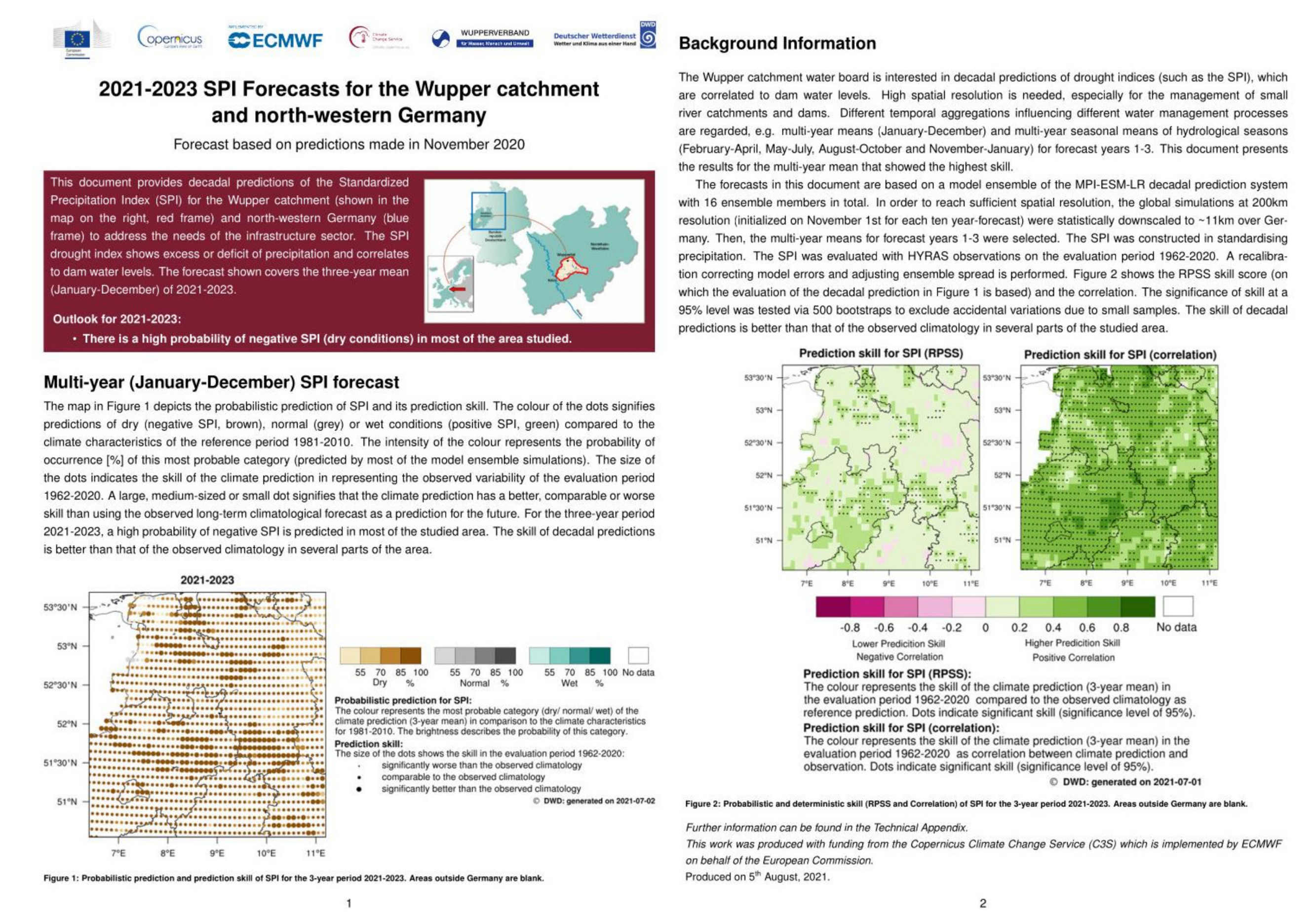


FIGURE 7 | Decadal probabilistic prediction for 3-year SPI of January–December **(A)**, February–April **(B)**, May–July **(C)**, August–October **(D)** and November–January means **(E)** for forecast years 1–3: The color represents the most probable category (dry/normal/wet) in comparison to the climate characteristics for 1981–2010. The brightness describes the predicted probability of occurrence of this category. The size of the dots shows the RPSS prediction skill in the evaluation period 1962–2020 (cf., **Figure 5**).

User Co-production and User Feedback on the Usability of the Product Sheet

The 3-year SPI product sheet and corresponding analyses of hydrological seasons were generated in close co-production with the Wupper catchment water board. They computed the SPI following their usual workflow based on the downscaled and recalibrated decadal predictions of DWD. After standardization, the skill analysis, computation of the probabilistic prediction


2021-2023 SPI Forecasts for the Wupper catchment and north-western Germany

Forecast based on predictions made in November 2020

This document provides decadal predictions of the Standardized Precipitation Index (SPI) for the Wupper catchment (shown in the map on the right, red frame) and north-ten western Germany (blue frame) to address the needs of the infrastructure sector. The SPI drought index shows excess or deficit of precipitation and correlates to dam water levels. The forecast shown covers the three-year mean (January-December) of 2021-2023.

Outlook for 2021-2023:

- There is a high probability of negative SPI (dry conditions) in most of the area studied.

Multi-year (January-December) SPI forecast

The map in Figure 1 depicts the probabilistic prediction of SPI and its prediction skill. The colour of the dots signifies predictions of dry (negative SPI, brown), normal (grey) or wet conditions (positive SPI, green) compared to the climate characteristics of the reference period 1981-2010. The intensity of the colour represents the probability of occurrence [%] of this most probable category (predicted by most of the model ensemble simulations). The size of the dots indicates the skill of the climate prediction in representing the observed variability of the evaluation period 1962-2020. A large, medium-sized or small dot signifies that the climate prediction has a better, comparable or worse skill than using the observed long-term climatological forecast as a prediction for the future. For the three-year period 2021-2023, a high probability of negative SPI is predicted in most of the studied area. The skill of decadal predictions is better than that of the observed climatology in several parts of the area.

Figure 1: Probabilistic prediction and prediction skill of SPI for the 3-year period 2021-2023. Areas outside Germany are blank.

1

Background Information

The Wupper catchment water board is interested in decadal predictions of drought indices (such as the SPI), which are correlated to dam water levels. High spatial resolution is needed, especially for the management of small river catchments and dams. Different temporal aggregations influencing different water management processes are regarded, e.g. multi-year means (January-December) and multi-year seasonal means of hydrological seasons (February-April, May-July, August-October and November-January) for forecast years 1-3. This document presents the results for the multi-year mean that showed the highest skill.

The forecasts in this document are based on a model ensemble of the MPI-ESM-LR decadal prediction system with 16 ensemble members in total. In order to reach sufficient spatial resolution, the global simulations at 200km resolution (initialized on November 1st for each ten year-forecast) were statistically downscaled to ~11km over Germany. Then, the multi-year means for forecast years 1-3 were selected. The SPI was constructed in standardising precipitation. The SPI was evaluated with HYRAS observations on the evaluation period 1962-2020. A recalibration correcting model errors and adjusting ensemble spread is performed. Figure 2 shows the RPSS skill score (on which the evaluation of the decadal prediction in Figure 1 is based) and the correlation. The significance of skill at a 95% level was tested via 500 bootstraps to exclude accidental variations due to small samples. The skill of decadal predictions is better than that of the observed climatology in several parts of the studied area.

Figure 2: Probabilistic and deterministic skill (RPSS and Correlation) of SPI for the 3-year period 2021-2023. Areas outside Germany are blank.

Further information can be found in the Technical Appendix.
This work was produced with funding from the Copernicus Climate Change Service (C3S) which is implemented by ECMWF on behalf of the European Commission.
Produced on 5th August, 2021.

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FIGURE 8 | C3S product sheet on decadal predictions for infrastructure: 2021–2023 SPI forecasts for the Wupper catchment and north-western Germany, started in November 2020 (published on https://climate.copernicus.eu/decadal-predictions-infrastructure).

and design of the product sheet was done by DWD. The development of the climate service included several feedback loops, but the close co-development guarantees that the resulting climate service matches the needs of the Wupper catchment water board in terms of content and format to be applied in their working routine. They consider the skill of the high-resolution SPI predictions for annual means and ASO to be promising and would be interested in receiving similar skillful products for the other seasons (to cover the whole annual water management cycle: water storage in winter with regard to flood protection and water usage in dryer seasons) and the SPEI as well. The latter describes also the possible losses from the water surface of greater reservoirs than the SPI. Thus, it correlates better to water levels of dams of bigger sizes (Lorza-Villegas et al., 2021), and would further improve the applicability of this climate service. Analyses of SPEI predictions were also performed in co-production and were part of the product sheet initialized in November 2019. However, they proved to be less robust and skillful after a model update for the predictions initialized in 2020 (see Section Conclusions). Nevertheless, first user needs of the Wupper catchment water board could be clearly fulfilled.

In addition, a common C3S_34c event was organized to showcase the four case studies on sectoral decadal predictions. Several German water managers were present to discuss the developed product sheet (the old version initialized in November 2019). They found it well-structured and understandable and could use it in their work. It shouldn't include any technical terms but the technical appendix could do so. The combined plot of prediction and skill is very interesting but probably needs some further explanation, e.g., more information on the thresholds of the categories of the probabilistic prediction (see below). Overall, the product sheet is important for water managers in communicating the probabilistic prediction and its skill. In addition, hydrological modelers would be interested in information on further atmospheric variables relevant for impact modeling for different German regions or temporal aggregations and would also need the downscaled data for modeling. An operational product sheet could be accessible *via* the C3S website or even sent per e-mail.

Some feedback could be considered already within the project and some is part of the outlook (see Section Outlook): we modified the product sheet with respect to technical terms and

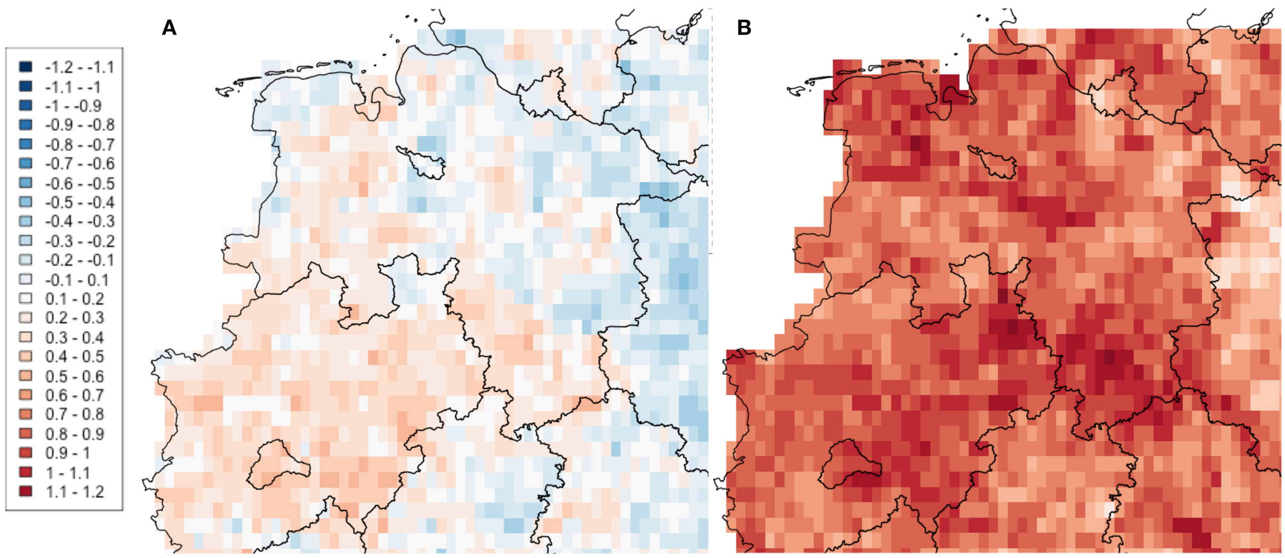

FIGURE 9 | Thresholds between the three categories of the decadal probabilistic prediction for 3-year SPI of January–December for forecast years 1–3, based on the 33% **(A)** and the 66% **(B)** terciles of observations in the reference period 1981–2010 (published on https://climate.copernicus.eu/sites/default/files/2021-09/Technical_appendix_2020.pdf, modified).

explanations of the combined plot and enlarged the study area of the (old) product sheet from the Wupper catchment area to whole north-western Germany (as shown in this paper) to fulfill similar needs of neighboring water managers. A map of the 33 and 66% terciles of observations in the reference period 1981–2010, defining the thresholds between low and normal SPI as well as normal and high SPI, respectively, was added to the technical appendix (**Figure 9**). In the north-eastern and south-eastern part of the study area the lower SPI threshold is below zero and the upper threshold above zero as expected. However, in the north-western, south-western and central parts both thresholds are above zero, indicating that the reference period reveals higher SPI values, i.e., wetter conditions, than the long-term evaluation period 1962–2020 chosen for standardization. This is especially true for the Wupper catchment area. Thus, the probabilistic SPI prediction for 2021–2023 in the product sheet showing widespread drying conditions for north-western Germany needs to be interpreted in the context that the reference period was clearly wetter than the long-term standardization period in several parts of the study area.

DISCUSSION

This final section provides a summary of the key findings of this study, discusses the major conclusions drawn from the results and gives a final outlook for future research.

Summary

In this study we present user-oriented high-resolution decadal drought predictions for German water boards, with focus on the Wupper catchment. To reach the desired horizontal resolution of ∼11 km the global decadal climate predictions of MPI-ESM-LR are statistically downscaled by EPISODES. This procedure succeeds in preserving the prevailing MPI-ESM-LR prediction skill at higher resolution. The skill assessment is performed applying (anomaly) correlation coefficients and the RPSS against the reference prediction "observed climatology." For the downscaled predictions, the standard recalibration version with a linear trend along start years does not produce the expected skill improvements as achieved with global predictions. However, an optimized recalibration version using a third order polynomial along start years is able to clearly enhance correlation and RPSS in many German regions. After standardizing precipitation predictions, the SPI drought index reveals similar or higher skill than unstandardized precipitation.

The 3-year SPI of annual means for forecast years 1–3 shows widespread positive RPSS skill in many parts of Germany, achieving significance in several north-western, central and south-eastern regions. Concerning 3-year means of hydrological seasons, the skill of ASO predictions is significantly positive in many northern and western areas. However, the positive skill in FMA and MJJ achieves significance only in some limited areas (which should not be over-interpreted), whereas significantly negative skill is found in western Germany in NDJ. The FairRPSS shows higher scores, thus indicating that there is a clear potential of further skill improvement with increasing ensemble size. Widespread significantly positive scores are found in all temporal aggregations, except for NDJ where skill remains limited to some smaller areas.

A user-oriented plot combining prediction and skill is applied for the probabilistic SPI prediction for 2021–2023, initialized in November 2020. The 3-year SPI of annual means results in dry conditions compared to 1981–2010 in most of Germany.

The predicted drying is similarly widespread in FMA but less extensive in MJJ and ASO, leaving some smaller areas for which wet and normal conditions are forecasted. In NDJ, the prediction of dry conditions is limited to central Germany, and wet conditions are computed for the northern and south-western parts. However, significantly positive skill is mainly found for annual means and ASO. The Wupper catchment area is a typical example in western Germany: Mixed conditions are predicted in NDJ and dry conditions in all other temporal aggregations, but skill might only be prominent for ASO and partly for annual means (which should be interpreted with caution).

A 2-page product sheet was designed including the main message, information on the probabilistic prediction and background information on data and methods used and resulting skills. The 3-year SPI of annual means was selected showing widespread high skill. Due to the limited space of the product sheet, the study area is focused on north-western Germany including the Wupper catchment area (instead of showing whole Germany). The product sheet based on predictions initialized in November 2020 is published on the C3S website (see text footnote 3), together with three other sectoral case studies. Detailed additional information on data and methods can be found in the C3S technical appendix (see text footnote 7).

Co-production of the product sheet with the Wupper catchment water board guarantees its usability. Their feedback and that of further German water managers was gathered at a C3S_34c showcasing event. They stated that the product sheet can be used in their work and considered the skill to be promising. Further product sheets and data for hydrological modeling would be useful. Following their needs, the study area in the product sheet was enlarged from the Wupper catchment area (old version) to north-western Germany, and a map of the observed tercile-based thresholds of the categories of the probabilistic prediction was included in the technical appendix. It shows that the reference period 1981–2010 was wetter than the long-term SPI standardization period in several regions. This needs to be considered in interpreting the widespread drying in north-western Germany in the product sheet.

Conclusions

(1) High spatial resolution of decadal predictions is needed by many users, especially water managers of small river catchments, such as the Wupper catchment water board. We find that the cost-efficient empirical-statistical downscaling procedure EPISODES is able to preserve the skill of the global prediction system at higher resolution of ∼11 km. This observed conservation of skill at higher resolution confirms also former findings of applying EPISODES to seasonal predictions of hydropower production in Germany and Portugal (Ostermöller et al., 2021).

(2) The optimized recalibration version applying third order polynomial parameters along start years can adjust high-resolution EPISODES precipitation to observed statistics and clearly improve correlation and RPSS in most of Germany. The standard recalibration version using a linear trend along start years (cf., Pasternack et al., 2018, 2021) is sufficient for global predictions at coarser resolution, e.g., for global drought indices at 5° or 2° resolution (Paxian et al., 2019). However, the variability of high-resolution precipitation in Germany makes the use of higher order polynomials, e.g., of the third order, necessary. This study reveals that statistical approaches can improve dynamical models which has also been shown by Sahastrabuddha and Ghosh (2021) applying multi-variate singular spectrum analysis, a computationally inexpensive data-driven model addressing oscillations and trends. The choice of approaches depends on variable, time and space under consideration and needs to be carefully considered in product development.

(3) Overall, skillful high-resolution decadal predictions for 3-year SPI of annual means are possible for several north-western, central and south-eastern parts of Germany, exceeding correlation coefficients of 0.6 and/or revealing significantly positive RPSS against the reference prediction "observed climatology." This also holds for 3-year mean ASO predictions in northern and western Germany. The skill of these high-resolution results is mostly similar to decadal drought predictions of former studies: Paxian et al. (2019) find similar skill for 4-year mean SPI predictions in different areas of the globe. Four-year mean SPEI predictions based on the Thornthwaite (1948) parametrization for PET achieve higher skills in the tropics due to large temperature trends but cannot be applied to colder seasons in Germany. Solaraju-Murali et al. (2021) find as well positive RPSS for 5-year mean SPEI predictions for the 6 months preceding the wheat harvest month in several regions worldwide, based on a multi-model. For northern Germany and Scandinavia, Solaraju-Murali et al. (2019) detect multi-model skill of five-year mean summer SPI. Finally, similar correlations and probabilistic scores are found for a NAO-based multi-model prediction of the 10-year mean winter precipitation for regional means of Spanish and Italian river catchments (see text footnote 1).

(4) The close co-production with the Wupper catchment water board in developing the product sheet is essential to guarantee that it is understandable, matches user needs and that format and content can be used in their working routine. They computed the drought index following their standard procedure because they use statistical relationships between drought index values and dam water levels based on this method. In addition, feedback of the Wupper catchment water board and further German water managers at the C3S_34c showcasing event was gathered. The usability of the product sheet in their work was confirmed, first feedback could be considered within the project, and we aim at developing further required products to consider the residual feedback in the future. This confirms similar experiences in the development of the DWD climate predictions website[8]. Users are involved in the product development *via* individual meetings, surveys and workshops, and such feedback loops strongly improve the understandability and applicability of the final climate service.

(5) This case study was part of the C3S_34c contract developing sector-specific applications. A close scientific exchange between the developers took place improving the prevailing

[8]www.dwd.de/climatepredictions

product sheet. The first case study using the decadal predictions initialized in November 2019 applied the downscaling of the old MPI-ESM version. The focus was set on the 3-year mean high-resolution SPEI of the FMA season, closely following the user need and applying the Penman-Monteith parametrization (Allen et al., 1998) for PET. Unfortunately, high-resolution observations for wind and radiation in Germany are only available for a short evaluation period of 1995–2012. However, after a model update to the new MPI-ESM-LR version the first case study was not skillful any more. The developers of the other case studies recommended to use a longer evaluation period to be more robust, more ensemble members from different models to be more resilient against model updates and to improve skill in Europe considering the signal-to-noise paradox of weak predictable model signals (Scaife and Smith, 2018) and skillful large-scale teleconnections to improve the skill (see text footnote 1)[9]. In the second case study based on the downscaling of the new model version initialized in November 2020 (and presented now in this paper) the 3-year mean high-resolution SPI is chosen, allowing for a long evaluation period and robust statistical recalibration due to available high-resolution precipitation observations. The FairRPSS results (cf., **Figure 6**) indicate a potential skill improvement with increasing ensemble size. However, a multi-model cannot be downscaled because the daily input data for EPISODES is not (yet) available (see Section Outlook). In addition, large-scale teleconnections between a multi-model NAO prediction (based on the four global models of the scientific partners) and high-resolution SPI and SPEI observations in Germany were analyzed but the link is not strong enough to improve skill (see Section Outlook). Nevertheless, a skillful high-resolution SPI prediction is found, highlighting the benefit of close scientific exchange in product development.

(6) The final conclusion is the most important one and directly results from the experiences described in conclusion (5). User needs and scientific capabilities need to be weighed against each other. Users often ask for very specific products, considering complex variables, high spatial resolution and short time periods. However, decadal prediction skill is mostly found for large-scale variables over large regions and time periods. Thus, if no skill is detected for a certain user need, a "compromise solution" might be found in analyzing other variables, but of a similar kind, larger areas or longer time periods as described in conclusion (5). Within the co-production of a climate service such alternative products need to be defined in cooperation with the user, of course.

Outlook

This study motivates further research to improve decadal prediction skill of high-resolution drought predictions for German water boards: first, the statistical downscaling EPISODES should be applied to more ensemble members of a multi-model ensemble. To reach this goal daily temperature, relative humidity and geopotential height fields at different levels need to be available from decadal prediction systems. In addition, EPISODES was developed to downscale climate projections and is thus, optimized to reduce bias but not to enhance skill. Thus, the downscaling should not only consider the best relationship between a large-scale input variable and a high-resolution output variable but also the best skill of the large-scale input. More skillful large-scale teleconnection patterns in a larger region of the North Atlantic/European sector need to be considered in statistical downscaling. A first analysis shows that the teleconnection of the NAO to Germany is not strong enough, but further teleconnections need to be investigated.

Second, the C3S_34c showcasing event revealed that German water boards are interested in decadal predictions of high-resolution droughts and further atmospheric variables relevant for water management and hydrological impact modeling. Concerning more robust SPEI predictions, high-resolution observations for radiation and wind with long time periods would be needed for the Penman-Monteith parameterization (Allen et al., 1998) of PET. In this context, it would be interesting to test the parameterization of Hargreaves and Samani (1985), requiring less input data than Penman-Monteith and thus, simplifying the search for high-resolution observations in Germany. Instead, the parameterization of Thornthwaite (1948) cannot be computed for cold seasons in Germany. Overall, DWD plans to publish operational predictions for high-resolution drought conditions in Germany for the next weeks, months and years based on sub-seasonal, seasonal and decadal climate predictions on the DWD climate predictions website (see text footnote 8). Further relevant variables such as wind, humidity or radiation might be added as well to cover the needs of German water boards and hydrological modelers. In addition, the access to the downscaled prediction data should be enabled. Regular exchange in user workshops, surveys and individual user meetings supports the development of this climate service to ensure that the presented operational prediction products are understandable and can be applied in the working routines of the users.

[9]https://climate.copernicus.eu/decadal-predictions-insurance

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

APax designed the methodological concept of the case study assisted by BF, KP, and MS. KP generated the global model data. AH and PL generated the downscaled data. APas and BM conducted the recalibration. ML-V, KR, and KP conducted the calculation of the SPI (and the SPEI in the first case study). KR and APax assessed the prediction skill, estimated probabilistic predictions, designed the product sheet, and considered the user feedback. APas executed a SPI (and SPEI) prediction based on a multi-model NAO prediction. APax wrote the manuscript and considered revisions of all coauthors. All authors contributed to the article and approved the submitted version.

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Designing Climate Information Services to Enhance Resilient Farming Activities: Lessons From Papua New Guinea

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Anthropogenically-driven changes in seasonal climate patterns are already jeopardizing traditional farming practices all around the world. These climatic changes increasingly expose farmers to challenging conditions, reducing the efficacy of existing farm practices and productivity. There is a plethora of information, tools, and practices that could be useful for farmers trying to respond to climate variability and change, including climate projections, horticultural advances, and agricultural management best practices. Whilst these tools and knowledge exist, they are often not contextualized in ways that equitably facilitate decision-making and action. To ensure weather and climate information services are accessible and useful to farmers, it is critical to understand and integrate considerations for the desired types, timing, and uses of the information. The one-size-fits-all information services that are often available don't account for regional or social differences, local physical conditions, or the needs of different populations. In order to improve our understanding of how weather and climate information services can better cater to farmers' needs when modifying and adapting their goals, risk management, and farm practices, we carried out a household survey in communities across three provinces in Papua New Guinea. The survey was developed to draw out key design considerations for seasonal climate forecasts in terms of timing, type of information, and applications. Based on the clustering and associations of these variables, this study identifies different profiles of information services content. It then examines whether specific profiles are associated with demographic groups or geographic locations. The findings demonstrate gender and geographic differences in the desired bundles of weather and climate information, and therefore can help to pinpoint specific components that would be beneficial to incorporate into extension and outreach programmes in different contexts within Papua New Guinea. This study highlights the value of tailoring weather and climate information services with specific groups of farmers, thereby enabling more equitable access to and use of critical knowledge for smallholders to build the capacity, knowledge, and systems to strategically adapt to climate change. At the same time, this study illustrates areas to gain efficiency and potentially scale up the provision of climate information services.

Keywords: climate information services, Papua New Guinea, smallholder farming, gender, cluster analysis

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INTRODUCTION

The Climate Challenge for Agriculture

Island nations are expected to be increasingly and severely vulnerable to adverse impacts of climate change (Mycoo et al., 2021). The residents of Pacific Island nations are likely to face particularly detrimental effects from climate change, including major impacts related to sea level rise and shifts in rainfall leading to freshwater challenges (Nurse et al., 2014). The Sixth Assessment report of the Intergovernmental Panel on Climate Change (IPCC) found that the Pacific will experience increasingly extreme weather, in terms of elevated temperatures, periods of heavy rainfall, flooding, and drought, and progressively more intense tropical cyclones (Ranasinghe et al., 2021).

Communities reliant on agriculture-based livelihood systems have been identified as particularly at risk from climate change, due to likely increases in crop failure, new patterns of pests and diseases, lack of appropriate seed and plant material, and loss of livestock (Taylor et al., 2016; Iese et al., 2020). These types of impacts are already reducing the growth in productivity of agriculture across most of the globe (Ortiz-Bobea et al., 2021). In the South Pacific region, recent shortfalls in agricultural production resulting from climatic variations and changes, in addition to changing export markets, commodity prices, population growth, and urbanization, have meant a greater reliance on imported foods, thus contributing further to regional food insecurity concerns for the future (Taylor et al., 2016).

In Papua New Guinea (PNG), the largest Pacific Island nation, around 80% of the food consumed is grown domestically (Iese et al., 2020). Historical analyses have shown that the variability of food production is strongly correlated with climate variability. For instance, a strong El Niño event typically reduces rainfall significantly below the mean in otherwise wet regions for extended periods, prolonging dry seasons, generating drought conditions, and reducing cloud cover (Smith et al., 2013). A decrease in rainfall can contribute to water stress and reduced crop productivity. Furthermore, the reduction in cloud cover and drier atmospheric conditions that promote radiative cooling in the highlands of PNG can also increase the probability of frost damage to crops (Smith et al., 2013). While there is still uncertainty around the extent to which elevated greenhouse gas concentrations will affect El Niño Southern Oscillation (ENSO), increasing rainfall variability associated with ENSO-like conditions in the Pacific is highly likely and will further stress agriculture production in PNG (Cai et al., 2014; Lee et al., 2021). Current and historical impacts are a portent of what can be expected to occur under projected climate changes.

The observed and projected climatic changes expose farmers increasingly to conditions outside of those they regularly experience, requiring new knowledge and adapted practices to respond. Farmers have begun to respond to stresses by altering planting times, shifting to better-adapted varieties of crops and livestock, improving soil organic matter, adopting agroforestry and low-carbon farming, and relocating farms (Iese et al., 2020). However, farmers will need to make the sufficient and efficient adjustments and potentially transformative changes in the face of worsening climate impacts (Rickards and Howden, 2012), which will require drawing on novel tools tailored to their needs.

This study aims to understand the information needs of farmers in order to assist the design of knowledge, tools, and practices to enable effective adaptation to climate variability and change. While there is a plethora of tools and knowledge that could be useful to farmers trying to adapt to climate variability and change, barriers related to accessibility, context, and use continue to persist (Hewitt et al., 2020). It is therefore critical to identify what factors influence adoption and adaptation of farm practices, and how to design fit-for-purpose information systems (Shepherd, 2019).

Informing Farm Adaptation

Access to extension and weather and climate information services has been shown to increase the abilities of farmers to adopt better management practices and adapt to climate variability (e.g., Belay et al., 2017; Juan, 2018). Such information services translate weather and climate information into advisories that can aid decision-making, such as supporting farm management choices (Tall et al., 2018). In the farm-level management context, weather and short-term climate information at timescales of days, weeks, months, and seasons are of greatest interest and use (Nkiaka et al., 2019). While weather and climate information can be produced through a variety of sources and methods (Singh et al., 2018), packaging it as an information service requires tailoring content and delivery so that it is salient for end users (Tall et al., 2018; Nkiaka et al., 2019).

Previous research has shown that access to weather and climate information can improve farmers' awareness of climate change, including what climate change is, the impacts it can have, and constraints to adapting (Roco et al., 2015; Habtemariam et al., 2016; Ng'ombe et al., 2020). Studies have also shown that smallholder farmers who have access to weather and climate information—particularly seasonal and sub-seasonal scale forecasts—are more likely to implement climate adaptation strategies, including late or early plantings, use of early maturing crops, agroforestry practices, and soil and water conservation measures (Belay et al., 2017; Dewi and Whitbread, 2017). Such climate and weather information is especially valuable where farming is vulnerable to climate variability, such as in smallholder rainfed systems (Meza et al., 2008), like those in PNG.

The form and content of weather and climate information can vary based on available resources, as well as the intended purpose or use of this information. Seasonal climate forecasts, one family of products that can guide choices farmers make, can reduce uncertainty for farmers when implemented systematically, by enabling them to differentially weight the possible outcomes in a season (Meza et al., 2008). Studies have shown that seasonal climate forecasts should be produced and have relevance at different levels—from national or regional, down to the local—in order to be context relevant and action orientated (Bouroncle et al., 2019). For example, in Colombia and Guatemala, Bouroncle et al. (2019) identified monthly and seasonal climate and agro-climatic bulletins and daily (agrometeorological) forecasts as available to farmers. Broadly, this information was used to advise on agricultural activity planning, provide early warning of extreme climate events or food security alerts, and for organizational planning. Conversely, a study in the Pacific Island nations of Vanuatu, Niue, Solomon Islands, and Tonga examining the types of information local communities used, found that most people preferred to use traditional knowledge-based forecasts, except during extreme events like cyclones, when contemporary forecasting systems were used (Chambers et al., 2019). In PNG, agricultural extension services encompass communication and learning activities for agrarian communities ranging from agronomy and cultivation, to business and marketing, to engineering and technology (Sitapai, 2012). However, current agricultural extension services do not explicitly integrate weather and climate forecasting.

What Affects Information Access and Use?

Often, the one-size-fits-all model for available information products doesn't account for regional cultural discrepancies, local physical conditions, or the needs of different populations. There is evidence from studies in Africa that broadly similar needs may exist across the continent, but information must be tailored for different socially-constructed user groups (Nkiaka et al., 2019). Gender has been highlighted as a critical factor in dictating the necessary content, form, and dissemination of weather and climate information services (Farnworth and Colverson, 2015; Chanana et al., 2018). In many cases these divergent information needs are attributed to established gender roles and unequal participation in decision-making (Jost et al., 2016; Mehar et al., 2016). As an example, in a study in Bangladesh, men were responsible for on-the-ground agricultural activities, marketing, and managing farm proceeds, while women undertook post-harvest work and livestock production (Jost et al., 2016). These roles meant men sought out climate information relevant to land preparation, cultivation, and crop varieties, while women sought information relevant to new income-generating activities, credit schemes, and coping mechanisms for times of food insecurity. Similarly, information needs varied in Ghana, where men reported accessing and using weather information to plan cropping areas and varieties, as well as household protections from storms (Jost et al., 2016). Conversely, women accessed information suited for planning their household chores, like firewood and water collection, milling, cooking, and washing. Research in Africa and Asia has argued that differences in access to assets (e.g., land, financial, natural, social) between men and women underpin adaptation strategies and consequently the types of weather and climate information required (Aryal et al., 2020, 2021; Islam et al., 2021). Following an intersectional approach, other socio-demographic factors, such as education, age, social status, and income have also been shown as influencing adaptation strategies in smallholder farming (Belay et al., 2017; Friedman et al., 2018; Tall et al., 2018; Carr et al., 2020; Lawson et al., 2020).

While a range of forecast tools and knowledge exist, they are often not contextualized or translated in ways that encourage or facilitate decision-making and adaptation (Lemos et al., 2012; Hansen et al., 2019). Review articles have identified and elaborated on a number of broad constraints and facilitating factors that influence access and use of climate information products, particularly climate forecasts. The relevance and credibility of the information and the legitimacy of processes are critical predisposing factors to adoption (Cash and Buizer, 2005). In sub-Saharan Africa, constraints relate to the information content, access to forecasts, and availability of resources to act on information (Hansen et al., 2011). Another global review outlined the issues of fit, interaction, and interplay as three areas of barriers and opportunities for using climate information services (Lemos et al., 2012). For this study, we examine aspects of fit, including the salience, timeliness, and utility of the information. To ensure weather and climate information products are accessible and of use to farmers, it is critical to understand and integrate considerations for what types of information are actually desired and applied, what they are used for, and at what points in the year, in addition to how information services can be best delivered.

With limited resources, and imminent climate threats, it is important to design weather and climate information services in the most efficient manner possible, while also ensuring that the needs of key potential users are addressed. Identifying clusters of information requirements within and between communities can facilitate the development of information products in a way that both captures the range of information and limits the amount of redundancy between products. This study aims to improve our understanding of how weather and climate information services can be developed to better fit farmers' needs in order to modify and adapt their goals, manage risks, and strategically implement management practices in the face of climate change. Specifically, we asked:

1. What are the information types and timings that smallholder farmers require to address the risks associated with weather extremes and variability in a changing climate? And for whom?
2. How is this weather and climate information applied to farm management decisions? And by whom?
3. How could these information needs translate into specific weather and climate information products?

Much of the work on this topic in relation to smallholder farmers has taken place in Africa (Hansen et al., 2011; Nkiaka et al., 2019; Born, 2021), Asia (Sivakumar et al., 2014; Tall et al., 2014; An-Vo et al., 2021; Hossain et al., 2021), and Latin America (e.g., Miralles-Wilhelm and Muñoz Castillo, 2014; Loboguerrero et al., 2018), while little examination of differential weather and climate information needs has occurred in Pacific Island nations. As such, this study helps to fill a critical geographical gap in research on the topic.

MATERIALS AND METHODS

Data Collection and Preparation

In this study, we carried out a household survey in communities across three provinces in PNG: Eastern Highlands; Morobe; and East New Britain (**Figure 1**). Eastern Highlands is one of the coldest regions in PNG, with a temperature range of 15–28°C (mean minimum to mean maximum), and a distinct dry

FIGURE 1 | Map of study provinces in Papua New Guinea.

season from June through September (McAlpine et al., 1983; WorldData.info). Morobe province has a warm, relatively stable temperature annually (ranging between 25 and 35°C), with a season of greater rainfall from December through March. However, the Markham Valley in Morobe, where the survey was administered, is the driest area in the province. East New Britain also has a tropical climate, with average temperatures ranging from a minimum 24°C to a maximum of 29°C, and comparatively wetter months between December and April. The country is largely agrarian, with at least 80% of the population reliant on the agricultural sector (Bourke and Harwood, 2009). Food for domestic consumption is primarily produced within the country in low-intensity, rainfed smallholder systems. Although diets vary considerably across PNG, staple foods such as root crops (e.g., sweet potato), sago, and banana, as well as coconut, nuts, and green vegetables are broadly consumed. Many farmers also earn income from domestic and export cash crops. Main export crops are coffee, cacao, oil palm, copra, vanilla, tea, and rubber, while fresh produce is sold at local and urban markets.

Overall, 1,281 respondents were engaged through data collection activities, conducted across two iterations of fieldwork, in October 2018 (Morobe and Eastern Highlands) and October 2019 (East New Britain). Study areas were identified in consultation with the National Agriculture Research Institute (NARI) in PNG to ensure relevance and feasibility, and then villages in each study area were randomly identified.

Survey teams, made up of local Papua New Guinean researchers from NARI and Anglo Pacific Research (APR), followed a stratified random sampling approach to identify respondents, while also filling sampling quotas to ensure a representative spread of the population by gender and age (18–25, 26–40, 41+) in target areas. The survey targeted participants who identified as farmers, were over 18 years old, engaged in crop-based agriculture, and who resided in the study areas. In all surveys conducted, female interviewers interviewed female respondents, and male interviewers interviewed males. All data were collected using the Akvo tablet-based data collection platform. The Human Research Ethics Committee at the Australian National University approved this study (2018/831) before commencing data collection, and all participants gave their informed consent.

The survey was developed to draw out key design considerations for seasonal climate forecasts in terms of timing, content, and use of information, as well as the social networks of information exchange (reported on in a different study). Because participants could provide multiple responses to some of the survey questions, the data was reformatted as binary response variables.

TABLE 1 | Variables used for the study analysis.

Clustering Variables	Description
Receipt of information from others	Binary variable: Yes; No
Important months for weather information and forecasts	Categorical variable: January; February; March; April; May; June; July; August; September; October; November; December
Important types of information	Categorical variable: rain-seasonal; rain-three monthly; rain-monthly; rain-weekly; rain-daily; temperature-weekly; temperature-daily; drought-season; frost-daily; tidal-daily; wind-daily; flooding; other
Information uses	Categorical variable: land preparation; crop type; planting times; transplanting seeds/seedlings; fertilizer application; application of insecticide/herbicide; harvest timing; taking produce to market; collection of produce from the farmer.
Predictor variables	**Description**
Weather impacts on farming activities	Categorical variable: land preparation; crop type; planting times; transplanting seeds/seedlings; fertilizer application; application of insecticide/herbicide; harvest timing; taking produce to market; collection of produce from the farmer.
Biggest challenges in accessing and using weather information	Categorical variable: not frequent; not locally relevant; not understable; not good quality; not trustworthy; no access
Socio-Demographics	Categorical variable: province
	Categorical variable: age (range)
	Binary variable: male; not male
	Categorical variable: education level (block)
	Categorical variable: occupation
	Categorical variable: garden purpose

Data Analysis

In the first instance, we used descriptive measures and statistics to understand how information needs were distributed across groups. Chi-Square analyses (with contingency tables) were carried out using the "gmodels" package (Warnes et al., 2005), to identify whether differences in the clustering variables existed based on the gender of farmers or their geographic locations.

Cluster analysis provides a useful method to examine the intersection and groups of multiple variables simultaneously. The variables related to timing, types, and uses of information were used to examine how climate and weather information could be bundled to form discrete information products (**Table 1**). To delineate particular profiles of information, we performed k-medoids cluster analysis using the "cluster" package (Maechler et al., 2021). Gower distance was used in the computation of pairwise dissimilarities. The number of clusters ($k = 5$) was determined using the silhouette method, an internal validation approach that compares silhouette measures indicating similarity of a data point to its own cluster compared to other clusters, for different numbers of clusters.

Once clusters were defined, the dominant information needs for each were summarized and described. Individual respondents were assigned a cluster number based on the fit of their responses. To better understand what characteristics could influence cluster membership, we used chi-square analyses between cluster number and socio-demographic variables. We also included perceived challenges to accessing and using information in the analysis in order to highlight potential barriers to rolling out the different cluster information products. All visualizations were created using ggplot2 (Wickham, 2016).

RESULTS

Information Types and Timing

The majority of farmers have similar needs in terms of information type and timing. However, patterns of divergence begin to emerge when broken down by gender and province (see **Supplementary Table 1**).

Seasonal rainfall is the most broadly desired information, followed closely by weekly and daily rainfall forecasts, drought warnings, and daily and weekly temperature forecasts. Men and women have distinct information needs ($\chi^2 = 309.46$, df $= 11$, $p < 0.001$). Men primarily want seasonal rainfall and drought information, while women relatively consistently cite seasonal and daily rainfall and daily temperature forecasts. The biggest discrepancies by province ($\chi^2 = 609.58$, df $= 22$, $p < 0.001$) are in East New Britain, where men cite daily wind information as important. Women favor rainfall and temperature as weekly forecasts in East New Britain, but on a daily timescale in Morobe. Rainfall is generally more important than temperature for women in the Eastern Highlands.

June is the most frequently-cited month for receiving information, followed by September and January. However, gender ($\chi^2 = 69.671$, df $= 11$, $p < 0.001$) and provincial ($\chi^2 = 244.56$, df $= 22$, $p < 0.001$) differences in key months are pronounced. September is more important for women, while July and January are for men. In Morobe, June is clearly the most important month to receive information, but September is relatively more important in Eastern Highlands Province and East New Britain for women, and January is for men in East New Britain and women in Morobe.

Information Uses

While some uses of climate and weather information dominated (**Supplementary Table 1**), these also varied by gender ($\chi^2 = 60.78$, df $= 11$, $p < 0.001$) and province ($\chi^2 = 155.07$, df $= 16$, $p < 0.001$). Women more often than men cited the use of weather and climate information as being important to inform planting and harvest times, while men cited using information to inform crop choice and market-related activities more than women. Both noted the importance of rainfall forecasts to inform land preparation, but this varied by gender and province; men more often cited this use in East New Britain and women in the Eastern Highlands and Morobe. The other main divergence of this type was women using information to transplant seedlings in East New Britain, while men were more likely in the Eastern Highlands. Weather and climate information guided fertilizer and insecticide application essentially only in the Eastern Highlands, and primarily for women.

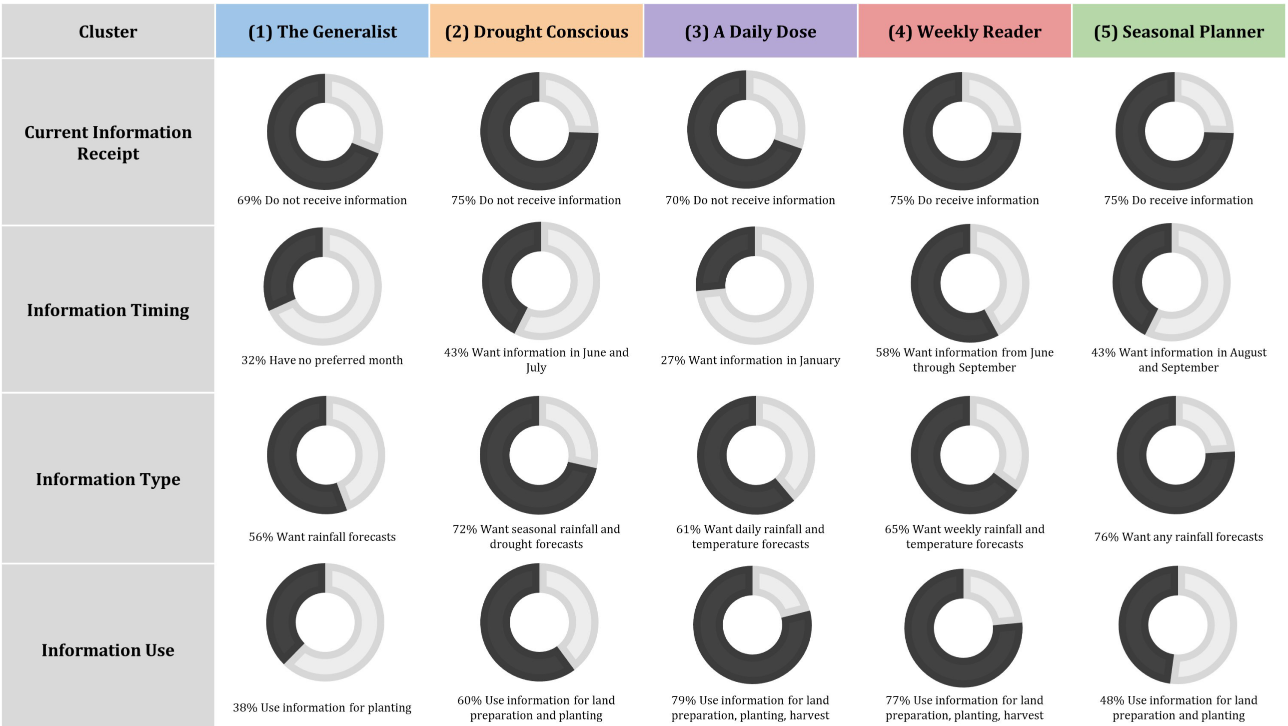

FIGURE 2 | Typology of climate information needs based on the cluster summaries.

Clusters—Information Needs Profiles

Five clusters of information needs were identified through the cluster analysis. The distribution and composition of the clusters reflect the skewed nature of the data itself. Membership of clusters ranged from 155 individuals to nearly 500 (**Supplementary Table 2**), highlighting groups that may have more specialized information needs to meet. The profiles of the identified clusters are found in **Figure 2**.

Most respondents fall into the first ($n = 470$) or second ($n = 294$) clusters. The majority of members in those clusters do not currently receive information (69% and 75%, respectively). Nearly one-third of members in cluster 1—**"The Generalists"**—identify all months as being equally important for receiving information. Daily temperature, and daily, weekly, and seasonal rainfall forecasts are the most important types of information. It is also the only cluster where frost forecasts are desired. Information is used primarily for determining when to plant, and then preparing the land and optimal time for transplanting seedlings or cuttings. Cluster 2—**"Drought Conscious"**—focuses mostly on the dry months of June and July, and seasonal forecasts of rainfall and drought. This information is used primarily to determine land preparation and planting, but to some extent the choice of crops and when to harvest.

Most members in Cluster 3 ($n = 155$)—**"A Daily Dose"**—do not currently receive climate or weather information (70%). Members of this cluster primarily desire daily temperature and rainfall forecasts, with some wind and flooding information. January (wet season) is seen as the most important time to receive information. Members of this cluster use information to plant, prepare land, and harvest crops. Members of the fourth cluster—**"Weekly Readers"**—already receive information (75%), and use it for land preparation, planting, and harvests. Weekly temperature and rainfall forecasts form the basis of this cluster, primarily for the dry months (June, July, and September). Finally, the fifth cluster—**"Seasonal Planner"**—is characterized by a majority of members currently receiving information (75%) for a broad range of uses. While still low, application of fertilizer and pesticides is most prominent in this cluster. The end of the dry season (September and August) is considered most important for receiving information, particularly seasonal and daily rainfall forecasts.

Targeting Information Products

Gender

There are significant differences in cluster membership based on gender ($\chi^2 = 68.63$, df $= 4$, $p < 0.001$). While Cluster 1 is nearly gender-equitable, Cluster 2 is composed of about two-thirds (66.7%) male, and Clusters 3–5 have predominantly female membership (60–65%). See **Figure 3** for breakdown of clusters by gender and province.

Province

Cluster membership is also tied to province ($\chi^2 = 289.72$, df $= 8$, $p < 0.001$). Around half of Cluster 1 membership is from East New Britain. Clusters 2 (46.6%) and 3 (63.9%) have greater membership from residents of Morobe province. Eastern

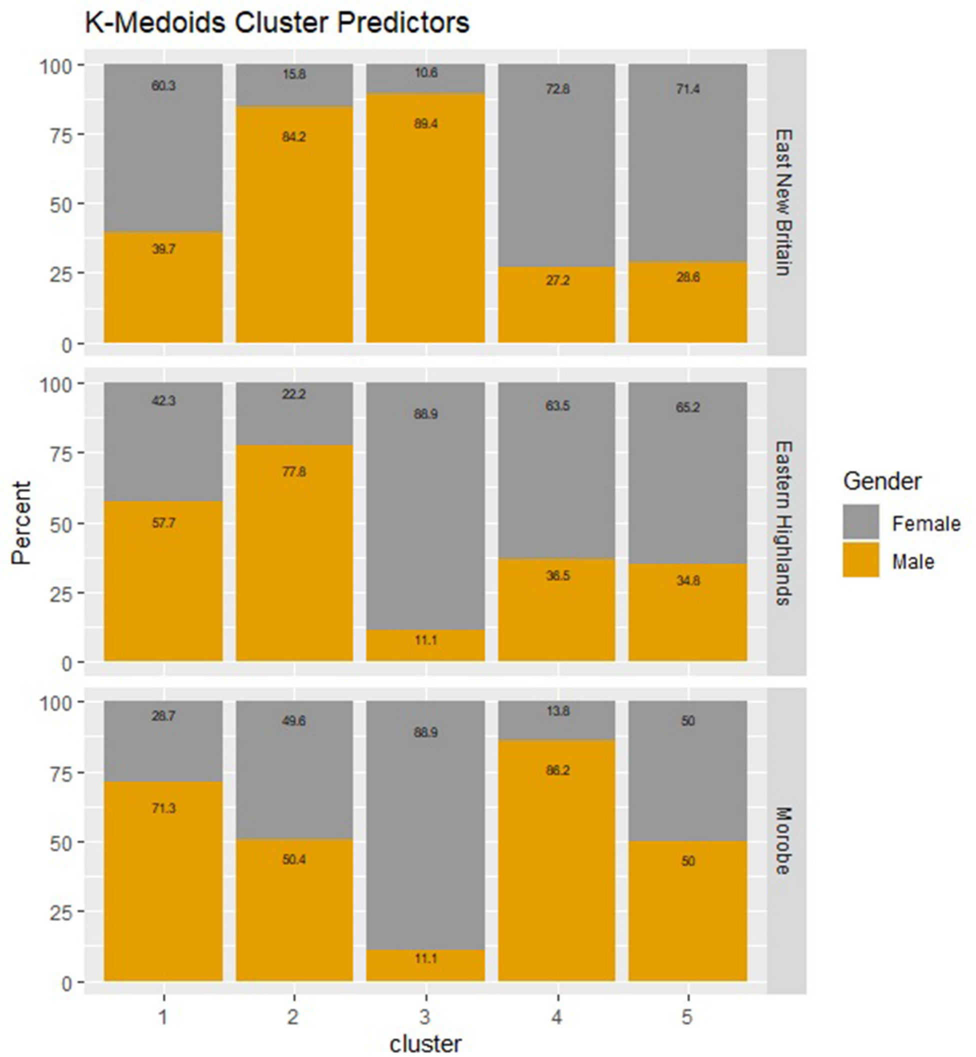

FIGURE 3 | Gender and provincial composition of cluster membership. Values are percentages within cluster.

Highlands (43.6%) and East New Britain (41.5%) share their prominence in Cluster 4. Eastern Highlands residents are most prevalent in Cluster 5 (68.9%).

Education

There are no significant variations in cluster membership based on education ($\chi^2 = 17.37$, df $= 12$, $p = 0.13$). Most respondents have completed primary or secondary education, thus those education levels dominate by sheer numbers, contributing to the lack of significant variation between clusters (**Supplemental Figure 2**). Percentage-wise, compared to other clusters, secondary school is most prominent in Cluster 1 (43.0%) and 4 (46.2%). Similarly, as a product of percentages within clusters, primary schooling is most prominent in Cluster 2 (35.0%) and Cluster 5 (37.1%). The highest rates of no formal schooling are in Clusters 3 (22.6%) and 5 (17.4%). And while only a small proportion of respondents have a tertiary or vocational education, they are comparatively more likely to be found in Cluster 1 (11.7%), with the most well-educated women in Cluster 2.

Occupation and Scale of Operation

While the majority of respondents state that farming is their primary occupation (60%), there are still significant differences between clusters ($\chi^2 = 206.81$, df $= 24$, $p < 0.001$). For instance, those in "other" occupations—self-employed, unemployed, and retired—are most apparent in Cluster 1 (16.4%). Those working at home or in a domestic capacity are prevalent in Cluster 3 (18.7%), and respondents employed as market operators, either at markets or selling to third parties, are most often found in Cluster 5 (21.6%). Students, government employees, and other wage earners are in the minority, and did not demonstrate any particular patterns. In terms of scale of operation, there were minor differences between cluster ($\chi^2 = 29.88$, df $=$

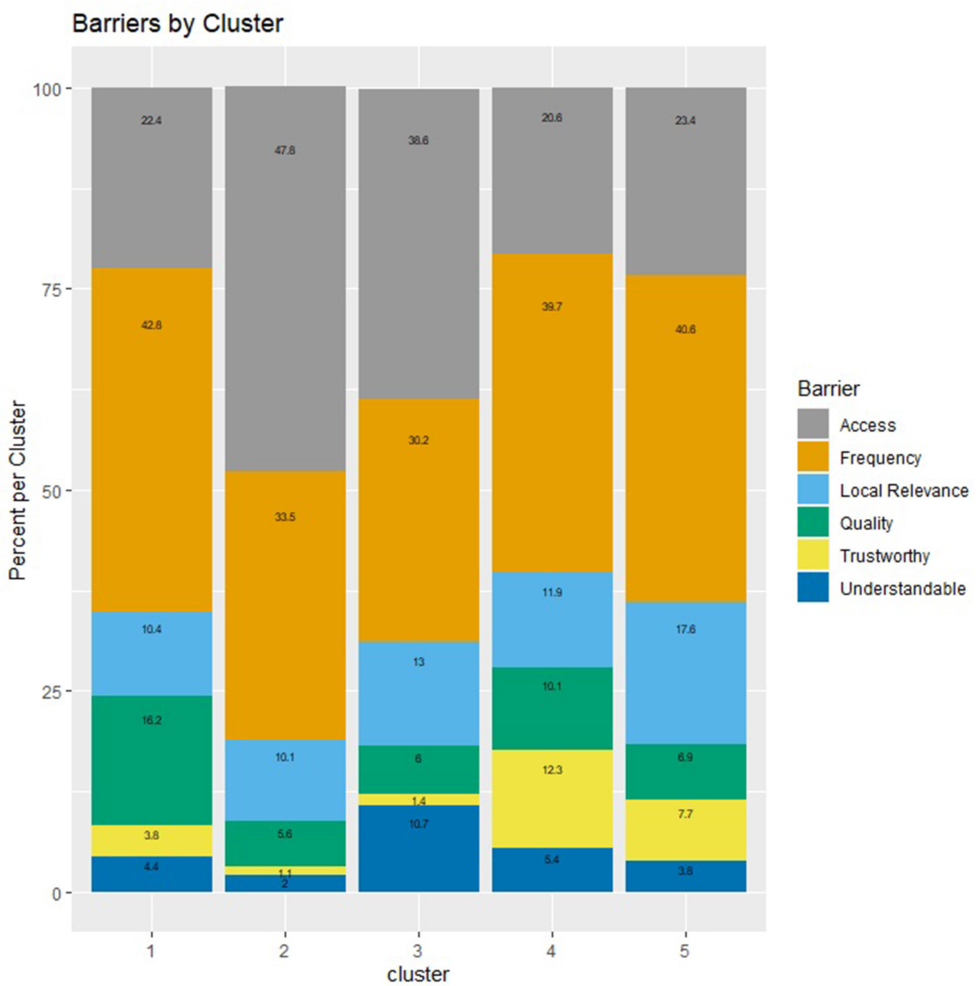

FIGURE 4 | Distribution of perceived barriers to accessing and using climate information by cluster. Values are percentages of the barriers within the cluster.

12, $p = 0.003$), although producing crops for both sale and subsistence dominated across clusters. The only major divergence was in Cluster 1, which had more subsistence-only farmers than expected.

Barriers

Perceived barriers also correspond to certain clusters ($\chi^2 = 213.37$, df $= 32$, $p < 0.001$) (**Figure 4**). The frequency of information is seen as the dominant barrier for Clusters 1 (42.8%), 4 (39.7%), and 5 (40.6%). Lack of access to information is clearly the most critical barrier for Cluster 2 (47.8%), and also important for Cluster 3 (38.6%). Information not being relevant to the local context is perceived as a barrier most in Cluster 5 (17.6%). Poor quality of information is mostly seen as a barrier by members of Cluster 1 (16.2%). Information considered not trustworthy is seen as a major barrier primarily by those in Cluster 4 (12.3%). And finally, difficulty understanding information is perceived as a barrier most by members in Cluster 3 (10.7%).

DISCUSSION

Through this study, we examined how climate and weather information needs differed amongst farmers, in order to guide improved climate information services that are able to enhance adaptation to climate change. We employed a clustering approach to illustrate relationships emerging between multiple climate information variables, demonstrating how desired information content is not consistent across regions or demographic groups. While it is useful to identify broad information needs, these clusters helped pinpoint groups who may otherwise find their interests under represented or marginalized.

Failing to consider how the needs and desires related to climate information services vary runs the risk of overlooking or even undermining the needs of some groups of farmers, and disempowering others to undertake adaptation activities. The distinct profiles of information needs depicted in this study map to social and geographic factors, such as gender, province, and occupation, and provide insights for developing products and advisories aimed at supporting adaptation for specific subsets of the farming population. While clustering algorithms seek to minimize within-cluster differences and maximize differences between clusters, the results of our analysis also show areas of similarities between clusters. This suggests the possibility for core messages and efficiencies to be gained when developing and scaling information services. Finally, it is critical to successfully connect clusters of information content to end users. An understanding of perceived barriers and how information flows in farming communities can facilitate successful integration of information services. Balancing efficient development of climate information services and the specificity of farmers' needs is essential both to rapidly build the capacity, knowledge, and systems to strategically adapt to climate change, and to facilitate more equitable access to and use of critical knowledge for smallholders.

Tailoring for Different Perceived Needs

Appropriately tailoring climate information services may have implications for building farmers' capacity to adapt to climate change, both in terms of ensuring farmers have the information they want, and whether that information supports or informs the sorts of decisions they may need to undertake to address climate stresses. There is evidence from other studies on weather and climate information services, largely in Sub-Saharan Africa, that the use of timely and well-tailored services can in fact prompt such necessary changes in farming practices and improve yields (Hansen et al., 2011, 2019; Nkiaka et al., 2019). However, considering factors such as salience—or the relevance and associated tailoring of information—and equity—inclusion of women, poor, and other socially marginalized groups—are critical for the success of climate information services (Hansen et al., 2011; Tall et al., 2014). Previous studies have demonstrated how the uptake and use of climate information depends on its local relevance (to biophysical, crop, and farmer characteristics) and how well it connects to livelihood or economic impacts for end users (Singh et al., 2018). Our study illustrates how factors, particularly gender and province, in combination can result in distinct information needs that would need to be accounted for in such tailoring.

The information content associated with clusters has implications for how effective information services might be at supporting the capacity to adapt to climate variability, extremes, and shifts. Clusters primarily diverged based on when information was desired and the type of information. In particular, preferences seemed to emerge related to seasonality (focus on wet season or dry season), and forecast length (ranging from a day to the whole season). While both shorter and longer term outlooks have utility when making decisions, the latter are critical for moving beyond coping mechanisms and instituting strategic foresight into farm management (Rickards and Howden, 2012). Clusters 3 and 4 in particular have short-term outlooks, which are crucial for operational management, but could potentially overlook long-term planning or adaptation needs. Whereas, Clusters 2 and 5 are more in-line with what we'd assume to be beneficial to farmers making plans in the face of climate change, such as early warnings for extreme events and seasonal forecasts. Seasonal forecasts are often used to make more tactical decisions around what seed varieties to choose, purchase of inputs, and spatial planning; whereas shorter-term daily and weekly forecasts are used to make calculated micro-adjustments to planting, applications, harvesting, and other operations (Nkiaka et al., 2019). Furthermore, repeated use of seasonal forecasts may help farmers to distinguish shifts over time and adjust to longer-term changes (Singh et al., 2018). While climate information that extends beyond the seasonal time-frame is considered valuable to achieving more transformative changes in response to novel climatic conditions, it is however often poorly suited to the types of decisions farmers need or are able to make at local levels (Singh et al., 2018).

The results of the cluster analysis show that prominent information needs vary by region and gender. In PNG, research has shown that while men are considered to be the heads of households and as such dominate decision-making particularly for cash crops (Eves and Titus, 2020), women are still involved in most aspects of agricultural production and tend to have greatest input into planting and harvesting of food crops and general maintenance tasks (Bourke and Harwood, 2009; Curry et al., 2019). It is therefore understandable that information needs might diverge based in some part on gender. Clusters 3, and 4 have majority female membership and tend to focus on shorter temporal windows (i.e., daily, weekly), which may support their primary farming roles but not be as conducive to adapting to climate change in the long-term. While both the majority female Cluster 5 and the majority male Cluster 2 prioritize information and timing that helps address periods of seasonal water scarcity, men claim they need information early in the dry season (June/July) and women toward the end (September). This highlights potentially distinct uses for the information, or constraints dictating optimal timing. Previous research corroborates these patterns, showing how the information needs, access, and uses for men and women may diverge in agricultural systems (Archer, 2003; Tall et al., 2014; Farnworth and Colverson, 2015; Carr and Owusu-Daaku, 2016; Diouf et al., 2019; Partey et al., 2020). For instance, in a case study in Senegal, researchers found that women farmers preferred to know about the cessation of seasonal rainfall, rather than onset (Tall et al., 2014). A study in Ethiopia showed that although women household heads were less likely to access quality extension services, receiving advice was positively related to adoption of improved varieties and inputs (Ragasa et al., 2013). As such, ensuring the timing and type of information matches users' needs is crucial to producing useful information products.

There are also geographic influences on the information needs of farmers, which could be both biophysically driven or underpinned by cultural differences or existing *in situ* information networks (Vogel and O'Brien, 2006; World Meteorological Organization, 2015). However, for Papua New Guinea, the nature of these connections is still speculative, as research on the topic is limited, and more research is needed to develop an understanding about cultural and social underpinnings of regional information needs. The survey region in Morobe is exceptionally dry, which aligns with the focus of

Cluster 2 on drought information early in the dry season (June). Eastern Highlands had a strong representation in Cluster 5, which favors rainfall information at the end of the dry season (September). This is a prominent transition month in the region, and could therefore be an important period of preparation for the wetter season. East New Britain was best represented in the General Cluster 1, which notably showed little temporal preference, probably reflecting the more stable, tropical climate there and hence smaller fluctuations in information needs across the year. Clusters 3 and 4 were less straight-forward, which may reflect farmers' perceptions around uncertainty and the interannual variability related to such forces as ENSO. For instance, Cluster 3 (Morobe dominant) centers on daily rainfall and temperature forecasts during the wet season (January), which is the peak of the wet season. The cluster comprises more women, those working in domestic occupations, and with the highest levels of no education, who all may perceive their information needs differently from the other clusters.

Practicalities and Efficiencies

While there are apparent distinctions in the information needs within the study area, the commonalities between clusters suggest there are also opportunities to gain efficiencies even when aiming to develop tailored forecasts. The process of translating broad climate information into context-specific products is resource intensive (Kalafatis et al., 2015), and there are trade-offs between individual user specificity and the practicalities associated with the timeliness and feasibility of information services (Dunn et al., 2015; Carr et al., 2020). As such, it is critical to achieve a balance between customization and universality in climate information services. While "scaling up and out" is a common refrain in the literature on climate and agricultural information services, there are considerable knowledge gaps, particularly in relation to the trade-offs between scale and local efficacy (Carr et al., 2020).

Results from this study provide initial insight into balancing efficiency and tailoring, which could be beneficial to achieving scalable climate information services. About one-third of respondents were members of Cluster 1—"The Generalist"—which has broad information needs in terms of timing, type, and uses. This demonstrates there is a perceived need for a more generalized information service, which could form the base in developing targeted advisories. All five clusters also overlapped considerably in terms of information uses, especially land preparation and planting time, suggesting a common suite of advice "types." However, the actual recommendations for farm management would vary depending on the local forecast conditions.

These findings support an approach to farm advisory development that incorporates a foundation of general information to satisfy the needs of most farmers, with additional tailored information for particular groups depending on the context. Our approach to developing a tailored "Seasonal Farm Advisory" in PNG first involves establishing a robust and relatively comprehensive table of farm management recommendations for a range of crops—particularly staples ones like banana, cassava, sweet potato, and taro—based on the available seasonal forecasts and creating a composite "base" document (see **Supplemental Figure 3** for crops in the survey). Targeted advisories can then be compiled from this composite document to reflect the needs of specific farmers, as demonstrated through the cluster analysis. This aligns with the modular design principles outlined by Koerner et al. (2021), which increase the diversity of options for users by enabling the use, reconfiguration, or repurposing of different components of the service. The authors argue that this mixing-and-matching can accelerate the process of scaling, multiplying the possible uses or contexts in which climate information services are relevant.

While the approach outlined in this paper can help guide the development of climate information services that meet needs of regional groups of farmers, and tracking these needs over time, there are still challenges to effective scaling that go beyond information services content (Tran et al., 2020). This requires institutions to work with farmers on the communication and use of climate services, and for information providers to be responsive and accountable to the evolving needs of farmers.

Implications for Communicating Information

While the clusters depict distinctions in information content, it is also essential to consider how to connect the information services with users. To overcome the barriers to scaling effective and equitable climate information services, studies like this one must be considered in tandem with complementary studies on information flows and communication strategies. These areas have decades of experience testing different models for producing and disseminating seasonal climate forecasts in Sub-Saharan Africa. In a review of these models, Jost (2013) identified radio, demand-driven extension, and mobile technology as key channels available for movement of climate information to farmers. Interpersonal and information networks within communities can also be critically important (Nkiaka et al., 2019). For example, a study in Ghana looked at the influence of mobile phone delivery of climate information, finding that the adoption of some adaptive practices improved (water management, multi-cropping), while others did not significantly change (e.g., erosion control, IPM, and resistant crops), suggesting the role of different communications channels in adoption (Djido et al., 2021). Because there are differences in access to, and use of, climate information communication channels between groups of farmers (e.g., McOmber et al., 2013; Djido et al., 2021), targeting information has relevance for both content and communication. As such, overcoming communications hurdles and other barriers is crucial to actually informing adaptation.

In this study, the discrepancy between respondents who currently receive information and those who don't highlights how communications strategies may need to differ between clusters. The majority of members in Clusters 1, 2, and 3 said they currently receive no climate or weather information, which adds the challenge of establishing appropriate channels to enable access to information to support adaptation. This raises an important question of when is it possible to tap into existing effective communication channels, and when new ones need to be created and cultivated in order to ensure desired information is accessible. There are likely opportunities to build on existing information exchange networks in PNG, particularly informal and community-based ones (Friedman et al., 2022), but in some cases building communication channels from scratch may be necessary. Furthermore, choice of information channel may also dictate the content, and so relying solely on existing networks may be limiting. Research on climate information and support services demonstrated how the choice of channel can influence what type of information is conveyed, particularly to marginal or vulnerable groups (Cherotich et al., 2012). Finally, a study in Ghana highlighted how the choice of communication channel impacts the successful adoption of climate adaptation measures. Membership in a farmer-based organization and access to extension services were both significantly positive influences on adopting adaptation measures (Owusu et al., 2021). This highlights how interwoven the content and communications sides of climate information services are to achieving outcomes.

Tailoring both content and communication can address barriers related to relevance, accessibility, and uneven distributional impacts (Vaughan and Dessai, 2014; Hansen et al., 2019). Barriers to information use, including the quality of information, local relevance, trustworthiness, and understandability, map more directly onto some clusters over others, suggesting possible challenges that need to be addressed for certain types of information, regions, or groups of farmers. For example, local relevance and understandability are relatively major challenges for Cluster 3, which had the greatest number of members without formal education and from a unique region in Morobe. While education levels were not significantly related to membership in a climate information cluster (i.e., desired content), they could have substantial impact on the feasible means of communicating this information, due to differences in literacy and familiarity with scientific concepts and uncertainty. Furthermore, research has highlighted how confidence in one's awareness and understanding of climate change can influence use of such information and adoption of adaptation measures (Ng'ombe et al., 2020; Nguyen and Drakou, 2021). As such, efforts could be focused on translating information into easily understandable and actionable formats. Trust and quality were relatively important for Clusters 4 and 5, which were also dominated by women, who tend to face greater barriers to accessing information. Here, taking an interactive approach to the design and dissemination of climate information, and improving institutional communication, could help overcome trust and related barriers (Lemos et al., 2012; Kumar et al., 2021; Belay and Fekadu, 2021). Accessibility was the overwhelming barrier for Cluster 2, hinting at the existing challenge of obtaining drought warnings in PNG. Overall, accounting for the perceived barriers hindering integration of climate information should be an integral part of the strategy for developing climate information services.

Caveats and Future Research

The survey and clustering results from the study present a useful starting point to develop more refined and user-oriented climate forecasts and advisories, yet there are also a number of considerations when examining the data. For one, the survey is taken at one point in time, but information needs do change throughout the year and over time. While this study provides a snapshot of how information needs may cluster at a given time, only longitudinal data will give us a sense of whether clusters and membership are stable or shift over the course of a year or between years. Further analysis should include data collected during both wet and dry seasons, and ideally over multiple years (including both El Niño and La Niña years).

This analysis demonstrated how different information needs manifest within and between communities. For instance, clear differences in the information needs of men and women emerged in this study. Additional research could provide nuance on what drives these differences, such as specific gendered roles and cultural norms, as well as decision-making responsibilities. Qualitative methods, such as focus groups and interviews can provide a stronger narrative behind why these gendered and other differences exist. They can also complement the cluster analysis in fleshing out how individual information products could be best tailored for specific groups. Additional quantitative information, such as size of farm and amount of crops produced for consumption and sale, could also improve understanding of what drives differentiated information needs.

Integrating this understanding into the development of climate information services for agriculture requires additional considerations in practice. Unlike in Sub-Saharan Africa, research has shown that in the Pacific Islands farmers tend to have limited reliance on contemporary weather forecasting, instead relying on knowledge of traditional forecasting to reduce negative impacts from extreme events (Chambers et al., 2019). There is thus an opportunity in the region for better integration of contemporary scientific forecasting with existing traditional knowledge to improve interpretation of technical information and ultimately achieve adaptation outcomes. While often discussed as an effective approach to both achieve scale and to ensure local relevance, very little work has been done on co-production of climate information services as a means of integrating traditional knowledge and other social or cultural interests (Carr et al., 2020). More research in this area may be key for facilitating the uptake of reliable forecasting in a manner that is contextually appropriate and locally relevant. However, development of guidelines for co-production principles is still emerging (Bremer and Meisch, 2017), and empirical evidence of the scalability of such strategies remains a gap.

Finally, this study focused on the content and timing of weather and climate information services, but not the dissemination. While the barriers to access and use of information included in the analysis provide some clues about what hinders communication, more research is needed to understand how farmers can actually obtain this information. In the particular context of PNG, it would be valuable to elucidate how farmers who currently use weather and climate information access it, and conversely what information is actually available that farmers are unaware of or are unable to access. This baseline research is foundational for setting up weather and climate information services that not only reach farmers but also cater to their needs.

CONCLUSION

Ultimately, the results of this study have shown the value in identifying how weather and climate information needs vary within and among farming communities, while also highlighting the complexity of accounting for multiple intersecting population traits when designing information services. Through this study, we aimed to identify how different types, timing, and uses of weather and climate information intersected, and who most desired these bundles of information to inform their farm management practices under climate variability and change. We found that gender and variables associated with geography played a role in shaping information needs, and could be used to help tailor specific climate information services. With limited time and resources, it is also necessary to find efficiencies in the development of these services. We proposed capitalizing on common uses of information across clusters, and using a modular approach to create specific tailored products. Finally, this study focused on the content of weather and climate information services, and how that may need to vary for different groups of farmers. However, the results of this study must be used in conjunction with developing appropriate communication channels to overcome perceived barriers to accessing and using information. Accommodating different needs in the design and delivery of weather and climate forecast services could substantially enhance their relevance, credibility, and legitimacy amongst smallholder farmers, with resultant improvements in lives and livelihoods across the Pacific.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: "Open Science Framework: https://osf.io/dfnr6/?view_only=1f41000fd5284b5a9d8119aa7ead2c6f".

ETHICS STATEMENT

The study involving human participants was reviewed and approved by the Human Research Ethics Committee at the Australian National University (2018/831). The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SC and RF conceptualized the study. RF carried out the analysis. RF, SC, RB, KI, and EM interpreted the results of the analysis. RF, SC, and EM wrote the paper with content and editorial input from RB, KI, and MH. All authors have read and approved 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.2022.871987/full#supplementary-material

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The Kake Climate Partnership: Implementing a knowledge co-production framework to provide climate services in Southeast Alaska

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This paper provides a case study analysis of knowledge co-production with an Indigenous community and Tribe in Southeast Alaska. The 24-month study provided climate services and information in support of climate adaptation and mitigation with community identified priorities of food sovereignty and food security. Our objectives are to (1) describe an application of a theoretical framework that is specific to co-production among Indigenous and non-Indigenous partners, and (2) reflect on the ways in which this application supports relevance and use of climate services in an Indigenous community. Methods included text analysis of written research logs, review of monthly project briefings and structured discussions among a diverse author team. We found that co-production can be used to explicitly define a collective vision among partners that is a transformative way of doing applied climate and environmental science. As such, the role of the university researcher shifted from focusing on personal research interests to a focus on supporting local needs and priorities. When the climate services process is centered on Tribal and community priorities and locally identified science needs, the climate science aspect becomes just one element in the implementation of a larger local vision and goals. Challenges our team encountered during the study were related to logistics, communication, juggling priorities of multiple partners, capacity, and conducting community-based research during a global pandemic. We recommend that future efforts to co-produce climate services through research, adaptation planning, and mitigation be institutionalized and maintained over decadal, not annual, timescales.

KEYWORDS

co-production, Southeast Alaska, research partnerships, Indigenous Knowledge, Traditional Knowledge, learning network, climate services, climate change

Introduction

The field of climate services emerged to better equip decision-makers with tools to manage the risks and opportunities arising from climate variability and climate change (National Research Council, 2001; Solomon et al., 2009; Hewitt et al., 2012; Brasseur and Gallardo, 2016; Daly and Dilling, 2019). Climate services are science approaches that focus on the usefulness, usability, and practical applications for climate change adaptation planning and mitigation (Brooks, 2013). Increasingly, co-production is acknowledged as a valuable mechanism for providing climate services (Vincent et al., 2018, 2020; Steynor et al., 2020; Vollstedt et al., 2021). Co-production can support the generation of climate services that are contextually credible, salient, legitimate (Buontempo et al., 2014; Bremer et al., 2019), and which go beyond the provision of climate information to support procedural benefits, including local empowerment (Baztan et al., 2020).

Co-production approaches are increasingly acknowledged as beneficial to actionable science in support of climate adaptation (Homsy and Warner, 2013; Meadow et al., 2015; Lavorel et al., 2020), and offer the opportunity to carry out climate research that uses meaningful methods to produce useful results for the public (Inukalik et al., 2020; Latulippe and Klenk, 2020; Yua et al., 2022). While there is a growing body of literature that describes characteristics of meaningful co-production (Beier et al., 2017; Wall et al., 2017b; Yua et al., 2022), processes of implementing (Djenontin and Meadow, 2018; Austin et al., 2019; Sikuaq Erickson, 2020) and evaluating (Wall et al., 2017b) co-production are not as prevalent.

Climate change is impacting the land and resources that Indigenous communities and Tribes in Alaska rely on for food security, food sovereignty, resource management, and cultural continuity, all of which are important Tribal and community priorities (ICC, 2012; Inukalik et al., 2020). Concurrently, Indigenous leaders are speaking out against the inequities in scientific research that have benefitted the scientific enterprise but left communities without tangible solutions to the challenges they face (Bahnke et al., 2020; Early, 2021). When climate science and adaptation planning are led by communities and Tribes, research and adaptation outcomes have the potential to be locally relevant (Kipp et al., 2019). Indigenous-led research can enable prioritization of Indigenous connections between the environment and wellbeing (Kipp et al., 2019). Indigenous peoples may be well positioned to use Traditional Knowledge in climate science and to inform adaptation planning, given historical and lived experience with adaptation and worldviews that promote holistic problem-solving (Vogel and Bullock, 2021). Conducting science with Indigenous methodologies and worldviews is a growing field (CTKW et al., 2014; TallBear, 2014; Johnson et al., 2016; Maldonado et al., 2016; Daniel, 2019; David-Chavez et al., 2020) and a model of knowledge co-production has been presented by Indigenous leaders in Alaska (Yua et al., 2022).

While co-production is widely put forward as a desired process for creating use-inspired science (Beier et al., 2017; Wall et al., 2017a; Wyborn et al., 2019; Norström et al., 2020), co-production among non-Indigenous researchers and Indigenous communities requires special considerations (David-Chavez and Gavin, 2018; Carlo, 2020; Sikuaq Erickson, 2020). Meadow et al. (2015) note a need "to refine our understanding…of what specific actions and activities most effectively produce the trusting, long-term relationships necessary to the co-production of usable science" (p. 189). In this paper, we present the specific actions and activities our team carried out while forming effective relationships to co-produce meaningful climate science among Indigenous and non-Indigenous partners in Southeast Alaska.

This paper presents an instrumental case study (Stake, 1995) of knowledge co-production with an Indigenous community and Tribe in Kake, Southeast Alaska, aimed at providing climate services (Brooks, 2013) in support of climate adaptation and mitigation. Our **objectives** are to (1) describe an application of the Yua et al. (2022) co-production framework (hereafter, Ellam Yua co-production) in the Kake Climate Partnership, and (2) reflect on the ways in which our application of Ellam Yua co-production is linked to the relevance and use of climate services in an Indigenous community.

For Objective (1), we documented our experiences over the first 24 months of our research partnership through tracking:

> *(1a) Accomplishments and financial spending over 24 months,* to better understand the potential repeatability of implementing Ellam Yua co-production in climate change research.
> *(1b) How the Ellam Yua co-production elements manifested in our work,* to compare our work with the ideal type of Ellam Yua co-production.
> *(1c) Challenges faced during the 24-month period of study,* to inform others who may choose to implement Ellam Yua co-production and provide a balanced analysis of our application of the framework.

For Objective (2), we present details about key features of the Kake Climate Partnership. We use the term 'study' throughout this paper to refer to our case study research of the co-production process.

Materials and methods

Co-production of knowledge

Jasanoff (2004) and others (e.g., Miller, 2004) use the term co-production broadly to mean how, "the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it" (p. 13). In a review of publications using co-production, Bremer and Meisch (2017) found no "common view of co-production" in climate research, and instead classify co-production in climate research across eight different lenses, or approaches. However, in climate and environmental sustainability research, it is common to encounter an outcomes-based understanding of co-production (Dilling and Lemos, 2011; Meadow et al., 2015;

Lemos et al., 2018; Kettle, 2019). For example, Lemos et al. (2018) discuss co-production as, "a focus of research and…practice among scientists, stakeholders, and funders" (p. 722), situated in terms of how well it can lead to sustainability outcomes for society. Daly and Dilling (2019) describe a focus on outcomes as a normative approach to co-production.

Although co-production practices are increasingly popular, Daly and Dilling (2019) found that normative co-production practices do not necessarily lead to transformational or usable climate services. Treating co-production as a means to an end, rather than a meaningfully reflexive process, can reinforce existing power imbalances and inequities without producing relevant or applicable climate services. In contrast to normative co-production, the Ellam Yua co-production framework we employed for this study is process-based (Figure 1).

Selecting a framework: Ellam yua co-production

We use the Ellam Yua definition of knowledge co-production, which is a "process that brings together Indigenous Peoples' knowledge systems and science to generate new knowledge and understandings of the world that would likely not be achieved through the application of only one knowledge system" (p. 2). Ellam Yua co-production involves 21 elements depicted in Figure 1.

Ellam Yua co-production was selected for this study because this framework was developed by Indigenous scholars in Alaska, for work among Indigenous and non-Indigenous Alaskans, and explicitly engages a holistic, Indigenous worldview (Daniel, 2019; Yua et al., 2022; Figure 1).

Tribal sovereignty—the authority to self-govern (NCAI, 2022)—is a central concept in Ellam Yua co-production. Following Ellam Yua, meaningful co-production takes place when Indigenous and non-Indigenous partners lead a project together from the beginning stages of developing a research idea through project design, data collection and analysis, and sharing of project outcomes, while upholding Tribal and data sovereignty (NCAI, 2018; Latulippe and Klenk, 2020). Creating and nurturing an equitable and meaningful process among partners is as important—and sometimes more important—than specific research or sustainability outcomes. It is expected that by focusing on an equitable process, outcomes will be relevant to and useful for Tribal and community partners.

Ellam Yua co-production aligns with epistemologies aimed at centering equity, ethics, and decolonization—disrupting legacies of imperalism and exploitation (Tuhiwai Smith, 2012; Marino et al., 2020)—across fields of study and policy (Bartlett et al., 2012; Tuck and Yang, 2012; Fryberg and Eason, 2017; Latulippe and Klenk, 2020; Reid et al., 2021), as well as specifically in climate change research (Mihlar, 2008; Whyte, 2013, 2017). Ellam Yua co-production shares characteristics with "Two-Eyed Seeing", as described by Bartlett et al. (2012) and Reid et al. (2021), in that both aim to weave together Indigenous and non-Indigenous knowledge systems. Ellam Yua co-production has similarities with some work in the realm of participatory action research (Peterson, 2011), political economy focused on climate vulnerability (Barnett, 2020), "transformative" worldview approaches to social science (Creswell, 2014), and other co-production approaches (Turnhout et al., 2020; Hauser et al., 2021), which are similarly centered in power- and justice-oriented scientific research.

Geographic area, research partners, and related activities

Land acknowledgment

As authors of this paper, everywhere we live and work is Native land. We recognize, appreciate, and honor Indigenous peoples and their past, present, and future land stewardship. The work we present in this paper has taken place on the unceded territories of many Indigenous peoples within the boundaries currently recognized by the United States Federal government as the State of Alaska. Most of our field research work has taken place on Tlingit Aani, in the unceded territories of the Keex' Kwaan Tlingit people in Southeast Alaska (Figure 2).

Geographic area: Kake, Alaska (Keex' Kwaan)

Kake is in the heart of Southeast Alaska, at the confluence of three major bodies of water: Frederick Sound, Chatham Strait, and Keku Strait (Figure 3). Kake is a Tlingit Alaska Native community in Southeast Alaska with a population of around 570 people (US Census 2018) and is accessible by boat or small plane. Kake is not accessible by road from other communities in Alaska, the contiguous United States, or Canada. The State of Alaska designates the community of Kake as encompassing 12.85 square miles of land on the northwest shoreline of Kupreanof Island (DCRA, 1988; Supplementary file A). The Organized Village of Kake Federally recognized Tribe recognizes an overlapping but much larger area of land and water as the traditional Kake Community Use Area for people in Kake (Figure 2).

Like other areas of Southeast Alaska, the coastal rainforest area surrounding the Kake Community Use Area is comprised of steep walled valleys and deep, narrow bays characteristic of glaciated terrain (CEC, 2015). Southeast Alaska has the mildest temperatures in Alaska, and typically experiences large amounts of precipitation year-round. Historically (1925–2021), monthly average temperatures have ranged between 16.6 and 59.6 degrees Fahrenheit and monthly precipitation has ranged between 0.41 and 27.97 inches in the area surrounding Kake (NOAA, 2022a,b). The forests are dominated by western hemlock and Sitka spruce and the coastal ocean waters are heavily influenced by glacial runoff (Gallant et al., 1995).

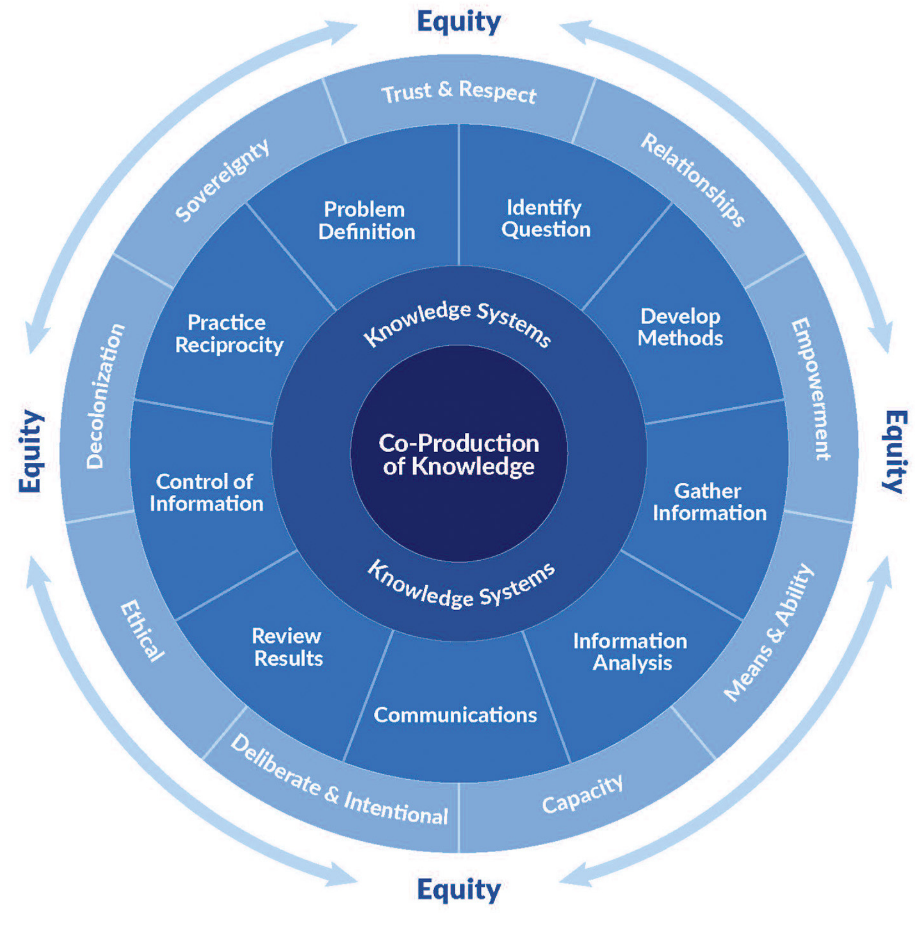


FIGURE 1
Reproduced from Yua et al. (2022) depicting a visual representation of the framework for Ellam Yua co-production of knowledge (CPK). Yua et al. (2022) explain: "The center of the framework shows the goal: co-production of knowledge. Surrounding the goal are the two knowledge systems (Indigenous Peoples' knowledges and science) that will come together in this process. The inner ring surrounding the knowledge systems is what we refer to as the "action circle." This circle, or inner ring contains various aspects of, or actions that are part of, a CPK research process. We emphasize that CPK is a process. The outer ring of the CPK framework holds all the concepts, referred to as "conceptual tools," that all participants in this approach need to implement and be continuously mindful of. These tools are the concepts that, when implemented together, can bring about equity. Lack of equity is a systemic issue in many research relationships with Indigenous Peoples. Without equity, a CPK approach is not possible. CPK is an iterative and cyclical process, rather than a simplistically linear approach" (p. 9).

Climate change impacts in Kake and throughout Southeast Alaska include increasing variability and extremes in weather events. For example, while annual precipitation in the region is increasing over long timescales, year to year fluctuations have led to extreme drought periods in recent years (e.g., 2017–2019; Thoman et al., 2019). Increasingly unstable weather patterns, including seasonal drought conditions, have led to large variations in stream depth and temperature and concerns about the potential for increasing harmful algal bloom incidence in ocean waters near Kake (Leffler, 2019). The long-term health of ocean water, creeks, and streams around Kake directly affect Tribal and community health, food sovereignty (Inukalik et al., 2020), and food security (Carlo, 2020; Inukalik et al., 2020) of local residents through impacts on foods like seaweeds, shellfish, and fish, including salmon. Linkages among climate change, the environment, and pollution are locally relevant, as they have potential to impact food sovereignty and food security through impacts to accessing healthy customary and traditional foods throughout the Kake Community Use Area.

Research partners and related activities

The Kake Climate Partnership (the Partnership) was formed in 2020 between a Federally recognized Tribe, a local Tribal corporation, a rural municipal government, and a research and boundary spanning (Kettle and Trainor, 2015) organization at a

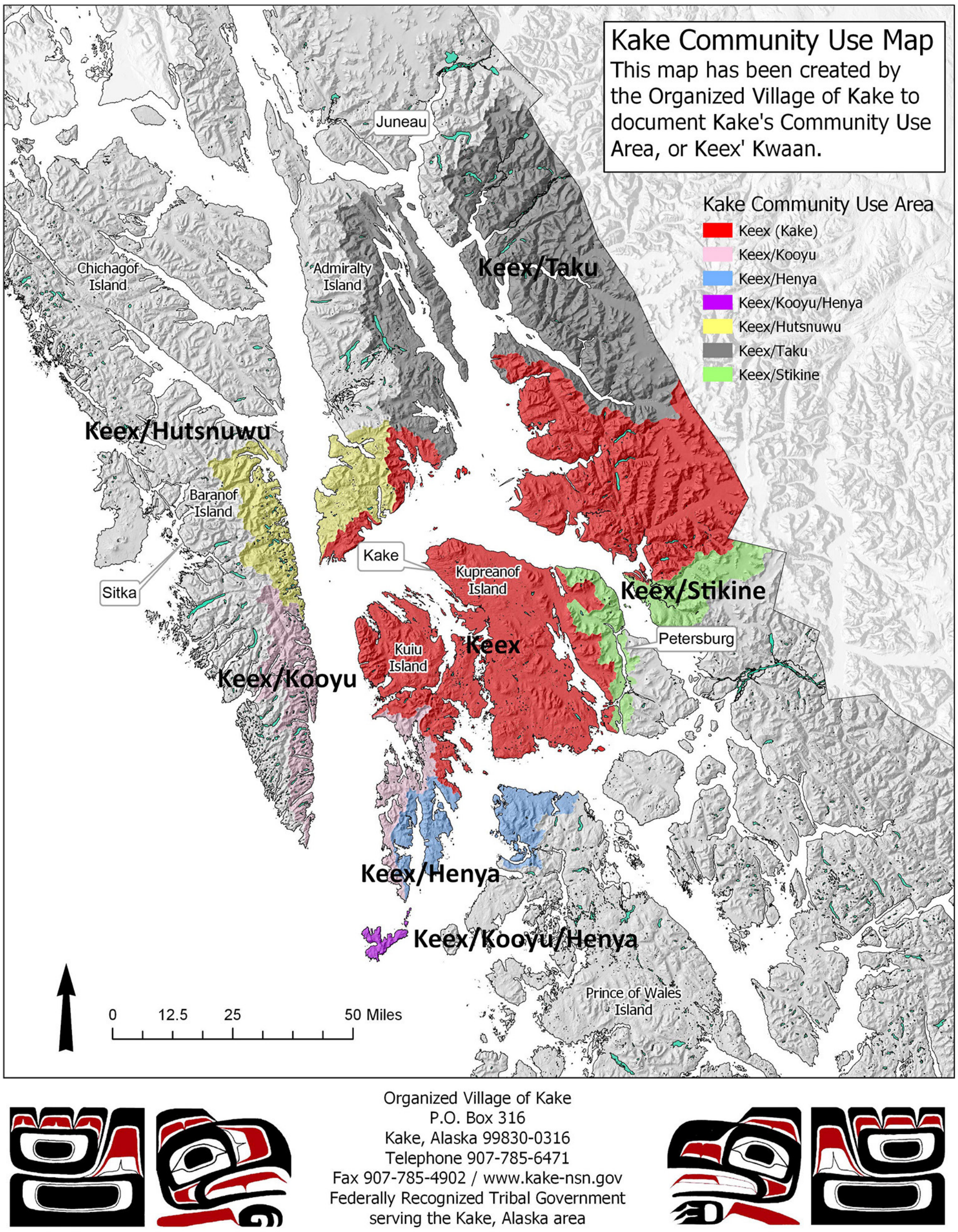


FIGURE 2
Kake Community Use Map, depicting traditional harvest areas for members of the Organized Village of Kake Tribe and residents of the community of Kake. Core Keex' Kwaan Customary and Traditional Use areas and shared areas total over 6,000,000 acres. This is a map that was created by Mike Ka.oosh Jackson (OVK Historian) and Bob Christensen (ESRI GIS Mapper).

public university: the Organized Village of Kake (OVK), Kake Tribal Corporation (KTC), the City of Kake (the City), and the Alaska Center for Climate Assessment and Policy (ACCAP) at the University of Alaska Fairbanks (Table 1). The Tribal, Tribal corporation, and municipal partners are based in the community of Kake, while the university partners are based in Juneau, AK, (E. Figus) and Fairbanks, AK (S. Trainor). All research projects carried out by the Partnership take place in and around Kake.

The Climate Partnership was modeled after the existing Keex' Kwaan Community Forest Partnership (Nix, 2019) and is aligned with broader work to strengthen food sovereignty and security and manage natural resources in the Kake Community Use Area. There are existing initiatives in Kake for a Tribal

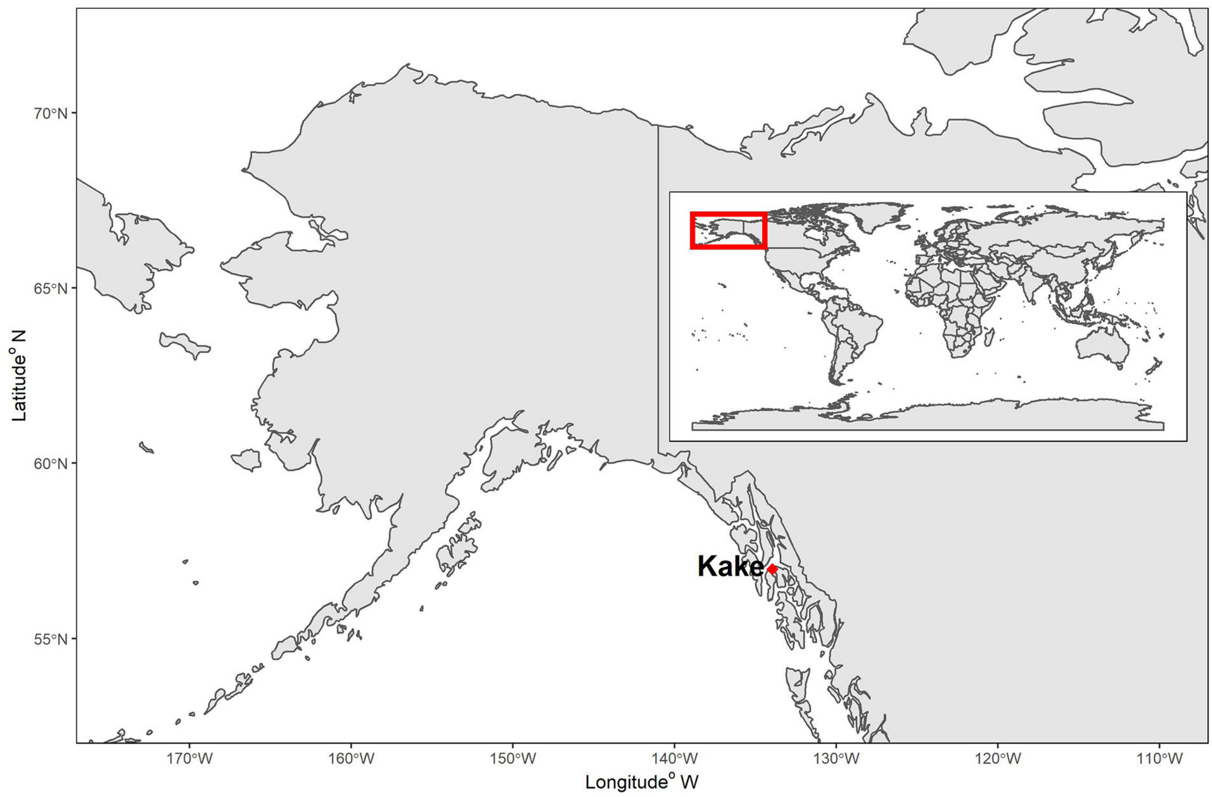


FIGURE 3
Alaska in relation to Earth, and Kake in relation to Alaska. Created by M. Rhodes-Reese in Adobe Illustrator.

Conservation District and an Indigenous Coastal Guardian Network. In 2018, OVK began pursuing status for the Kake Community Use Area to become a Federally recognized Tribal Conservation District (TCD; NRCS, 2020)[1]. Status as a TCD provides eligibility to apply for funding support from 22 departments within the United States Department of Agriculture to monitor and protect the TCD area. OVK and KTC agreed to sign an MOU with the USDA to form the Keex' Kwaan Tribal Conservation District. In November of 2021, the MOU forming the Keex' Kwaan Tribal Conservation District was signed by the United States Secretary of Agriculture (USDA, 2021). The Tribal Conservation District is described in greater detail in Table 2.

OVK is part of a growing movement aimed at creating an Indigenous Coastal Guardian Network in Southeast Alaska, modeled after an existing Guardian Watchmen program across the North Pacific Coast, to "uphold and enforce traditional and contemporary Indigenous laws...in protecting and managing coastal territories" (CFNGBI, 2022a). The Coastal Guardian Network is described in more detail in Table 2. Creation of the Keex' Kwaan Tribal Conservation District and a Coastal Guardian Network program in Southeast Alaska have the potential to support greater local and Tribal sovereignty to manage natural resources and exercise authority over climate change adaptation planning and mitigation in the Kake Community Use Area.

1 B. Ki'yee Jackson personal observation, 2021.

Instrumental case study

We use an instrumental case study (Stake, 1995) analytical approach in this paper to address both Objective (1) and Objective (2). In this application, the Kake Climate Partnership is treated as a "program" (Stake, 1995) studied to learn about the "process" of Ellam Yua co-production. Co-authors on this paper brought three different perspectives to this work. During the study, E. Figus was a university research center postdoctoral fellow with full-time work capacity devoted to the Partnership. E. Figus was a non-objective (see Stake, 1995, p. 8) participant observer in the study, who simultaneously recorded and examined meaning of Kake Climate Partnership activities during the study period. B. Ki'yee Jackson was a Kake resident, an enrolled member of OVK Tribe, a shareholder in KTC, and was a full-time staff member at OVK with part-time work capacity devoted to the Partnership throughout the 24-month period of this study. S. Trainor was a co-Director of the ACCAP

TABLE 1 Description of each entity in the Kake Climate Partnership, including their primary role in the Partnership.

Description of Kake climate partnership member entities

Partner member	Member information	Participation in the co-production process
Organized Village of Kake (OVK)	OVK is one of 229 Tribes within the State of Alaska recognized by the United States Federal government (BIA, 2022). and makes decisions via its Indian Reorganization Act (IRA) Council. OVK had 1,002 enrolled tribal members as of February 2022.	OVK IRA Council members, members of OVK staff, and enrolled members of the OVK Tribe all participate in designing and carrying out the partnership field projects. Updates on the Kake Climate Partnership are presented monthly at OVK meetings.
Kake Tribal Corporation (KTC)	KTC is the for-profit Alaska Native village corporation in Kake. Created by the Alaska Native Claims Settlement Act (ANCSA) of 1971, KTC owns land in the vicinity of Kake (Supplementary file A). KTC had 748 shareholders as of March 2022.	KTC makes decisions *via* a Board of Directors. KTC Board members, members of KTC staff, and KTC shareholders all participate in designing and carrying out the partnership field projects.
City of Kake (the City)	The City of Kake is a First-Class City in the unorganized Wrangell/Petersburg Borough (ADCCED, 2015). It functions as the municipal authority for the community and makes decisions *via* regularly held meetings of their City Council.	The City Council votes on key aspects of the Kake Climate Partnership and individual members of the City Council and City staff participate in designing and carrying out the Kake Climate Partnership field projects.
Alaska Center for Climate Assessment and Policy (ACCAP)	ACCAP is a Regional Integrated Sciences and Assessments (RISA) program funded by the Climate Program Office at the National Oceanic and Atmospheric Administration (NOAA; NOAA, 2022c). ACCAP is housed in the International Arctic Research Center at the University of Alaska Fairbanks and conducts innovative and collaborative research and engagement to inform climate policy, decision-making, and action for a just and sustainable future.	ACCAP serves as a boundary spanning organization for the Kake Climate Partnership, providing organizational, logistical, and scientific support.

RISA program in Alaska with connection to the Partnership *via* her role as E. Figus supervisor throughout the 24-month period of this study.

Building a partnership through written and agreed upon principles and expectations

In December 2019, E. Figus contacted OVK, KTC, and the City of Kake to propose a climate research partnership using the Ellam Yua co-production approach. In January of 2020, the OVK Council passed a resolution to partner with E. Figus and ACCAP, and to extend a partnership invitation to KTC and the City. In May of 2020, all four potential partners held a joint meeting virtually *via* Zoom video conferencing software (Banyai, 1995) to discuss whether and how to finalize a broader partnership. At the meeting, ACCAP, OVK, KTC, and the City created a set of explicit Principles and Expectations (following Naquin et al., 2019; Supplementary file B) to guide the work of the Partnership. The Principles and Expectations document stipulates broad ideas (e.g., shared values among partners) and narrowly defined responsibilities (e.g., who is responsible for record-keeping). The KTC Board of Directors and the City Council subsequently passed resolutions to formalize the Kake Climate Partnership during the summer of 2020.

Travel

Following Ellam Yua co-production elements in the 'Conceptual Tools' and 'Action Circle' rings of the model (Figure 1), E. Figus traveled to Kake in person early and often in this process, spending a total of 10.5 weeks in Kake during this study. E. Figus made four short trips to Kake between December 2019 and March 2020, before needing to

TABLE 2 Detailed descriptions of two ongoing activities in Kake related to the Kake Climate Partnership.

Descriptions of two activities in Kake related to the Kake climate partnership

Related activity	Description
Keex' Kwaan Tribal Conservation District	A Tribal Conservation District (TCD) is an area of traditionally Tribal land that is managed through a Memorandum of Understanding (MOU) between a Federally recognized Tribe and the United States Department of Agriculture (USDA; See text footnote 1). "*The goal of tribal conservation districts is to set local priorities for conservation and ensure sustainable use of natural resources for subsistence, economic opportunity, resource development, and cultural preservation*" (NRCS, 2020). *"[A] TCD has the Traditional Knowledge*; [the] *USDA has the assistance, funds, [and] experience to help with technical needs"* (ATCA). A Tribal Conservation District MOU may include the local ANCSA corporation with lands overlapping a traditional Tribal area. In Oct 2021, OVK and KTC created an MOU with the USDA to create a TCD in Kake. The Board of Directors for the Keex' Kwaan Tribal Conservation District will include members from both OVK and KTC.
Southeast Alaska Coastal Guardian Network	Modeled after an existing Guardian Watchmen program across the North Pacific Coast, the Indigenous Coastal Guardian Network in Southeast Alaska, is a growing movement focused on: *ensuring resources are sustainably managed, that rules and regulations are followed, and that land and marine use agreements are implemented effectively… They uphold and enforce traditional and contemporary Indigenous laws and continue the work of their ancestors in protecting and managing coastal territories* (CFNGBI, 2022a). The Nature Conservancy describes Coastal Guardians in Alaska as a network to: *support community land and resource stewardship by connecting existing local programs, aspiring community leaders and natural resource managers. The network provides technical and social support to strengthen community-based stewardship region-wide* (Woll, 2018). The Coastal First Nations Great Bear Initiative explains that: as *Indigenous peoples we derive our authority and jurisdiction from our traditional laws to manage and safeguard the lands and waters of our territories for the health of future generations* (CFNGBI, 2022b). Work to implement the Indigenous Coastal Guardians Network in Southeast Alaska has been led by the Sustainable Southeast Partnership, of which OVK is a leading member (Woll, 2018).

pause travel for 6 months due to the onset of the COVID-19 pandemic. During those first four trips to Kake, E. Figus was able to present in person at meetings of the OVK IRA Council, the Kake City Council, and at the Annual Meeting of the OVK Tribe, as well as meet individual members of the KTC Board in person. In addition, E. Figus and OVK staff worked with the teachers and administrators at the Kake City Schools to provide guest lectures and an intertidal field trip for middle and high school students in Kake in January and March of 2020, respectively. E. Figus subsequently made two three-week trips to Kake (to allow for quarantine periods), in October 2020 and March 2021, and made three short trips to Kake (when quarantine was not needed) in May and September 2021.

Determining field projects

Field research topics were determined by partners from Kake using consensus to choose a set of projects to work on together. During the spring of 2020, OVK, KTC, and the City held informal meetings to discuss ideas for climate change field projects and ACCAP partner E. Figus documented the various ideas (Supplementary file C). At the formal joint meeting in May of 2020, E. Figus presented the lists of potential projects, and all partners agreed on which of the ideas to prioritize.

Funding for field projects

Because the field projects were determined through the co-production process, leveraging existing funds and securing new funds to support project costs took place during the study. Members of the Kake Climate Partnership carefully tracked their spending related to their co-production process as well as to individual field projects. We provide a general overview of the financial spending associated with the Partnership in later sections of this paper.

Documenting the partnership and process

Co-author (and ACCAP employee) E. Figus was the only partner with full-time work capacity devoted to the Partnership. Therefore, the bulk of the documentation responsibilities were placed on her. We documented our partnership and our co-production processes in three ways:

1. Written Logs: Co-author E. Figus kept written logs between November 2019 and October 2021, to document Partnership activities and specific reflections about the co-production of knowledge process (Supplementary file D). Li (2018) notes, "reflexivity is an important research device for the social construction of new knowledge and production of competent research identities" (p. 17). In

line with Li (2018), the written logs allowed for *self-reflexivity* (Alvesson and Skoldberg, 2009) and a process of *self-questioning* about methodological, theoretical, and practical issues (Silverman, 2010; Li, 2018) by the primary university partner throughout the study.

2. Written monthly updates: E. Figus prepared monthly update briefings between May 2020 and October 2021, which were emailed to all project partners.

3. Reflective conversations among co-authors: Co-authors met four times for a period of 1 h each during the Fall of 2021 to discuss our observations and experiences over the 24-month period. Co-authors E. Figus and B. Ki'yee Jackson further met weekly during the Fall of 2021 for 30–60 min each, to discuss the study. Reflective conversations added *collaborative reflexivity* (Alvesson and Skoldberg, 2009) to this work. These conversations were important because they provided a diversity of perspectives as well as important space for all co-authors to share observations and perspectives and ensure those were documented in this paper. Co-author E. Figus documented these conversations in written notes, and all three co-authors used those notes to reach consensus about key outcomes from the study.

Analysis

Objective 1: describe an application of the Yua et al. (2022) co-production framework.

In documenting our partnership and processes we tracked items (1a), (1b), and (1c). Analyses for each item are described below.

(1a) Accomplishments and financial spending over 24 months.

Co-authors reviewed monthly project updates and the Principles and Expectations document and used reflective conversations to summarize accomplishments of the Kake Climate Partnership. Accomplishments during the study are organized in relation to our shared set of Principles and Expectations.

We summarized our approximate spending across each of 3 broad categories: Travel, Salary/Direct Payments, and Field Project Costs. The category "Travel" includes only travel by E. Figus to Kake, as other travel was canceled during the 24-month period of the study, due to the COVID-19 pandemic. The category "Salary/Direct Payments" refers to E. Figus's salary, partner staff time, and payments to local residents in Kake for work related to the Partnership. The category "Field Project Costs" includes purchase of supplies, shipping, sample processing, and any direct payments to people not residing in Kake who assisted with Partnership work during the 24-month period.

(1b) How the Ellam Yua co-production elements manifested in our work.

(1c) Challenges faced during the 24-month period of study.

Responses to items (1b) and (1c) were determined through analysis of written logs and reflective conversations among co-authors. Monthly logs were written and analyzed by project facilitator, E. Figus, and were coded based on intentions and outcomes. For example, use of the code 'Equity', could refer to an intent to create equity or an outcome of equity. Coding was not split between these two perspectives. This approach to coding was made possible because the coder was the same person who had written the log entries. The dual role of researcher and practitioner played by E. Figus may have caused added 'strain' for her lived experience during the study (Arber, 2006), but this reflexive activity enabled us to gain awareness of how the study and relationships developed within it shaped both the researcher (E. Figus) and the research (the Kake Climate Partnership).

Written logs were analyzed in the NVivo text analysis software program (QSR International Pty Ltd., 2020) using both deductive and inductive coding (Bernard, 2011). Deductive codes are determined prior to analysis and are used to test a hypothesis or seek out predetermined themes in a text. Inductive codes are identified during the coding process and are used to allow themes and understanding to emerge from a text without predetermined ideas. Individual logs for each of the 24 months from November 2019 through October 2021 were uploaded to a single NVivo file. A total of 22 deductive codes were created at the beginning of the text analysis process. Twenty-one of the codes correspond to elements in the Ellam Yua co-production framework (Figure 1), and one code was created for "Challenge", specifically to capture information relevant to item (1c). We use the term "elements" throughout this paper to refer to the 21 pieces of the Ellam Yua co-production framework (Figure 1) as defined by those authors. The code for "Challenge" was defined as difficult tasks or problems our team encountered, including caveats and deviations from Ellam Yua co-production. The code for "Challenge" was analyzed alongside the Ellam Yua elements and is described with them in the section titled, "Results from coding monthly logs."

Additional codes were created inductively during the coding process, which were not part of the Ellam Yua framework. Deductive codes were subsequently analyzed in the NVivo software program for incidence, clustering using Pearson's and Jaccard's correlation coefficients (Egghe and Leydesdorff, 2009), and qualitative characteristics. Qualitative themes were explored in the inductive codes and correlation analyses were not run on them. The content of the codes was summarized to respond to (1b) and (1c). Coding results were visualized using NVivo software. Selected quotes were also chosen from the logs to aid in descriptions throughout the paper.

Objective 2: reflect on the ways in which our application of Ellam Yua co-production is linked to the relevance and use of climate services in an Indigenous community.

We used collaborative reflexivity (Alvesson and Skoldberg, 2009) in the form of reflective conversations among co-authors to build upon findings from our analysis of items (1a), (1b),

TABLE 3 Abbreviated list of principles and expectations of kake llimate partnership with examples of how each one was accomplished during the 24-month period of this study.

Abbreviated list of principles and expectations of Kake climate partnership with examples of how each one was accomplished

Principle	Meaning	Example during this study
Southeast traditional tribal values	Members acknowledge and respect the values established by the regional tribal government in Southeast Alaska (Central Council; CCTHITA, 2019).	The Southeast Traditional Tribal Values are at the forefront of all actions in the Kake Climate Partnership.
Respect and equity	This work should set an example of respectful, equitable research between a Tribe, a City, a Tribal Corporation, and a university.	Building a partnership centered around respect and equity was an iterative and ongoing process throughout the 24-month period of this study.
Food sovereignty	All parties acknowledge that food security and food sovereignty is a key value and should play a role in all aspects of this work.	All research projects characterize impacts of climate variability and pollutants on traditional foods.
Knowledge and wisdom of elders	This work aims to learn from elders through respectful documentation of their knowledge.	Partners planned a Traditional Knowledge documentation project with Elders in Kake.
Data sovereignty	Data sovereignty for the Tribe and individuals in Kake should be upheld at every stage of this work and in perpetuity.	Through use of a Memorandum of Agreement, non-disclosure agreements, and the Tribal archives, the team upholds local and Tribal authority over data collected.
Baseline data collection	All parties acknowledge the importance of strengthening a local database about the changing environment to support future resilience.	During the 24-month period of this study, partners completed two seasons of baseline climate data collection (project 1 in Table 4).
Workforce development	Importance of creating meaningful learning experiences, training, and economic opportunities for local residents and Tribal members.	More than 30 local residents worked as paid members of the research team during the study (Table 4).

(Continued)

TABLE 3 Continued

Principle	Meaning	Example during this study
Publication values	All parties agree to publish about this work in ways that are respectful.	The team generated zero peer-reviewed publications, but successfully planned three potential manuscripts with equitable co-authorship.
Expectation	**Meaning**	**Example during this study**
Data/information ownership	Data sovereignty is a key value of this work. All parties agree to negotiate agreements about data & information ownership, including memoranda of understandings, as necessary.	OVK, KTC, and the City negotiated a MOA for all data collection for the ocean monitoring project.
Project facilitation	Staff from each partner entity are primary facilitators for this work.	Partners maintained a core group of facilitators defined for all partners.
Regular updates	Regular updates will be provided by E. Figus so parties can provide feedback and recommendations to project facilitators about ongoing work.	E. Figus provided updates each month from May 2020 through October 2021.
Project assessment	Project assessment will take place at regular intervals.	During May 2021, representatives from each partner entity participated in an evaluation in the form of a facilitated Talking Circle.
Outcomes	Preserving stories/knowledge from elders in Kake; local collection of climate data; professional development experiences for locals who participate.	Two seasons ocean monitoring data archived locally; presentations at science conferences; field trips with local high school students.
Follow up	Results will be presented to the community.	Team members presented results at an Annual Meeting of the Tribe during 2021.

Refer to Supplementary file B for the complete principles and expectations document.

and (1c) to identify and understand the relevance and usefulness of climate services generated through Ellam Yua co-production to Kake.

Results

Objective (1a) accomplishments and financial spending over 24 months

Our entire study was based around relationship building. As a process that does not end, relationship building was both a key accomplishment of this work and an ongoing process. As such, it is noted in multiple parts of this section.

Alignment of accomplishments with mutually agreed upon principles and expectations

Project partners agreed on a shared set of Principles and Expectations (following Naquin et al., 2019; Supplementary file B) 6 months into the 24-month study. Partners agreed to uphold eight principles and six expectations for the life of the Partnership (Table 3, Supplementary file B). Much of the content in the Principles and Expectations document is typical of best practices for any research partnership following Yua et al. (2022) and similar methods (Naquin et al., 2019; e.g., "Respect & Equity"). Partners additionally included items specific to the context of Kake such as Southeast Traditional Tribal Values and workforce development (Supplementary file B).

The document stipulates that all partners have agreed to work together to benefit the community of Kake. The document also details that the Partnership and all projects within it address local needs and priorities for youth training and workforce development related to climate adaptation. However, it stops short of stipulating research project topics or outlines in detail. In line with Ellam Yua co-production, research priorities were set by the partners in Kake and were carried out within timeframes amenable to community and Tribal needs. The Principles and Expectations document functions as both a guide for Kake Climate Partnership work and a measuring stick, against which to gauge successes over time. Table 3 presents a list of accomplishments in relation to the eight principles and six expectations, and accomplishments are described in detail below.

Building a partnership centered around respect and equity was an iterative and ongoing process throughout this study. The "respect and equity" principle is closely aligned with the Ellam Yua elements for "Equity" and "Trust and Respect," which are explained in greater detail in the section titled, "Results from coding monthly logs."

The term, "sovereignty," in the Principles and Expectations was used to refer to Tribal sovereignty of OVK as well as supporting KTC and the City in exercising their local authority over decisions and information related to the Partnership. Concerns about food sovereignty and food security were the local drivers for interest in climate and environmental research in Kake.

Field projects

During the 24-month period of this study, partners designed five field projects aimed at characterizing local impacts of climate variability and pollutants on customary and traditional foods (Table 4).

Ocean monitoring (begun June 2020)

All three partners from Kake identified ocean monitoring as their top priority for the Partnership's first climate research project. In 2020 and 2021, a team of more than thirty local residents collected baseline climate and pollutant indicator data in seawater and shellfish tissues (including pH, salinity, conductivity, temperature, ammonia, nitrogen, fecal coliform, saxitoxin, metals, and mercury). Local partners determined project goals and outlined potential analytes of interest for data collection. E. Figus then connected with experts in the field of ocean monitoring in Alaska to advise local partners about how to design and implement the ocean monitoring program to achieve their goals. E. Figus assisted in all stages of ocean monitoring design and implementation, including: obtaining necessary permits; distributing leveraged funding; organizing training for locals on the sampling team; mentoring high school and college students on the sampling team; acting as field coordinator from her office in Juneau throughout the field seasons (assisting with supplies purchasing, creation of field log templates, sample shipments, sampling event scheduling, communications with outside labs, etc.); working with outside experts to review and summarize sampling data under non-disclosure agreements (NDAs); complying with permit reporting requirements; and prepping all project records to be stored in the OVK Archives.

Evaluation (meeting held May 2021)

During May 2021, representatives from each organization participated in a facilitated Talking Circle (based on FNPO, 2009; OVK, 2013) to reflect and tell the story of the Partnership. Analysis of this meeting and additional evaluation activities were planned for future years.

Research film (filmed summer 2021)

Three undergraduate interns (all Kake High School graduates) and one local videographer in Kake wrote, directed, filmed, and edited a science communication film about the Partnership, with the objective of sharing information about the Partnership with a broad audience. Film editing was ongoing at the end of the study period.

TABLE 4 Field projects in order of priority and timing.

Kake Climate Partnership Field Projects Nov 2019-Oct 2021

Project	Method(s)	Amount completed	% Team time*	# Kake residents paid to work on project
1. Ocean Monitoring	Western science sample and data collections	2 seasons data collected	50%	30
2. Evaluation**	Facilitated Talking Circle	Meeting held in May 2021	5%	4
3. Research Film	Led by local student interns	Filming complete, editing begun	5%	3
4. Stream Monitoring	A) Traditional Knowledge interviews B) Western science sample and data collections	Planning completed	25%	3
5. Climate Change Adaptation Plan for Kake	Mixed	Planning begun	5%	1

Priorities have been set by all partners using consensus during biannual meetings. *Adds to 90%, because about 10% of team time is spent on administrative, outreach, and other activities not directly related to any field project. **Project aligns with Assessment item from Principles and Expectations document (see Supplementary file B and Table 3).

Stream monitoring (planned spring/summer 2021)

Partners planned a project to combine Traditional Knowledge with western science for monitoring water quality in local salmon streams. Salmon is an important local and traditional food to Kake residents. Methods included plans to A) train local residents to conduct interviews (Bernard, 2011) documenting Traditional Knowledge of changes in local salmon and streams over time, including observed changes in temperature, water levels and salmon runs in local creeks and streams through interviews with Elders and experts in Kake; and B) install temperature loggers and passive sampling instruments in stream locations near Kake documenting climate and pollutant indicators that may affect the ability of salmon to thrive in those streams.

Climate change adaptation plan for Kake (planning begun in January 2021)

Partners began creating an Adaptation Plan based on the Traditional Knowledge and scientific data collected by the Kake Climate Partnership, in line with CCTHITA (2019).

The two baseline data collection projects—ocean monitoring and stream monitoring—took up most of the Partnership team's work time (Table 4) during the study. Stream monitoring was planned but not begun during the 24 months of this study. Ocean monitoring data collections were completed during both years of this study, across a total of ten sample sites in the Kake Community Use Area (Supplementary file E).

E. Figus spent up to 25% of her time mentoring local youth and students during the study. Field projects emphasized mentorship, training, and paid work opportunities for local residents and Tribal members. In addition to providing part-time work opportunities for local adults, co-authors E. Figus and B. Ki'yee Jackson supervised nine students from Kake High School, who worked as paid research assistants during the study. For more than half of these students, working on the Partnership team was their first professional job. E. Figus, B. Ki'yee Jackson, and other team members also guest lectured at the Kake High School and hosted local students on two field trips. E. Figus further mentored one undergraduate research assistant/senior thesis project (Davis, 2021) and three undergraduate student interns—all of whom received living wage compensation for their work.

Understanding that ideas of 'open data' and 'open science' do not fully align with Indigenous Peoples' rights and interests (GIDA, 2019) or the rights and interests of non-academic entities, partners have supported Tribal and local control over all data and information gathered under the Partnership. During this study, partners used a Memorandum of Agreement (MOA) and multiple NDAs as tools to formalize this local control. As an example, the local undergraduate who used ocean monitoring data in her senior thesis signed an NDA for the duration of her use of the data. Her academic adviser, mentor E. Figus, and outside reviewer signed NDAs as well.

Defining the key facilitators for this work early in the Principles and Expectations document (Supplementary file B) provided clarity for the team. Assessment was made possible through consistent creation of monthly updates and holding a formal evaluation for all partners in May of 2021. Ocean monitoring (and planned stream monitoring projects) documented critical information to support local climate adaptation and mitigation. In the 24-month period of this study, partners produced numerous reports and presentations, including for Tribal and university meetings, and regional and national science conferences. The Partnership supported one undergraduate senior thesis project by an enrolled member of OVK Tribe (Davis, 2021), and received recognition from local, regional, and national media (Adapt Alaska and Figus, 2020; McKinstry, 2020; NOAA and Figus, 2021; Sea Grant and Figus, 2021). At the close of the 24-month period of this study, all partners agreed to continue and expand the Kake Climate Partnership and were engaged in negotiations to lengthen the existing MOA and expand the terms to include other planned projects.

Financial spending

The Partnership was formed knowing that university partners had 24 months of funding to cover co-author E. Figus's salary and travel from two different funding sources (NOAA and USDA). University funding also covered: travel for E. Figus and partners to attend science conferences (virtually); travel for E. Figus to visit colleagues throughout Alaska; and supported some parts of field research data collection in Kake. In addition to the university funding that was available at the project outset, OVK in Kake had existing grants from the Bureau of Indian Affairs and the Environmental Protection Agency to support field project costs and local salaries/direct payments. During this study, the Partnership secured (in new funds) or leveraged (pre-existing funds listed above) over $50,000 for directly paying local residents, including the nine paid high school research assistants, one paid undergraduate research assistant, and three paid undergraduate summer interns. Sources of new funds for paying residents came from successful applications for the Partnership to host paid interns (from NOAA and Alaska Sea Grant) and for a paid undergraduate research stipend during the academic year (from the University of Alaska Fairbanks).

Field projects were designed to fit within existing funding as appropriate. Table 5 summarizes spending in the 24-month period across each of three broad categories: Travel, Salary/Direct Payments, and Field Project Costs, and provides a basic overview of spending related to this type of co-produced research, without focusing on the specifics of our budget. Partners spent over half a million dollars, not including indirect/overhead costs, to carry out co-production in Kake over 24 months.

While not able to anticipate all potential salary/direct payment costs prior to forming the Partnership, the university partner anticipated a need for funds to hire and train local research assistants or provide honoraria to local partners who volunteered time. Once the Partnership was formed, partners worked together to secure new funding to support summer internships and research stipends for local undergraduate students (through NOAA, Sea Grant, and UAF).

TABLE 5 Total approximate financial spending during the 24-month period of this study including all leveraged funds across three basic categories: Travel, Salary/Direct Payments, and Field Project Costs.

Approximate financial spending during study

Expense	Amount (approximate values)
Travel	$35,000.00
Salary/direct payments	$350,000.00
Field project costs	$175,000.00
Total	**$560,000.00**

The category "Travel" includes travel of co-author Figus, as other travel was canceled during the 24-month period of the study, due to the COVID-19 pandemic. The category "Salary/Direct Payments" refers to costs of Figus's salary, partner staff time, and payments to residents in Kake for work related to the Kake Climate Partnership. The category "Field Project Costs" includes costs of supplies, shipping, sample processing, and any direct payments to people not residents of Kake who assisted with Kake Climate Partnership work during the 24-month period. All values refer to funds used, and do not include indirect/overhead costs.

Results from coding monthly logs

All the text in each of the monthly log files was coded with at least one of the deductive or inductive codes. In some cases, multiple codes were assigned to the same portion of text. One additional code—"Flex-Pivot"—was created inductively during the coding process, yielding a total of 23 codes (Table 6).

Objective (1b) how the ellam yua co-production elements manifested in our work

In the review of E. Figus' logs, the most prominent elements from the Ellam Yua framework (Figure 1) were "Relationships", "Capacity", "Means & Ability", and "Communications" (Table 6). Elements "Deliberate & Intentional", "Empowerment", and "Gather Information" also had high incidence in the text analysis. Five of the seven most referenced Ellam Yua elements in written logs were from the "Conceptual Tools" of the Ellam Yua framework, with two elements from the "Action Circle"—"Communications" and "Gather Information." We also report results from analysis of the "Challenge" code here as it had the second highest incidence overall.

Other elements—including "Trust & Respect", "Decolonization", and "Practice Reciprocity"—had a lower incidence of occurrence in E. Figus' log notes. "Knowledge Systems" and "Equity" had the fifth and seventh lowest incidence in coding from the logs overall. The Ellam Yua elements with lowest incidence in the review of logs were "Ethical", "Problem Definition", "Identify Question", and "Sovereignty".

The highest incidence codes were encountered >10 times more often in the monthly logs than the lowest incidence codes.

TABLE 6 Type of code (Deductive or Inductive); Code Name (either an element from the Ellam Yua co-production framework or an inductive code); which part of the Ellam Yua co-production framework each code belongs to (see Figure 1; not applicable for the 'Challenge' and 'Flex-Pivot' codes); and # References (absolute incidence) of each code used in our analysis.

Type	Code name	Part of Ellam Yua Co-Production Framework	# References
Codes used in text analysis of monthly logs			
Deductive	Equity	Outer Ring	27
Deductive	Trust and Respect	Conceptual Tools	66
Deductive	Relationships	Conceptual Tools	281
Deductive	Empowerment	Conceptual Tools	148
Deductive	Means and Ability	Conceptual Tools	213
Deductive	Capacity	Conceptual Tools	234
Deductive	Deliberate and Intentional	Conceptual Tools	165
Deductive	Ethical	Conceptual Tools	15
Deductive	Decolonization	Conceptual Tools	45
Deductive	Sovereignty	Conceptual Tools	22
Deductive	Problem Definition	Action Circle	16
Deductive	Identify Question	Action Circle	17
Deductive	Develop Methods	Action Circle	64
Deductive	Gather Information	Action Circle	123
Deductive	Information Analysis	Action Circle	26
Deductive	Communications	Action Circle	201
Deductive	Review Results	Action Circle	34
Deductive	Control of Information	Action Circle	53
Deductive	Practice Reciprocity	Action Circle	40
Deductive	Knowledge Systems	Converging Through the Process	23
Deductive	Co-Production of Knowledge	Goal	70
Deductive	Challenge	N/A	249
Inductive	Flex-Pivot	N/A	17*

* Absolute incidence of this code is not meaningful, as it was inductively added partway through the coding process, without returning to re-coding earlier texts.

Figure 4 shows a visual representation of this relative incidence across all deductive codes.

Elements of "Sovereignty", "Ethical", "Problem Definition", and "Identify Question" had low incidence of coding from log notes but were nevertheless prominent in the 24-month study period, as evidenced in the jointly agreed upon Principles and Expectations document (Supplementary file B) and research processes.

We ran queries for Pearson's and Jaccard's correlation coefficients across the 22 deductive codes, to seek meaningful clusters of codes and to attempt to capture codes that were prominent in the Principles and Expectations but did not have high incidence in the coding. Results from a query using Pearson's correlation coefficient across the 22 deductive codes did not yield any obviously meaningful groupings of codes. Results from a query using Jaccard's correlation coefficient across the 22 deductive codes in the E. Figus logs showed how the elements were clustered in *project activities* during the study (Figure 5).

The six Jaccard's correlation clusters displayed how the 21 Ellam Yua elements and the deductive code for 'Challenge' were correlated in the monthly logs. We found the six clusters represented five meaningful groups in the context of the Kake Climate Partnership project activities during this study: Action Circle Basics; Human Interactions; Field Projects; Partnership Operations; and Big Ideas.

Action circle basics

This group includes two clusters of basic research steps from the "Action Circle" that had low incidence in coding. The first cluster includes the codes 'Identify Question' and "Problem Definition" in a single cluster. These codes had low incidence in the logs but were successfully achieved during the study. Partners in Kake had clearly defined problems and research questions from the beginning of our partnership, thus, the team did not spend a lot of time on these Ellam Yua elements, beyond achieving consensus about prioritizing an order of project completion (see Supplementary file C). In contrast, the

FIGURE 4
Word cloud displaying relative incidence of the 22 deductive codes used in our analysis, with the higher incidence codes displaying larger and lower incidence codes displaying smaller, with size dependent on absolute incidence of each code. Colors do not display any categorical difference between codes and were chosen to match colors in Figure 7. Created by M. Rhodes-Reese in Adobe Illustrator, using NVivo software output.

second cluster including "Information Analysis" and "Review Results" had low incidence in the logs because these elements were not completed in the 24-month period.

Human interactions

This group includes codes "Trust & Respect", "Deliberate & Intentional", "Communications", and "Relationships." "Relationships" had the highest coding incidence in the E. Figus logs. The other three codes in this cluster were not in the top four for incidence but were correlated with 'Relationships,' as they were a key part of relationship-building. Partners communicated regularly *via* emails, phone and video calls, and face-to-face meetings, and E. Figus traveled to Kake nine times during the study period (see section titled, "Building a partnership through written and agreed upon principles and expectations").

Field projects

This group includes five high incidence codes: "Gather Information", "Empowerment", "Means & Ability", "Capacity", and "Challenge." This group demonstrates how the field projects were more than simply data collection. Field data collection was the cornerstone of "Empowerment" in the form of employing and mentoring local undergraduate and high school students. Partners also had to secure and maintain necessary "Capacity," in the form of local people available/able to do the work, and "Means & Ability," in the form of funding and supplies for the work. The code for "Challenge" was strongly correlated with elements in this field project theme.

Partnership operations

This group includes three low incidence codes from the "Action Circle:" "Practice Reciprocity", "Control of Information", and "Develop Methods." These three codes formed a key part of day-to-day operations for the Kake Climate Partnership during the study. For example, how partners chose to "Develop Methods" was related to how information gathered during field projects was stored and shared (i.e., "Control of Information"). As with two of the codes in the "Action Circle Basics" group, these elements were coded with low incidence, not because they were unimportant, but rather because they were fully established during the first few months of the Partnership. Processes of meetings and decision-making involved "Practice Reciprocity"—often in the form of sharing stories and sharing food—and all these actions were guided by broader concepts in the "Big Ideas" group (see below).

Big ideas

A final group for six big ideas from the Ellam Yua framework includes: the "Outer Ring" code for "Equity"; "Conceptual Tools" codes "Ethical", "Decolonization", and "Sovereignty"; the code for converging "Knowledge Systems"; and the goal of achieving "Co-Production of Knowledge." These "Big Ideas" codes had lower incidence as they were not closely related to the day-to-day operations of the Partnership, which constituted the core content of the written logs.

Objective (1c) challenges faced during the 24-month period of study

The "Challenge" code had the second highest incidence of any code in our analysis. We identified five themes in the "Challenge" code: Logistics, Priorities, Communication, Capacity, and a Global Pandemic.

Logistics

Logistics (coordinating people, supplies, funding, projects, etc.) are a challenge in any type of research. In the geographic context of Alaska, and the context of Kake as a rural community not connected to other communities by road, it is common for projects to have unexpected delays due to weather or shipments of supplies. We anticipated added costs for all aspects of our field projects and in-person meetings, as compared with projects in the contiguous United States. Other challenges during the study included: balancing logistics across four different partners with team members in multiple communities across Alaska; leveraging, securing, and administering multiple sources of funding; achieving multiple goals on a limited timeline; and maintaining the focus needed to pay careful attention to the Ellam Yua co-production elements at every stage of our work.

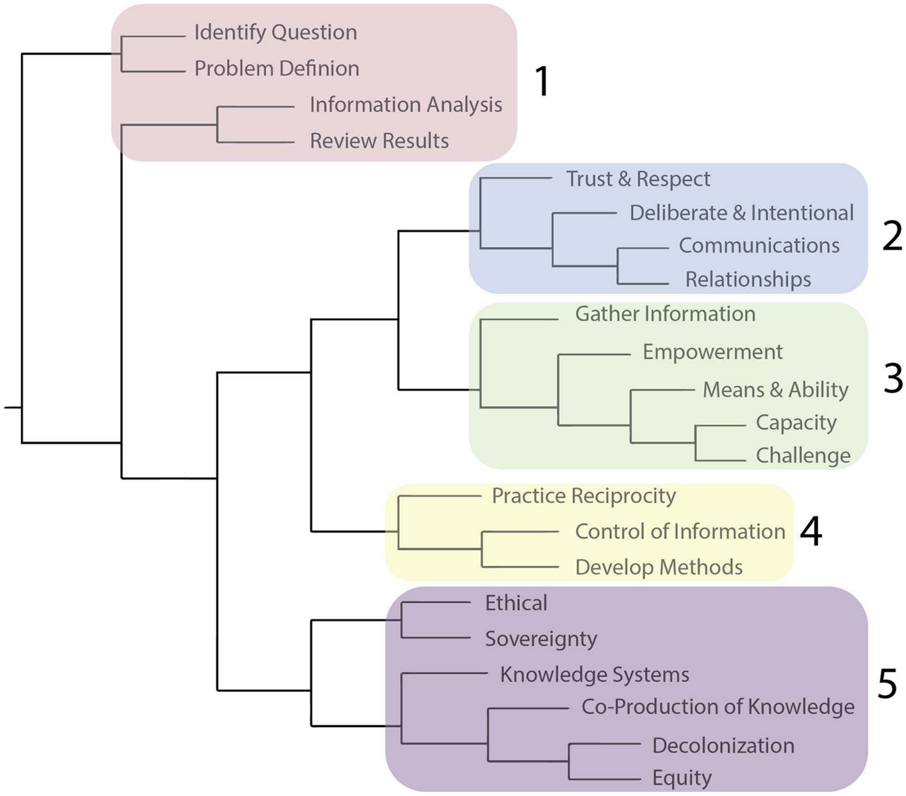


FIGURE 5
Six clusters of codes based on similarity of words coded among them. The six clusters represent five meaningful groupings in the context of the Kake Climate Partnership project activities during this study. The clusters are displayed as branches in the above tree diagram, while the five meaningful themes are displayed using rounded transparent boxes, numbered 1-5. Each number corresponds to a meaningful group as follows: 1. Action Circle Basics; 2. Human Interactions; 3. Field Projects; 4. Partnership Operations; and 5. Big Ideas. Colors are used to differentiate clusters. Created by M. Rhodes-Reese in Adobe Illustrator, using NVivo software output.

Priorities

Juggling the priorities of multiple partners and multiple projects was a challenge throughout this study. Partners had diverse goals for how to prioritize their time and efforts. For example, ACCAP had priorities related to attending conferences and compiling peer-reviewed papers, while OVK, KTC, and the City shared priorities related to balancing research schedules with the schedules of Tribal and community events and customary and traditional food harvests. The team also experienced occasions of needing to shift priorities—often in the form of slowing down field projects—to uphold elements of "Trust & Respect", "Empowerment", "Decolonization", "Practice Reciprocity", and "Sovereignty".

Communication

Some partners preferred to communicate *via* email, others *via* phone, and some preferred face-to-face meetings. Some partners worked on typical weekday 9am−5pm schedules, but most did not. Additionally, the community of Kake had limited bandwidth capabilities for Wi-Fi and intermittent blackouts of cellular service during this study—as is typical of many rural communities in Alaska.

Capacity

The Partnership experienced *capacity limitations* and *capacity imbalance* throughout the study. The primary capacity limitation was that only one team member had full-time work dedicated to the Partnership.

> *In my role as... the one person who is full-time committed to the Partnership, I must find balance across the three types of interests: my boss (or the larger entity I represent in academia), myself, and my partners. This is not an easy task, and it is one that feels like burnout at times. Because there is always something more that needs to be done for one of the 3 spheres.*–E. Figus log notes June 2021

The primary capacity imbalances were (a) this was a university-initiated partnership with full-time capacity coming solely from the university partner; and (b) the university and Tribal partners were the most active in terms of time and funding dedicated to the Partnership during the study period, with the City and KTC dedicating less capacity.

> *I feel like a lot of this work is turning into ACCAP and OVK, with a side of everything else. I hope that is not a weakness that will turn into a fissure for the Partnership...*–E. Figus log notes April 2021

Global pandemic

The COVID-19 pandemic interacted with the four other "Challenge" code themes through rapid and unexpected changes to our research goals, project design(s), timelines, travel, and funding structures. The pandemic exacerbated typical logistical challenges, caused a shift in our project priorities, improved our remote communications, and had mixed impacts on our capacity.

Flexibility in responding to challenges

The "Flex-Pivot" code emerged inductively during the coding process of E. Figus' logs. 'Flex-Pivot' is not part of the Ellam Yua framework and was added partway through the coding process to highlight a need for flexibility/to pivot that was central to the study. As it was added partway through the coding process, 'Flex-Pivot' is not fully represented in the final set of codes and the absolute incidence ($n = 17$) of this code listed in Table 6 is not meaningful.

The "Flex-Pivot" code content includes ways partners pivoted in response to challenges that occurred during the study. While not an exhaustive list of responses to challenges, the 'Flex-Pivot' code sheds light on both the need for flexibility in any co-production process, as well as ways that E. Figus and other partners chose to pivot in response to various challenges. We identified five themes in the 'Flex-Pivot' code, each of which represents an applied example or a set of examples from the first 24 months of the Partnership (Table 7).

Use of language

In Kake, this work was defined as a 'partnership' because terms like 'co-production' and 'actionable science' did not have clear meanings in the non-academic spaces of Tribal and community partners.

Rethink the role of scientific research and researchers

Typical academic research may include 5–10% outreach or engagement of some kind. The Partnership work done during this study was at minimum 50% Tribal and community engagement, youth mentorship, and administrative support for Tribal and community partners.

Flexibility in communication styles

Some partner entities wanted to be in constant communication, while others preferred to communicate only when there were specific decisions to be made. Over the study period, E. Figus provided monthly presentations to one partner entity, while the other three partners chose to receive written updates via email each month. Tailoring communications to fit individual needs took extra time in the beginning of the Partnership but saved time and effort once a rhythm was established.

Flexibility in process with dedication to core principles

In the face of unexpected events, short- and medium-term goals must shift. Major events, like a global pandemic, or minor events, like a mechanical breakdown of a sampling boat, can impact project timing and funding. Partners made alterations to almost every aspect of their work over the course of the 24-month study period, including changes to: funding sources; the order in which partners carried out projects; who were lead contacts from some partner entities; the way(s) each partner chose to participate and communicate with larger group; and the way(s) partners were able to meet with one another. However, partners *did not change* the core principles and expectations from the written and agreed upon document created in May of 2020 (Supplementary file B). Knowing when to be willing to flex and pivot was just as important as understanding when to stick to core long-term goals. In this study, having a document that clearly stipulated a shared long-term vision and day-to-day expectations meant no partner had to guess about whether a near-term activity was aligned with long-term goals.

Transparency in acknowledging successes and challenges

The Kake Climate Partnership enjoyed many successes in the 24 months of this study. Partners were also transparent with one another from the beginning about challenges. Through open discussions, partners were able to identify and respond to the key challenges presented in this paper.

Discussion

In this study, we found that creating the Declaration of Principles and Expectations (as recommended in Naquin et al., 2019; Supplementary file B) was key for success. By intentionally situating the Traditional Tribal Values (CCTHITA, 2022) in the Principles and Expectations, partners were able to use the document as an implicit and explicit tool for decolonization throughout their work. We also found that carrying out regular check-ins between individual partners and as a group was key to ensuring expectations were met over time in a transparent fashion. It was important for partners from outside the community to measure the time spent in Kake in weeks or months, not days, each year. This work was also expensive, and some costs were not possible to anticipate. While some costs of this work were known at the beginning, such as

TABLE 7 Example quotes from the monthly logs across the five themes that emerged from the 'Flex-Pivot' inductive code.

Examples of the 'Flex-Pivot' code across five themes

'Flex-Pivot' theme	Example Quote(s) from monthly logs
1	*. . . the jargon creates a smokescreen that does not always make sense in communities [Research Colleague pers. comms, 2020]. In the context of Kake, we have defined ourselves as a 'Climate Partnership' and more generally as a 'Research Partnership' rooted in climate and environmental projects—September 2020*
2	*. . . I think I [typically] unconsciously focus 75% [of my time] on scientific research, including [Indigenous Knowledge] as part of scientific research, with about 25% community engagement. I have not thought about this fully yet. How much of my current [co-production] work should be scientific research*—September 2020
	[Knowledge Bearer from Kake] recommend[ed] that I let my voice be quiet while doing the work to support the capacity of my research partners, my Indigenous partners, to lead our projects in a way that satisfies their goals. So, I can run around and get project materials and help design methods for water sampling, but I need to step aside and back when it comes to leadership and big decisions, as well as how we present our work to the outside—September 2020
3	*It feels like a huge weight has been lifted. I felt uncomfortable with worry for a week, but I am glad I simply thanked the [partner] for their time and got off their call. They are happy with the Partnership (or at least not disappointed) and just [did not] want me [presenting at] their monthly meetings*—January 2021
4	*Every few days, I have drafted a new potential sampling schedule, just in case things are ready to go. But no sampling took place. . . due to [boat] mechanical and COVID issues. . . COVID is spreading in Kake. We had a plan to get calibrations completed and potentially two sampling events completed, but one of our lead samplers is hunkering down due to a positive case of COVID in the family, and the case count in Kake continues to rise. Another 'hurry up and wait' week for ocean monitoring, while we deal with the stress and worry of everyone's safety*—August 2020
	The [Declaration of Principles and Expectations] has become part of everything that we do, and it is the strongest glue holding us all together throughout this pandemic. The [Declaration of Principles and Expectations] is a work product, a deliverable in itself because it reciprocally defines us as we define it. . . The [Declaration of Principles and Expectations] is meant to be our application of the [co-production] model [from Ellam Yua et al. (2022)]. The [Declaration of Principles and Expectations] ensures that we are all at the Kake Climate Partnership 'table' for the same reasons. We all understand that this partnership is much bigger and more meaningful than any of the individual pieces or people involved. We agree explicitly to uphold the principles of the [Declaration of Principles and Expectations] in all that we do—November 2020
5	*I [am] struck by how quickly 12 months has gone by. . . We have had great success, but also great challenges and potentially upcoming failure...I am losing faith in the idea that meaningful [co-production], partnership work can be conducted in a 24-month window. Certainly, it could not be done in 12 months*—October 2020
	During the last week of February, I was informed by [university funding staff] that paying for Covid testing prior to and during travel to Kake will not be an 'allowable expense' on the [Federal] grant [we are using to cover my travel]. My travel plan was not reviewed by anyone other than [my supervisor], to my knowledge. This trip planning is very different from the trip in October. I made an appointment at [the regional Tribal health consortium] in Juneau for a pre-departure test and prepaid the $145 charges. I wonder if there is a more flexible fund that we can pull money from to pay this cost—February 2021
	There are many different balls in the air that require my attention at the moment. . . This is the month where [co-production] turns into [a] choice of who gets the money from the emptying pot—January 2021
	A nice outcome of this month (and the trip to Kake) was that I walked away with confidence that our partners want to carry on past November 2021, so we have a bit more time to complete our goals together—March 2021
	OVK and everyone in Kake have adeptly and gracefully molded the [Kake Climate Partnership] into their other ongoing initiatives. In this way, I am confident that [Kake Climate Partnership] has constructively contributed to long-term projects and planning in Kake in a positive way. But I do hope we can find a way to make this a more lasting program—October 2021

The numbers 1-5 in the table correspond to five types of 'Flex-Pivot' themes as follows: 1. Use of language; 2. Rethink the role of scientific research and researchers; 3. Flexibility in communication styles; 4. Flexibility in process with dedication to core principles; and 5. Transparency in acknowledging successes and challenges.

travel for in-person meetings, many other costs could not be foreseen, for example, costs of projects or field research that were only developed after the Partnership was formed. Funding uncertainties were exacerbated in our study by the COVID-19 pandemic. Flexibility was key for all partners—for everything from defining research objectives to managing time.

Our inductive 'Flex-Pivot' code demonstrates the importance of adaptability in implementing Ellam Yua co-production. We also found that this type of co-production work takes much more than 24 months of time. While individual projects can be designed, implemented, and completed over shorter timescales (e.g., a few months), the process of building any meaningful partnership takes years, and may be expected by a community to last much longer.

The Kake Climate Partnership used many of the elements of co-production during this study, but did not employ a 'wholly' co-productive approach as described in Yua et al. (2022):

> *The use of some of the conceptual tools of co-production should not be—though increasingly is—confused with employing a wholly co-productive approach. That is not to say that we discourage the use of a subset of the conceptual tools presented here, but rather that a true CPK [co-production of knowledge] approach requires equity through the entire research process, from the very beginning. Additionally, it is far more important to do co-production than it is to talk about it or label things as it* (p. 27).

We found that in the 24-month period of this study, it was not feasible to fulfill the elements of 'Review Results' or 'Information Analysis' in a meaningful way. Similarly, many elements were less prominent than they might be over a longer time period. 'Decolonization' was a shared goal among partners but was not commonly identified in coding. Kake Climate Partnership field projects included both Western science (e.g., ocean monitoring) and Indigenous Knowledge (e.g., Talking Circle Evaluation), but during the 24 months of the study, partners did not achieve the bringing together of two different 'Knowledge Systems' as described by Yua et al. (2022) (Table 8) in a concrete way.

Partners engaged in actions for the elements 'Trust & Respect' and 'Practice Reciprocity', but in just 24 months of time and starting from scratch (no prior relationship between ACCAP and the other partners), partners did not completely fulfill these elements (Table 8). Partners seeded strong roots for the less prominent elements to be fulfilled in the future, but these less prominent elements would likely require more than 24 months of time to fulfill in any co-production partnership.

Geographical context of Kake

Delivering salient climate services hinges on understanding and responding to specific characteristics of user needs, including local knowledge and geographic context (McNie, 2013; Clifford et al., 2020). The Partnership research priorities were community-driven and field research was grounded in the landscape, geography, and Tribal context of the Kake Community Use Area. While Ellam Yua co-production may be applied in many different regions, there may be features of the Partnership that are unique to its geographic context.

The work presented in this paper is based around four entities cooperating to come up with a group plan to best study climate change impacts and plan for adaptation throughout the Kake Community Use Area (Figure 2). The food sovereignty and food security project priorities in Kake may or may not align with those of other regions, and financial spending in Kake may not align with costs in other regions. Kake is also a community where the leadership entities have a strong track record of working together for the betterment of their community (See text footnote 1). Not every Alaska Native community has cooperation between the municipal government, Tribal corporation, and Federally recognized Tribe. In communities that lack this level of coordination, the complex, tripartite, colonial-imposed system of governance in Alaska Native communities (Carlo, 2020) can create obstacles to climate adaptation.

We found that the Ellam Yua co-production framework developed for use in the Arctic was applicable in Kake, even though Kake is not located in the Arctic. We expect Ellam Yua co-production could be useful for other research partnerships among Indigenous and non-Indigenous entities, regardless of geographic context. Similarly, some characteristics of Kake's geographic context may be relevant in other settings. For example, non-Indigenous academic researchers seeking to partner with Indigenous Tribes and/or rural or remote communities in other regions may find some key parallels in our descriptions of travel, time, funding, and capacity needs for their work.

Reflections about challenges during this study

COVID-19

Challenges related to the COVID-19 pandemic heavily impacted this study by influencing *how* co-production activities were able to take place. Interestingly, however, while the pandemic created some challenges for day-to-day work—especially due to limitations on in-person gatherings—the Partnership was especially well-positioned to continue functioning throughout the pandemic with limited risk. For example, the COVID-19 pandemic unexpectedly improved our team's remote communications abilities, through increased affordability of Wi-Fi, cellular service, and increased access to laptops and computers purchased through Federal relief funding. The pandemic also normalized the use of and access to online video conferencing software[2] like Zoom, which made it easier for our team to communicate with one another remotely. This allowed our locally led ocean monitoring work to proceed with limited interruptions. Writing about COVID-19, Marino et al. (2020) ask researchers to, "pause and reflect on the ethics of research in times of acute risk exposure." Marino et al. (2020) also correctly urge researchers to question whether their work is "beneficial, collaborative, or necessary." By using Ellam Yua co-production methods—including centering local priorities,

2 E. Figus and B. Ki'yee Jackson personal observations, 2021.

TABLE 8 Example quotes from monthly logs of elements from the Yua et al. (2022) framework that were not fully achieved (fulfilled) during this study.

Limitations to fulfilling Ellam Yua co-production elements

Type of limitation	Example quote from monthly logs
'Trust and respect' element	*[The] biggest hurdle is trust; I like the term 'moving at the speed of trust' because that is what I do... it is a reality for myself and the Indigenous people of Alaska and probably around the world; we cannot go into things trusting because it has just been proven, years of oppression of our people by a system that was created not for people of color; it was created for the people of European descent; nothing that is on the books, whether it is policy, law, whatever; that wasn't written for people of color. We came as an afterthought... there is always something else behind what is being asked us. I don't know how to explain that, but there is always an underlying issue... I am leery of people that want to come and help our community. Not that I'm not appreciative of their efforts; it is that we have to keep our guard up; always, as Indigenous people... I think mainly it comes down to trust. It is sad that that's always there for me, but I'm not going to go into something without mentioning that. And I won't ever hide that from anybody. Trust is earned, and it won't come easy*-–OVK President Joel Jackson (excerpt from log notes, October 2020)
'Practice reciprocity' element	*What is in it for them? This is the key to the whole [co-production of knowledge] process. What purpose does it serve an over-extended tribe and small community to get lip service and paperwork from the university? Without financial and temporal investment, the Partnership is meaningless. When I proposed designing climate research with the aim of providing tangible benefits to Kake, our partners at the tribe and city and corporation all said emphatically that workforce development HAD to be part of what we did. And field work ideas came pouring out of the tribal staff and leadership. The implication from early on was that I needed to find or bring money to the table to support those endeavors. Otherwise, what am I doing here in this 'partnership' space*—January 2021

training, and mentoring local residents to carry out fieldwork, and supporting the outside researcher E. Figus in coordinating fieldwork activities from her home office—the Partnership was able to thrive despite the pandemic.

Other challenges

We found that challenges related to 'Logistics,' 'Priorities,' and 'Communication' were inevitable and likely would be ubiquitous across any similar partnership, while challenges related to 'Capacity' were contextual.

Capacity imbalance has the potential to be a positive aspect of co-production, for example when an entity with ample funding assists an entity with less funding capacity. However, when a capacity imbalance is sustained throughout a co-production partnership it has the potential to perpetuate inequitable power differentials that impede local and tribal sovereignty in the research.

During this study, the Partnership leaned heavily on the efforts of a few members (including co-authors E. Figus and B. Ki'yee Jackson) and workload was not balanced across all four partner entities. Challenges with 'Capacity' were strongly influenced by a *constricted timeline* and *directional formation* (as interpreted from the monthly logs and reflective conversations among co-authors).

Constricted Timeline: This paper reports experiences in the first 24 months of the Kake Climate Partnership. While the Ellam Yua model is nonlinear, field projects had strict linear timelines, and the Partnership depended on full-time work capacity from co-author E. Figus. E. Figus' position as a postdoctoral researcher (and coordinator/facilitator of the Partnership) was limited to a 36-month period, after which the future of the Partnership was unclear.

Directional Formation: ACCAP initiated the Partnership with the goal of attempting to carry out co-production within a 24-month timeframe. In this approach, the work in this study deviates from the Ellam Yua framework, which recommends that Indigenous partners play a role in initiating partnerships for their benefit. Some challenges faced by the Partnership, including concerns about balanced input and participation from all partners, stem from this one-sided approach to forming a partnership (David-Chavez and Gavin, 2018).

The 'Capacity' challenges of a constricted timeline and directional formation were specific to this project and could be eliminated from future work through careful and deliberate planning. If the project had been planned on a longer timeline from the beginning (5 or more years), both types of capacity issues could have been resolved. With a longer timeline for work, it is likely that: (a) the Partnership would have been able to fulfill all the Ellam Yua elements to achieve a wholly co-productive approach (see beginning of section titled, "Discussion"); (b) there would have been less of a focus on linear scheduling during the first two years; and (c) there could have been more time devoted to planning, with the opportunity to deliberately structure balanced input and participation from all partners.

A note about potential limitations of this study

While the Partnership provided tangible benefits to the community of Kake, the constricted timeline of 24 months and directional formation (described above) limited the ability of partners to employ a wholly co-productive approach to this work.

The written logbook notes and monthly update documents were analyzed by the same individual who authored them; however, results of the analysis were discussed by the author team in our reflective conversations. While only two of our four research partner entities were participants in the reflective discussions and are co-authors on this paper, drafts and the final version were reviewed and approved by all partner entities prior to publication. More formal evaluation of the Partnership that engages all project partners was ongoing at the time of this writing and will be reported elsewhere.

Key features that made Kake Climate Partnership climate services relevant and useful for tribal and community partners

The field of climate services is broadly aimed at producing climate data, information, products, or knowledge that is/are usable in decision-making, planning, or policy (Brasseur and Gallardo, 2016; Daly and Dilling, 2019). Co-production has been put forward as a process that yields a greater likelihood of usefulness and usability in climate services (Lemos and Morehouse, 2005; Dilling and Lemos, 2011; McNie, 2013; Kruk et al., 2017). In the Kake Climate Partnership, several features have been significant in creating climate services and products that are relevant and useful for the Tribe and community partners.

Workforce development

One of the most important priorities for local members of the Partnership during this study was building local climate capacity through workforce development. Indigenous communities and Tribes around the United States face barriers to successful workforce development, including: low self-confidence; a lack of professional role models; a paucity of 'living wage' job opportunities; or little room for professional advancement (NCAI, 2020b). All these barriers commonly lead to a 'brain drain' dynamic, where young people leave Indigenous communities to look for jobs elsewhere (NCAI, 2020a,b). There is a critical need to build capacity in the form of appropriate education, training, and job opportunities necessary for locals to take the lead in climate change research, adaptation planning, and mitigation.

We acknowledge barriers to workforce development faced by Indigenous communities around the United States (NCAI, 2020b), while recognizing the local talents and capabilities of people in Kake. In Kake, it is challenging to grow local research and management programs because there is a lack of people to fill jobs (See text footnote 1). But it is critical to create job openings to provide for local college graduates upon completion of their degree programs. While it is common for a university to harness scientific expertise in a research partnership, it is less common for university partners to seek guidance from Indigenous experts, to trust and follow community and Tribal lead, and center research efforts around local workforce development. Providing local workforce development opportunities in rural Alaska is especially relevant for the young people (NCAI, 2020a) who will comprise the next generation of climate change adaptation leaders.

One element in the larger local vision

We found that *when the climate services process is centered on Tribal and community priorities and locally identified science needs, the climate science aspect becomes just one element in the implementation of a larger local vision and goals*. In contrast to climate service models that provide downscaled scenarios to end-users for use in planning, the Partnership started with local needs and priorities. Projects were aimed at increasing adaptive capacity to climate change in Kake, based on local priorities of food security/sovereignty and data sovereignty. With an emphasis on process, Ellam Yua co-production goes beyond the provision of climate information by generating procedural benefits for local partners such as local empowerment. Our case study in Kake supports findings from Dilling et al. (2019), that the most critical adaptation-related needs may not directly relate to climate and instead relate to empowering communities in the face of climate change. The Partnership did not attempt to carry out climate services co-production as described in Baztan et al. (2020). However, we similarly found that process-related benefits of co-production have the potential to generate local capacity that may be mobilized to face climate change. Through providing workforce development opportunities in Kake, bounded research projects contributed to strengthening long-term local capacity for climate adaptation.

During this study, the Partnership provided climate services and information through field project scoping, design, implementation, and archiving of data for use by local leaders and future generations in Kake. The Partnership provided tangible benefits for individual residents of Kake in the form of compensating local members of our field teams and mentoring youth in every project. Tangible benefits for the Tribe and community of Kake were realized by meeting local information needs and conducting climate research to directly support local adaptation planning, through building two local climate monitoring programs (ocean and stream monitoring) and focusing on archiving the resulting data locally in Kake for future use.

The two climate monitoring projects addressed high priority food resource issues that were identified on both local and regional levels. For example, the regional Central Council of the Tlingit and Haida Tribes of Alaska Climate Change Adaptation Plan (CCTHITA, 2019) lists salmon as a species in the category of "very high priority" area of concern, due to, "cultural, social, and economic value and the limited tribal control over their adaptive capacity" (p. 25). The ocean monitoring project in Kake collected information necessary to carry out the 'Resilience Strategies' for salmon stocks, listed on p. 28 of the Adaptation Plan. Local partners led the ocean monitoring field project during 2020 and 2021, while outside experts (including E. Figus) provided additional capacity as needed to achieve a program that produced data that was relevant, salient, and useful for the Tribe and community in Kake.

Collection and storage of ocean monitoring data in Kake laid the groundwork for local leaders to carry out successful adaptation planning in the face of continued climate change, specifically about the management of customary and traditional food resources. During this study, OVK, KTC, and the City used the data generated to educate the community about climate impacts on customary and traditional foods (Davis, 2021). In the future, local partners plan to use data and information from ocean and stream monitoring to compare with regional data to inform decisions including whether and how to: expand stream and coastal restoration projects near Kake; introduce legislation limiting what ships are allowed to discard or discharge into State and Federal waters around Kake; alter storage practices at the local dump; and shift the time and location of customary and traditional food harvests.

FIGURE 6
A mixture of traditional Tlingit formline drawing techniques and European line drawing techniques to display connections in the Kake Climate Partnership. Two hands are pictured in the figure, holding up a rendition of a pristine natural environment pictured inside a circle (mountains, forests, water, sun). One hand represents Traditional Knowledge and the other represents Western science. Both hands share a vision of a pristine environment with clean water and healthy forests. The two hands are coming together with a common goal to protect and maintain that pristine natural environment through understanding climate change and adapting to it. Each hand is reaching out to the pristine environment, emphasizing that partners are all connected and have a common goal of preserving the natural environment as best we can. The phrase underneath the hands, 'We are all connected', communicates a shared vision among partners that everything is connected—partners have a shared vision of unity and common goals for the future. The phrase, 'Kake Climate Partnership', forms the top of the drawing, symbolizing how it is made possible through the two hands of Traditional Knowledge and Western science working together. Artist credit: B. Ki'yee Jackson; digitized by Lori Styczynski at Roy's Embroidery, in Juneau, Alaska.

Transformative climate and environmental science

The field of climate services is increasingly focused on holistic, integrated, and 'next generation' approaches (Jacobs and Street, 2020; Irumva et al., 2021; Tudose et al., 2021), including transdisciplinary co-production (Steynor et al., 2020). Vogel and Bullock (2021) note that Indigenous worldviews that "promote holistic problem-solving through social capital, collaboration and capacity-building" lend themselves well to climate change adaptation. In the Kake Climate Partnership, we found that *co-production can be used to explicitly define a collective vision among partners that is a transformative way of doing applied climate and environmental science.* Partnership members have a shared vision to deliberately shift away from colonialism in research and resource management (Tuhiwai Smith, 2012), and toward Tribal and local control over research and management of resources. In line with Dilling and Lemos (2021), we found that successful research co-production for climate services requires a commitment on the part of outside researchers to understand what Tribal and community members view as equitable and desirable outcomes. Creating a shared vision makes it possible to avoid harming communities (Dilling et al., 2019) and conduct climate research that provides tangible benefits for Tribal and community partners. This was especially relevant, as our study took place during the COVID-19 pandemic. Funding to accomplish the community designed and led research during this study was leveraged from a range of sources and multiple partners contributed funds approximately equally (OVK and ACCAP).

The Partnership was formed as a deliberate attempt to implement Ellam Yua co-production. Partners worked as a team to define challenges, identify strategies, collect data, and use findings from climate change research in support of adaptation planning. As such, all partners were both consumers and producers of climate information. Figure 6 shows a visual depiction of Partnership Principles and Expectations and connection among partners. Created by co-author Ki'yee Jackson, this image underscores the significance of holistic approaches to climate adaptation. Including artistic and culturally relevant elements in addition to scientific elements in the delivery of climate services constructs more enduring adaptive actions to climate change than are otherwise possible (Benson et al., 2020).

Boundary spanning

To use climate services to support truly transformational adaptation Boon et al. (2021) argue that climate service providers need to widen their scope and skills. In this study, *the role of the university researcher shifted from focusing on personal research interests to focusing on supporting local needs and priorities.* Respecting and engaging with Indigenous methodologies necessitates focusing climate services work on process, relationality, and service to community (Wilson, 2008). Postdoctoral researcher E. Figus from a NOAA RISA program acted as a boundary spanner (Bednarek et al., 2018; Posner and Cvitanovic, 2019) to connect community and Tribal leaders with capacity and support to achieve their climate research and adaptation goals. The Partnership team emphasized Tribal and community driven priorities and decentered the academic university perspective. ACCAP's role was primarily to provide training and mentorship, while respecting the sovereignty, intellectual property rights, and values of Tribal and community partners. Partners in Kake had a shared interest in collecting the scientific data that they needed to manage the Kake Community Use Area and the university partner mentored local partners in going after that scientific data.

Kake Climate Partnership supports a co-production learning network

Throughout the United States, NOAA RISA programs like ACCAP have been designed as human learning networks, prioritizing wide participation in learning to support transformational climate services (Combest-Friedman et al., 2019). In learning networks, the development and application of knowledge is multifaceted and individual team members must play multiple roles in the climate services process (Kettle et al., 2017). As boundary spanning organizations, the RISA programs can serve multiple roles to link science and decision-making in support of regional learning networks (Kettle and Trainor, 2015).

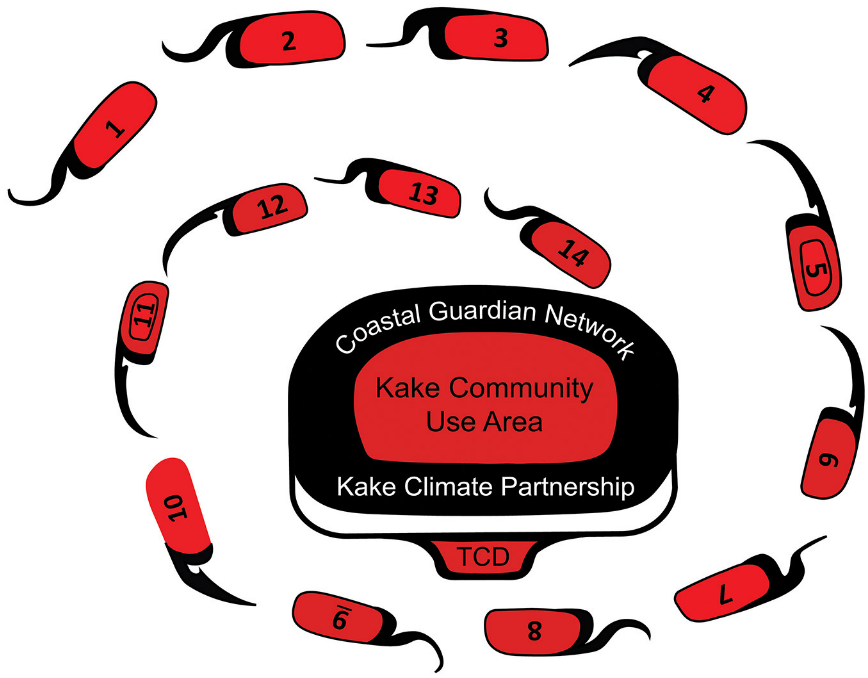
The Kake Climate Partnership was made possible in part because of the existing local initiatives for a Tribal Conservation District and a Guardian Watchmen Network, and by an existing regional learning network—the Sustainable Southeast Partnership. In turn, the work of the Partnership during this study was able to seed potential *future* learning networks, by creating trust relationships and collecting data necessary to support the Guardian Watchmen and Tribal Conservation District initiatives. The first 24 months of the Partnership was a seed for all three programs—the Kake Climate Partnership, Guardian Watchmen, and a Tribal Conservation District—to work together in unison, as 'one hand helping the other' (Figure 6). For example, developing the ocean monitoring program provided the Tribal and community leadership in Kake with some of the experience and capacity necessary to embark on a Guardian Watchmen program in the future. In this way, the Partnership became a *co-produced learning network* that brought together not only climate service professionals, but also a Tribe and community to support each other's work and increase potential positive impacts of climate change adaptation planning and mitigation in the context of the local vision of sustainability across a broad geographic and temporal scope. Figure 7 shows actions and processes that lead to a co-produced learning network.

Conclusions

In this paper, we have presented an instrumental case study (Stake, 1995) analysis of a research partnership among Indigenous and non-Indigenous partners in a rural community in Southeast Alaska. In line with Stake (1995), our aim was to learn about the Ellam Yua co-production process by thoroughly understanding the particulars of the Kake Climate Partnership. Co-authors carefully recorded and interpreted the co-production process over 2 years in the context of a single research program. While our aim was not to generalize about co-production based on our single case study, we have described the context and key features of our work that may be applicable to other co-produced climate services programs.

Stakeholders and practitioners in Alaska are calling for climate science that is more inclusive, transparent, collaborative, and accessible (Knapp and Trainor, 2013). In this paper, we have demonstrated how co-production explicitly designed for application in partnership with Indigenous communities is a transformative way of conducting science which holds great promise. When projects are meaningfully co-produced among academics, Tribes, communities, tribal corporations, schools, and other organizations, it is possible to: focus research and adaptation planning on topics that are most relevant for local people (Kipp et al., 2019); pursue multiple objectives simultaneously[3] leverage funding sources and capacity from multiple entities[3] and produce more usable science (Dilling and Lemos, 2011; Lemos et al., 2012) to maximize actionable outcomes.

3 E. Figus personal observations, 2021.



1) Form partnership among OVK and ACCAP
2) First joint meeting
3) Formalize partnership among OVK, ACCAP, KTC, and the City
4) First season ocean monitoring
5) Undergraduate mentorship
6) Second joint meeting
7) Begin second season ocean monitoring
8) High school student mentorship
9) Stream monitoring planning
10) Traditional Knowledge interview planning
11) Partnership evaluation May 2021
12) Research film
13) Undergraduate interns
14) Complete Second season ocean monitoring

FIGURE 7
Traditional Tlingit formline drawing techniques to display actions and processes that lead to a co-production learning network. The large ovoid in the center of the figure represents the center of the eye. The Kake Climate Partnership forms the base of this central ovoid, and acts as a seed for the future Coastal Guardian Network (see Table 2). The Coastal Guardian Network is situated across the top of the central ovoid, as a goal for the future. The 'TCD' stands for the Tribal Conservation District (see Table 2), which has a root connection to the ovoid in the eye and supports everything above it. The Kake Community Use Area is in the innermost ovoid, as the central point of all efforts. Each small ovoid with a tail on it is unique and symbolizes a main event from the first 24 months of the Kake Climate Partnership—actions partners have taken as a team to build the Partnership and support the long-term vision in Kake. Each small ovoid with a tail is numbered. The numbers correspond to a key underneath the spiral that displays descriptions of each major accomplishment of the Kake Climate Partnership during the 2 years of this study. Artist credit: B. Ki'yee Jackson; digitized by M. Rhodes-Reese.

We found co-produced climate services work conducted in authentic partnership with an Indigenous community and Tribe involved:

- establishing and abiding by shared principles and expectations;
- focusing on local priorities, local values, workforce development (NCAI, 2020a), and local leadership in research;
- upholding data sovereignty and intellectual property for all partners; and
- allowing academic and agency partners to play a supportive, boundary spanning role rather than a leadership role (Bartlett et al., 2012; Bednarek et al., 2018; Reid et al., 2021).

This work required expanding interpretations of research to include centering local workforce development while harnessing scientific expertise and seeking guidance from Indigenous experts. To achieve success, outside partners trusted and followed Tribal and community leadership. The outside partner (ACCAP) also acknowledged that climate change and climate services are just one part of larger Tribal and community visions and needs.

Using a case study of the Kake Climate Partnership, we have shown how co-production can be used to provide climate

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services through facilitation, support, and boundary spanning. OVK, KTC, the City of Kake, and ACCAP built a deliberate and equitable partnership, blending cultural and scientific elements of climate services (Benson et al., 2020) and blurring the distinction between producers and consumers of climate information (Dilling and Lemos, 2011). We have described our application of co-production over a 24-month period and reflected on linkages between the Ellam Yua framework and climate services in Kake. Deliberate and reflective application of this model through partnerships achieved relevant and useful climate services in Kake and could likely do the same elsewhere. Most of the challenges faced during this study were typical of any collaborative research, and we believe those that were atypical could be resolved by lengthening the timeline to be 5–10 years, instead of two. Aligned with Sikuaq Erickson (2020), we recommend that future efforts to co-produce climate services through research, adaptation planning, and mitigation be institutionalized and maintained over decadal, not annual, timescales. Research programs with five or more years of funding are well-situated to develop such longer-term plans for co-production of climate change research and adaptation with Tribes and communities.

Data availability statement

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

Author contributions

BKJ and EF led the field projects described in the manuscript. EF created the monthly updates and monthly logs used in the manuscript, conducted reviews of monthly updates, text analysis of monthly logs, and wrote the first draft of the manuscript. ST supervised the research, contributed to the framing, organization, and writing of the manuscript. BKJ created all artistic contributions (Figures 6, 7). BKJ, EF, and ST revised and approved the final draft, contributed to the objectives put forth in the manuscript, jointly wrote the outline, and contributed background literature to inform the findings described in the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

This study was conducted in partnership with Kake Tribal Corporation, a for-profit entity. Kake Tribal Corporation

donated time and guidance to this work but did not provide direct funding.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Improved representativeness of simulated climate using natural units and monthly resolution

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There is a considerable discrepancy between the temporal and spatial resolution required by climate impact researchers, policy makers, and adaptation planners on the one hand and climate data providers on the other hand. While the spatial and temporal aggregation of climate data is necessary to increase the reliability and robustness of climate information, this often counteracts or even prohibits their use in adaptation planning. The problem is twofold (i.e., space and time) and needs to be approached accordingly. Climate impact research and adaptation planning are the domain of impact experts, politicians, and planners, rather than climate experts. Thus, besides the spatial and temporal resolution, information also needs to be provided on platforms and in data formats that are easily accessible, easy to handle, and easy to understand. We discuss possible steps toward bridging the gap using an example from the federal state Hesse (Germany) as illustration. We aggregate the climate data at a level of "natural units" and provide them as monthly data. We discuss the pros and cons of this kind of processed data for impact research and decision making. The spatial aggregation to "natural units" delivers suitable spatial aggregation, while maintaining physical geographic structures and their climatic characteristics. Within these "natural units," single grid cell values are usable for climate impact analyses or decision making. The temporal resolution is monthly values, i.e., deviations of single month values for the scenario period from climatological monthly values in the (simulated) reference period. This resolution allows analyzing compound events or consecutive events on a monthly scale within a climatological (30-year) period.

KEYWORDS

climate model data, spatial resolution, natural units, user-tailored, impact research

Introduction

Climate modeling communities share their data for impact research, adaptation planning, and other uses. With the knowledge about the pros and cons of climate models and their results comes a responsibility to advise the best uses of the data and to warn against (unintended) misuse of the data. Climate model output does not have the same characteristics as observed (station) data. For example, while measurements at stations provide point data, climate model output is grid-box area average data. Therefore, the statistics of observed station data and simulated grid-box data don't match: typically, model data shows less extremes and generally smoother distributions of simulated parameters in space and time. With increasing model resolution, finer details become available in model data, but some processes remain unresolved. Additionally, all models have errors. They may stem from simplified model equations or parameterizations, which are necessary to make the models computationally feasible. They may also result from the assumptions within the scenarios used or from unknown or not represented interactions in the climate system, particularly interactions with human actions. However, mostly the errors are not systematically in all models, but statistically distributed between the models. It is therefore common practice to use ensembles of models (either multi-model-ensembles, e.g., Johns et al., 2011; Eyring et al., 2016, or single-model ensembles, e.g., Allen et al., 2000; Kay et al., 2015; Deser et al., 2020) to provide a more reliable bandwidth of climate simulation results (e.g., Kreienkamp et al., 2013). Additionally, climate modelers warn against taking single cell and/or single time-step information as input for impact modeling or other uses since areal and temporal averaging improves the reliability of the model output data and avoids over-interpretation.

Regarding spatial resolution, it is typically advised to use averages over at least nine grid cells surrounding the location of interest to smooth out unrealistic spatial effects. Regarding temporal resolution, the use of long-term averages, preferably 30-year-averages, is advised.

However, compliance with these principles is often a challenge for impact research (e.g., Kreienkamp and Huebener, 2021, and references therein). Typically, impact models are trained using station data. Consequently, for running impact models with climate model data, the climate model output is expected to display the same characteristics (no bias, time series statistics like variability and extremes, etc.) as observations. This is, however, typically not the case and the aforementioned averaging requirement even further smooths the distributions and it is thus often deemed unsuitable for impact research. This is particularly true for research areas located in small valleys or near steep gradients in topography. Here, the rectangular averaging area often mixes the properties of quite different climatological regions (e.g., river valley and adjacent mountains).

A step toward bridging this gap is the development of gridded observation data sets (e.g., Uppala, 2001; Dee et al., 2011; Bollmeyer et al., 2015). These data sets provide the spatial aggregation from point measurements to grid-box averages. Using gridded observations for the training of impact models is a step toward bridging the gap between observations and climate model results. However, still a large gap between gridded observations and climate model simulations of the past remains. Climate models usually display a (more or less pronounced) bias and generally don't exactly reproduce the observed climate. Besides model errors, this is also due to the fact, that climate models represent only one possible realization of the climate system under recent conditions. Due to internal climate variability, simulated recent climate might not match observed recent climate without the climate model being "wrong" (Marotzke and Forster, 2015; Deser et al., 2016; Hawkins et al., 2016). Furthermore, climate data users and climate information users (in the definition of Rössler et al., 2017) often need much finer grained information in time and space than 30-year-averages over large areas (e.g., Van den Hurk et al., 2018, and references therein for crop modeling or flood assessments; e.g., Sutmöller et al., 2021, for forestry).

There is considerable ongoing activity to improve the communication between climate modeling communities and climate impact or other user communities (e.g., Lemos et al., 2012; Huebener et al., 2017b; Rössler et al., 2017; Chimani et al., 2020; Tart et al., 2020; Hewitt et al., 2021; Suhari et al., 2022). There are also numerous activities to provide suitable user-tailored climate simulation information and climate services (e.g., Goddard, 2016; Buontempo et al., 2018; Bülow et al., 2019) or tools to generate said information (e.g., Raoult et al., 2017; Pérez-Zanón et al., 2021).

Besides the aspects of data retrieval (e.g., Chimani et al., 2020; Pérez-Zanón et al., 2021), simulation evaluation (e.g., Kotlarski, 2014; Vautard et al., 2020; Zier et al., 2021), bias correction (e.g., Cannon, 2018; Casanueva Herrera et al., 2020), ensemble selection (see e.g., Dalelane et al., 2018, for an ensemble reduction method), and visualization (e.g., Christel et al., 2017; Pérez-Zanón et al., 2021) the question remains how to improve the spatial and temporal representativeness of the climate simulation data for further use.

In this paper, we describe a climate data set which is a compromise between the scientific demand of the climate modeling community for averaging large regions and climatological time-steps and the practical demand of the (multiple and different) user communities for specific information in space and time. Therefore, we present an example from the German federal state Hesse in post-processing climate model output on "natural units" (i.e., landscape units defined for joint geographic and climatological characteristics) and monthly resolution. We then discuss the pros and cons of this approach in general.

Section Methods and Results explains the methods of the aggregation to "natural units" and presents the results. Section Summary and Conclusion provides lessons learned and discusses the practice presented in the context of general development toward providing actionable, user-tailored climate information.

Methods and results

Hesse is a federal state in central Germany, consisting of some mid-range mountain areas, some lowlands along the Rhine

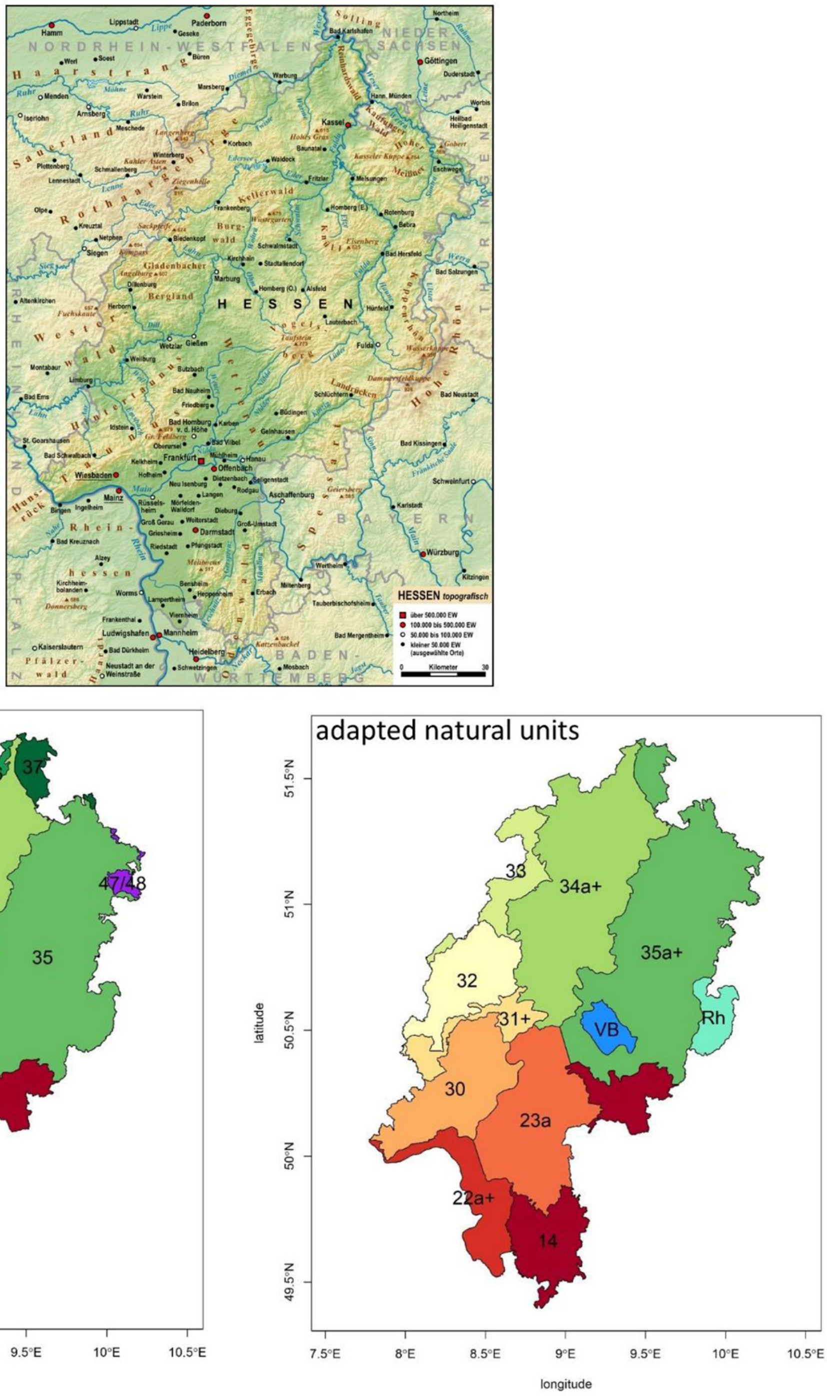

FIGURE 1
Topographic map of Hesse (top, https://de.wikipedia.org/wiki/Hessen#/media/Datei:Hessen_topografisch_Relief_Karte.png) and map of "natural units" in the second refinement layer (Haupteinheiten) from the original Klausing-classification (bottom left) and resulting adapted natural units for spatial aggregation of climate model output (bottom right). Numbers correspond to: 14, Hessen-Franconian Mountains; 22, Upper-Rhine Lowland; 23, Rhine-Main Lowland; 29, Mittelrhein; 30, Taunus mountains; 31, Gießen-Koblenz-Lahn valley; 32, Westerwald mountains; 33, Bergisch-Sauerland mountains; 34, West Hesse mountain and valley Area; 35, East Hesse mountain area; 36, Weser mountain area; 37, Weser-Leine mountain area; 47/48, Thuringia basin (Klausing, 1988). VB, Vogelsberg; Rh, Rhön; "a", adjustment of units by changing the boundary of the original unit; "+", merging of original units.

river, and some mild-climate areas in the middle (Figure 1, top). Hesse also contains some larger cities (e.g., Frankfurt/Main) and an urban sprawl in the Rhein-Main-Area. The cities are not well-resolved in climate models, thus we cannot expect to find the full urban climate effects (in particular the urban heat island) in the simulation results. But, to some degree the urban effects become visible in high resolution model results.

Several sophisticated methods exist for creating spatial climate patterns, like cluster analysis (e.g., Mahmud et al., 2022) or PCA (e.g., Pineda-Martínez et al., 2007). Alternatively, we started from a well-known and established pattern: the "natural units" (or "landscape units") as defined by Klausing (Klausing, 1988) (Figure 1, bottom left). The main reason was to use a concept that is readily understandable for many users, not only in climate impact research, but also outside science: in policy and society.

According to climate modeling advice, we aimed for creating spatial units that comprised at least nine grid cells (of the 5 km resolution) for any spatial unit. The Klausing natural units are defined for all of Germany, but we used only the Hesse-part of them. The natural units are based on a large-scale climatological mapping (within central Europe). Finer scale differentiation (i.e., in Hesse) draws on geological information. We thus started our exercise with testing the representativeness of the finer scale (second order) natural units for climatological values. The natural units have the advantage of well-defined physical, geographic, and geologic areas. These areas correspond well with characteristic and well-known regions in Hesse (e.g., low-lying "Wetterau" for apple orchards, Rhine plain "Hessisches Ried" for vegetables growing or the viticultural area "Rheingau" along the "Mittelrhein" in the Rhineland slate mountains), but they do not match administrative units. They neither match hydrological units, which typically span areas from source regions in mountainous terrain to the river mouth in a lowland region, even though in some areas borders of hydrological units match borders of the natural units.

Natural units from HYRAS data

To identify climatological units based on Klausing's natural units, we used HYRAS data, a high-resolution (5 × 5 km) gridded dataset of daily mean (T_{mean}), minimum (T_{min}) and maximum (T_{max}) temperature, precipitation (PR), and relative humidity (RelHum) (Rauthe et al., 2013; Frick et al., 2014; Razafimaharo et al., 2020). Based on these daily data, we calculated long-term seasonal means (sums for precipitation, respectively) for the time period 1951–2010. Additionally, we determined the following meteorological parameters per calendar year: ice days ($T_{\text{max}} < 0°\text{C}$), frost days ($T_{\text{min}} < 0°\text{C}$), summer days ($T_{\text{max}} > 25°\text{C}$), hot days ($T_{\text{max}} > 30°\text{C}$), very hot days ($T_{\text{max}} > 35°\text{C}$), and tropical nights ($T_{\text{min}} > 20°\text{C}$).

When selecting the parameters to be considered in the study with HYRAS data, it was ensured that the parameters are available in the high-resolution data of the regional climate models to which the methodology will eventually be applied. In this way, a consistent data set aggregated to natural units can be provided for Hesse.

First, the natural area means based on Klausing's natural units (second order) were calculated for the listed parameters by weighting the individual cell values according to their area percentage in the respective natural area of Hesse:

$$X^n = \frac{\sum w_{ij}^n X_{ij}}{\sum w_{ij}^n}$$

with

w_{ij}^n : Area percentage of the grid cell (i,j) in the natural unit n,

X_{ij} : Calculated parameter in grid cell (i,j).

In the next step, the deviation from the natural area mean X^n for each parameter was investigated in each grid cell. For reducing the residual deviations, the natural units were adapted.

The decision-structure for adapting the natural units used seasonal and half-yearly mean temperature fields in the first step and aimed for reducing the residual deviations. The decision of redistributing grid-cells from one natural unit to another was made under the following premises (in this order):

1. Keep the alterations as small as possible, to preserve the structure of the original units as well as possible;
2. for units with only a few grid-boxes in Hesse, check if they can be matched with neighboring units to fulfill the area size criterion (at least nine grid boxes of the 5 km resolution fields);
3. check, if distributing the grid cell to a neighboring unit reduces the residual error field;
4. check, if a higher order natural unit (third order) exists, that matches the error pattern and is still large enough to fulfill the area size criterion;
5. if necessary, combine third order units or add an appropriate single grid cells to fulfill the size criterion.

We processed these steps using the seasonal and half-yearly mean temperature field and thereafter checked if the resulting units reduced the residual errors in the other parameter fields, too. This was the case, so we kept the units as determined from mean temperature. Examples of the resulting error fields for mean temperature and summer precipitation are given in Figure 3.

As an example, Figure 2 shows the spatial distribution of the long-term mean air temperature over the winter period from October to March for Hesse. The original classification of the Hessian natural units according to Klausing already corresponds well with the spatial structure of the temperature field. This is due to the fact, that Klausing's natural classification is not based on administrative units, but on scientific data, which in particular takes into account the geography and thus also the climatological differences in

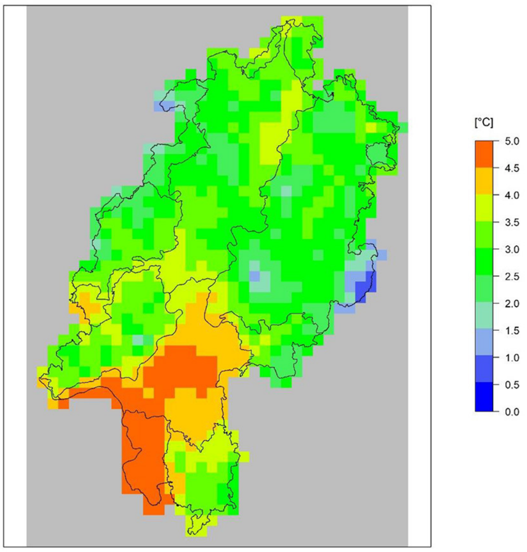

FIGURE 2
Monthly means of the air temperature in Hesse averaged over the period from 1951 to 2010 and over the winter period from October to March based on HYRAS data. The natural units of Hesse according to Otto Klausing are shown as polygons in black.

Hesse. For example, the lower temperatures in the Hessen-Franconian Mountains are well-distinguished from the northern Upper-Rhine Lowland and the Rhine-Main lowlands. The slightly higher temperatures in the Giessen-Koblenz Lahn Valley are also mapped in a separate natural unit, separated from the Taunus in the south and the Westerwald in the north.

On the other hand, it can also be seen that smaller-scale structures are missing from the original classification by Klausing. For example, the Rhön and the Vogelsberg stand out with lower temperatures and thus also fewer summer days and higher precipitation than in the assigned rest of the East Hesse mountain area.

By looking at the grid point-specific deviation from the respective assigned natural area mean, the local differences become clearer and by adjusting the natural unit classification, improvements in the subdivision can be made visible in the form of smaller deviations. This approach is illustrated in Figure 3. Whereas, with an underlying subdivision according to Klausing, deviations of −2 to −2.5 K were recorded for the Vogelsberg and the Rhön (Figure 3, top right), after separating these two regions the deviations in temperature could be reduced to −1 K (Figure 3, bottom right).

That these separations lead to an improvement is also confirmed in the other selected parameters such as precipitation (Figure 4). When using Klausing's original subdivision, the higher summer precipitation in the Vogelsberg and the Rhön compared to the rest of the East Hesse mountain area of 15–25 mm can be clearly seen. After separating these two areas, the deviations here can be reduced to <10 mm.

This procedure was carried out taking into account all the selected meteorological variables, so that finally an adapted classification of the natural units was obtained with the following maximum deviations in the individual meteorological variables: T (−1.7 K/+1.6 K), T_{min} (−1.1 K/+1.4 K), T_{max} (−2.5 K/+1.7 K), PR (−18 mm/+34 mm), and RelHum (−3%/+4%).

In the end, the following alterations were made to the Klausing units for further use of the climate spatial units:

1. The Rhön and the Vogelsberg as low mountain ranges, which belong to the East Hesse mountain area (No. 35), should be considered as separate natural units. Here, due to the blocking effect of the mountains and their altitude, precipitation is significantly higher and temperatures lower than in the rest of the East Hesse mountain area.
2. In the transition from the Rhine-Main Lowland (No. 23) to the East Hesse mountain area (No. 35), the southwestern part of the western lower Vogelsberg should be assigned to the Rhine-Main Lowland, since here the long-term seasonal monthly mean temperature is higher than the area mean of the East Hesse mountain area.
3. The Rhine valley, which according to Klausing is assigned to the Upper-Rhine Lowland (No. 22) and the Rhine-Main Lowland (No. 23), was completely integrated into the Upper-Rhine Lowland (No. 22) and merged with the very small natural unit of the Mittelrhein (No. 29), which is covered by only three grid cells.
4. The Weser mountain area (No. 36) was integrated into the West Hesse mountain and valley Area (No. 34).
5. The Thuringia basin (No. 47/48) and the Weser-Leine mountain area (No. 37) was merged with the East Hesse mountain area (No. 35).
6. The Giessen Lahn valley, which according to Klausing is assigned to the West Hesse mountain and valley Area (No. 34), was instead merged with the Giessen-Koblenz Lahn valley (No. 31), because the long-term seasonal monthly mean temperature is higher and the long-term seasonal monthly mean relative humidity is lower than the area mean of the West Hesse mountain and valley Area (No 34).

Figure 1 (bottom right) shows the map of the newly adapted natural units.

Subsequently, these adjusted natural units were used for post-processing of climate model outputs in natural units.

Regional climate model data in natural units

We used regional climate model data from the projects ReKliEs-De (Huebener et al., 2017a) and EURO-CORDEX

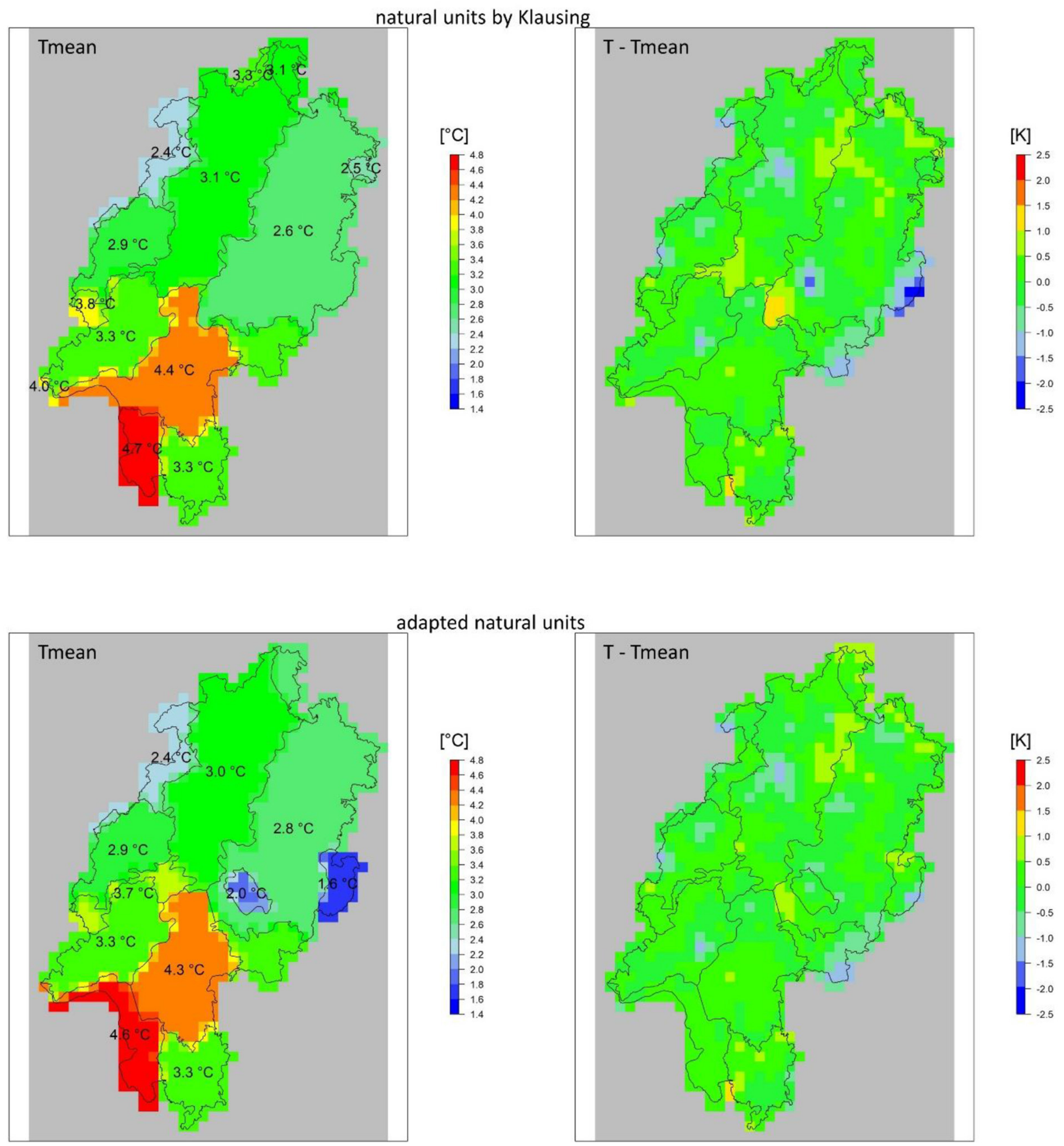

FIGURE 3
(Left) Multi-year (1951–2010), over the winter period (October–March) and over the natural units averaged monthly means of the air temperature in Hesse based on HYRAS data (T_{mean}). **(Right)** Grid point-specific deviations from the long-term natural units mean of the air temperature in Hesse averaged over the winter period ($T - T_{mean}$). The natural units of Hesse used for the averaging are drawn in black as polygons (top: natural units according to Otton Klausing, bottom: adapted natural units).

(Jacob et al., 2013) in a 0.11° resolution (approximately 12 km). The data was then bias corrected (Cannon, 2018) and disaggregated to a 5 km resolution by the German Weather Service (DWD) (Krähenmann et al., 2021). The disaggregation process included high-resolution spatial and climatological information and is therefore of sufficiently high spatial quality to be used on this scale.

We provided the following data spatially aggregated at a level of natural units as described above:

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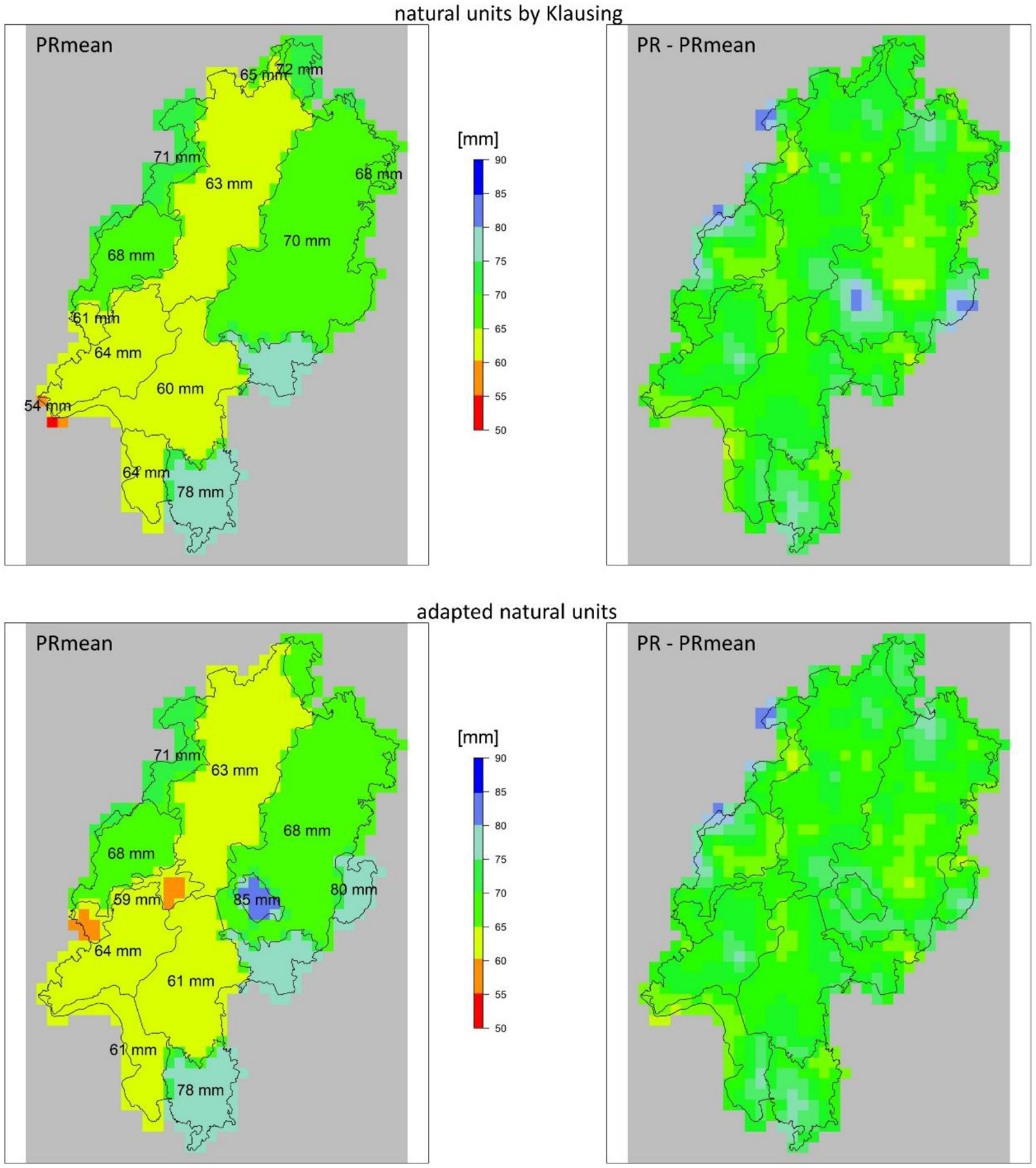

FIGURE 4
(Left) Multi-year (1951–2010), over the summer period (April–September) and over the natural units averaged monthly sums of precipitation in Hesse based on HYRAS data (PR_{mean}). **(Right)** Grid point-specific deviations from the long-term natural units mean of precipitation in Hesse averaged over the summer period ($PR - PR_{mean}$). The natural units of Hesse used for the averaging are drawn in black as polygons [**(top)** natural units according to Otton Klausing, **(bottom)** adapted natural units].

- for the reference period 1971–2000 (control run) and for the period 2071–2100 (RCP2.6 and RCP8.5):
  - single values for each month from January 2071 to December 2100
  - climatological monthly values (averaged for 2071–2100)
- difference between single month values for the period 2071–2100 and climatological monthly values simulated by the respective model for the reference period (1971–2000).

for the parameters

- daily mean temperature (T_{mean}) as monthly mean
- minimum temperature (T_{min}) as monthly mean
- maximum temperature (T_{max}) as monthly mean
- precipitation (PR) as monthly sum
- relative humidity (RelHum) as monthly mean
- number of days per calendar year:
  - ice days ($T_{\text{max}} < 0°C$)
  - frost days ($T_{\text{min}} < 0°C$)
  - summer days ($T_{\text{max}} > 25\ °C$)
  - hot days ($T_{\text{max}} > 30\ °C$)
  - very hot days ($T_{\text{max}} > 35\ °C$)
  - tropical nights ($T_{\text{min}} > 20\ °C$)

The cartographical projection of the data is Lambert conformal conic (LCC) and the data format is NetCDF, readable and processable in standard GIS programs.

Lessons learned

The aggregation method presented here aims at improving the spatial representativeness of gridded model output while maintaining the averaging process for insuring robustness of the results (i.e., eliminating spurious single grid cell values or systematic shifts within a natural unit). We applied only relatively minor, albeit essential alterations to minimize the relative errors of the mean values compared to the single cell values. The procedure thus seems a viable path for other regions, too, for improving spatial representativeness of climate model data.

Additionally, the provision of monthly values for the future period (single month values for each year from 2071 to 2100, each as deviation from the simulated climatological monthly value of the reference period 1971–2000) now allows to analyze consecutive or combined events in the future on monthly time scales, even without the knowledge and capacity to handle the direct climate model output.

Such events might include consecutive dry summers or combinations of hot and dry spring months. Possible applications could be in fields like hydrology (e.g., filling of reservoirs, groundwater recharge), agriculture (e.g., irrigation needs), forestry (e.g., conditions for bark beetle infestation or fire weather), health (e.g., habitat for invasive mosquitos), or ecosystem services (e.g., evaporative cooling from urban green spaces during dry summers).

A large number of impact research methods require daily data, particularly when considering extreme heat or heavy precipitation events. These events cannot be resolved by the monthly data. We don't expect the method to work equally well for daily data. On the daily time-scale spatial variability is much larger (particularly for rainfall) and events like temperature inversions defy their expression in the simple spatial methods used here. Thus, a number of impact relevant extremes occurring on the daily time-scale cannot be assessed with these data.

Assessing the study results, on the "pro" side, we were positive surprised how well the original natural units fit with a number of relevant quantities for climate and climate impact analyses. The good fit of mean temperature with the adjusted natural units was expected, since the topography—particularly height above sea level—strongly controls mean temperatures. However, minimum and maximum temperatures, precipitation, and relative humidity are not as clearly controlled by this parameter. This is an added value of the results presented here.

The provision of data aggregated to the adjusted natural units presented here results in a much higher plausibility of local climate data compared to aggregation over rectangular areas. With this product, downstream users can now select a natural unit as surrogate for a local grid-box and use the data for their further analyses.

On the "con" side, spatial variations within the natural units are not resolved and the monthly resolution will still be insufficient for some impact assessments. This limits the use of the data for certain impact research questions. For some impact research questions, however, it might be possible to use monthly data even though current impact models use daily data as input. In these cases, the impact researchers might further develop their methods or models to cope with monthly data, and might in some cases even improve the robustness of the results. Here, we need further developments to bridge the remaining gap between the requirements of the impact research community and the climate modeling community.

Summary and conclusion

There is still a considerable gap between climate data, particularly climate model results, and the user needs for climate information to derive climate adaptation measures. The gap has many dimensions: from the nature of climate simulations as only one possible realization of the climate system, different future scenarios, model deficiencies, biases, spatial and temporal resolution, to unwieldy data-formats.

There are numerous ongoing efforts to improve the usability and user-orientation of climate information and climate services (e.g., Alexander and Bruno Soares, 2017; Buontempo et al., 2018; Le et al., 2020; Williams and Jacob, 2021), particularly within the Global Framework on Climate Services (Hewitt et al., 2012). We particularly welcome and support the efforts of transdisciplinary research, of co-production of climate knowledge and of integration of local knowledge to understanding climate change and its impacts (e.g., Buontempo et al., 2018; Hewitt et al., 2021; Neset et al., 2021; Williams and Jacob, 2021). The example presented here may be considered as a small contribution within the field of spatial integration of climate data and information for use in climate impact research (as discussed in the review paper, Giuliani et al., 2017). Our effort is part of the information transfer chain, insofar as it purposefully uses a well-known, if simple, concept (the natural units or landscape units) instead of more sophisticated methods like cluster analysis or PCA. Thus, we take a step toward making the data easier to integrate with data from other disciplines or from outside science. It may also be considered part of the information chain, that the work presented here was incentivized and commissioned by a local environmental agency, so in fact as a transdisciplinary effort.

In this paper, we focus on the resolution of climate model output in space and time. We propose a compromise between the positions of the climate modeling community and of the user community (or communities). The impetus to this effort resulted from discussions with climate impact modelers, presenting their challenges in using climate model data.

The German federal state Rhineland-Palatinate also uses natural units as analysis units for the display of climate and climate change facts (see RLPKK, 2022). Here, the original natural units—as derived from the geological properties—are used to calculate area mean values without prior changes to the areas. This leads to a few natural units, which combine different climatological regimes, like the unit "Taunus mit Lahntal" (which covers areas in both federal states, Hesse and Rhineland-Palatinate), which contains part of a mountain range (Taunus) as well as a river valley (Lahn-Valley); for Hesse we used a sub-division between the two parts of this unit. Additionally, for Rhineland-Palatinate only climatological 30-year averages are on display.

Solutions to improve the usability of climate model data differ according to the intended use. There is no one method to satisfy all user demands. The compromise solutions for improving spatial and temporal resolution presented in this paper only bridge part of the gap between climate simulation data and impact research needs. While this might suffice for some analyses, clearly further steps are needed to bridge this gap to the satisfaction of climate modelers as well as impact researchers. However, this bridging process needs to come from both sides: from the climate modeling community in improving their products as well as from the impact modeling community (Kreienkamp and Huebener, 2021; Sutmöller et al., 2021). Some climate model limitations cannot be overcome by improving the models or post-processing the output data. They stem e.g., from scenario uncertainty or internal climate variability. Thus, a dialog between climate data providers and users should always be part of climate data provision (Van den Hurk et al., 2018). It will need further model and method development within the impact research community to facilitate optimal use of climate model output and data.

We are confident, that the use of (possibly adjusted) natural units increases the spatial representativeness of grid-box data and thus the applicability for impact research. We are also confident, that the provision of monthly projection data (as anomaly to monthly climatological means of the reference period) are scientifically sound enough to allow impact analyses of consecutive or combined events. We encourage other climate data providers to test these methods and to evaluate their applicability to further data sets.

Data availability statement

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

Author contributions

HH contributed the general project idea and the concept of this work, JL and UG provided the actual calculation and data provision. All authors contributed to discussing the results and writing the paper.

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Conflict of interest

Authors JL and UG are employed by MeteoSolutions GmbH. Author HH works at the funding agency HLNUG.

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TRANSLATE: standardized climate projections for Ireland

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The TRANSLATE project was established in 2021 by Met Éireann, the Irish national meteorological service, to provide standardized future climate projections for Ireland. This paper outlines the principles and main methods that were used to generate the first set of such projections and presents selected results to the end of the 21st century. Two separate ensembles of dynamically downscaled CMIP5 projections were analyzed. These produce very consistent results, increasing confidence in both, and in the methods used. Future projected fields show plenty of detail (depending on local geography), but the change maps relative to the base period are much smoother, reflecting the global climate change signal. Future forcing uncertainty is represented by 3 different emission scenarios, while model response uncertainty is represented by sub-ensembles corresponding to different climate sensitivities. The resulting matrix of distinct climate ensembles is complemented by ensembles of temperature threshold-based projections, drawn from the same underlying simulations.

KEYWORDS

CMIP5, CORDEX, downscaling, future projections, bias-correction, quantile mapping, uncertainty

1. Introduction

Within government and private-sector institutions, and among the general public, there is growing awareness of the risks of future climate change—partly due to climate model predictions, and partly to increasingly robust observational evidence of recent and current climate change [The Royal Society (UK), National Academy of Sciences (USA), 2020]. In Ireland, the development of climate resilience is channeled through the National Adaptation Frameworks (NAFs) (Department of Communications, Climate Action and Environment, Government of Ireland, 2018). The NAF focusses on ensuring that adaptation measures are taken at all levels of government to prepare Ireland for the impacts of climate change. As mandated by the NAF, each of the 31 Local Authority administrations in Ireland has their own Climate Change Adaptation Strategy.[1] These documents report that the main hazards of concern are heavy rainfall and associated flooding, heatwaves, drought, and storm events, all of which can affect the provision of local government and other utility services. Local Authorities and utility service providers need to understand how climate change will affect their activities, and so there is increasing demand for reliable climate projections in order to plan and implement suitable adaptation and mitigation measures.

Given this context, the TRANSLATE project[2] was established by the Irish national meteorological service, Met Éireann, in 2021 to produce standardized climate projections for Ireland, as a basis for the provision of other more wide-ranging climate services, and to support activities such as hydrological modeling. This paper describes the

1 E.g., the climate adaptation strategy for Co. Cork is available at https://www.corkcoco.ie/sites/default/files/2021-11/cork-county-council-climate-adaptation-strategy-2019-2024-pdf.pdf.

2 https://www.met.ie/science/translate

main principles and methods used to produce the first set of such projections and shows a small but indicative sample of the results obtained. Our work was guided to some extent by similar projects undertaken by other geographically small countries, such as UKCP18 in the UK (Lowe et al., 2018; Murphy et al., 2018), KNMI'14 in the Netherlands (Van den Hurk et al., 2014; Lenderink et al., 2015), and CH2018 in Switzerland (CH2018, 2018).

Many other countries or regions have also developed their own national climate scenarios based on CMIP global simulations, and some of these are listed in Supplementary Table S1. Ruosteenoja et al. (2016) describe downscaling CMIP5 GCM projections for Finland as an experimental extension of the more operationally oriented ACCLIM project, which derived climate projections for Finland from earlier CMIP3 simulations. These projections were updated by Ruosteenoja and Jylhä (2021) to use the latest CMIP6 shared socioeconomic pathway (SSP) scenarios, but without any downscaling. In Austria, the ÖKS15 project (Chimani et al., 2016) used 13 EURO-CORDEX regional models to downscale global simulations from two CMIP5 scenarios to the end of the 21st century. Technical aspects of the Norwegian climate projections are described by Hanssen-Bauer et al. (2017), while the utility and value of such projections is demonstrated by how they are disseminated and used to develop a "chain" of climate services, as reported by Nilsen et al. (2022). Similar projects undertaken by other nations are not cited in the interest of space, while no doubt there are others that we are unaware of, especially those that remain at the level of research projects, or where the information generated is available only in the local languages or simply not converted into publicly accessible products. Given the variety of approaches even among those few countries mentioned above, however, it is clear that the generation of standardized national climate projections does not have a "one size fits all" solution.

Most localized climate projections depend on a chain of future climate simulations that starts with ensembles of relatively coarse-resolution global climate models (GCMs). These may be dynamically downscaled to smaller, regional domains by ensembles of higher-resolution regional climate models (RCMs) each nested within one or more of the GCMs. High-resolution RCMs can also be nested within coarser ones, as done by Nolan (2015) and Nolan et al. (2017) for domains centered on Ireland (see, e.g., Figure 1.2 and related text in Nolan, 2015). Further statistical post-processing (e.g., detrending, bias-correction, and further downscaling), leads to a distilled reference set of climate data and spatial maps representing annual, seasonal, monthly, or even daily statistics for a range of variables at different time-periods or thresholds in the future, under different external forcing scenarios. The reference set typically encompasses alternative climates from both the lower and higher climate sensitivity ranges, as determined by the spread of the underlying ensembles.

The resulting set of climate scenarios described in this document could be viewed as spanning a small 3-dimensional matrix, as shown in Figure 1, which is adapted from Figure 10.9 of the latest Swiss climate scenario report (CH2018, 2018). In this view, future time-periods (specifically 2021–2050, 2041–2070, and 2071–2100) lie along one dimension. A few external forcing scenarios form a second dimension. For the first TRANSLATE implementation, these are Representative Concentration Pathways (RCPs) 2.6, 4.5 and 8.5, as used for the Coupled Model Intercomparison project Phase 5 (CMIP5; Taylor et al., 2012). These three scenarios can be viewed as a measure of future forcing uncertainty. The third dimension in Figure 1 spans a set of three different "climate sensitivity" levels among the ensemble of RCMs, where climate sensitivity is measured by the mean surface temperature change over Ireland during 2071–2100 under RCP4.5 and RCP8.5, as simulated by each ensemble member. These low, medium and high-sensitivity sub-ensembles provide a measure, however crude, of model response uncertainty. All changes are measured relative to the reference period 1976–2005, which was chosen to correspond with the last 30 years of the CMIP5 "historical" period.

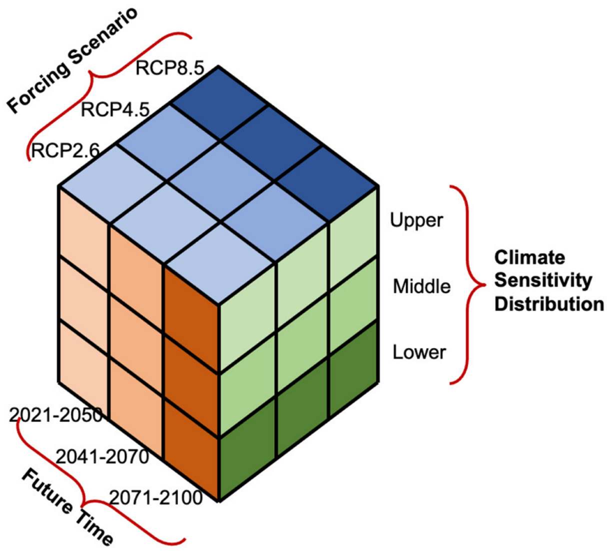

FIGURE 1
Schematic of how future climate uncertainties can be accommodated in a limited set of possible climates, adapted from Figure 10.9 of CH2018 (CH2018 Report, 2018). Each sub-cube shown corresponds to an ensemble of long-term climate simulations. Different RCP emission scenarios represent forcing uncertainty, while the climate sensitivity axis represents response uncertainty.

The different climates corresponding to each of the 27 sub-cubes in Figure 1 were supplemented by a further time-slicing approach, which aggregated the forcing scenarios and future time periods into three new "warming level" scenarios, centered on the years when each underlying GCM crossed global surface temperature change thresholds of 1.5, 2.0 and 2.5°C, resp. A template for constructing such threshold-based climate scenarios is provided by Vautard et al. (2014), and Supplementary Figure S1 shows a sample case of how it was done for TRANSLATE. In practice, in almost all RCP scenarios, global temperature crosses at least the 1.5°C threshold, while the 2.5°C threshold is crossed in all the RCP8.5 simulations and most of the RCP4.5 ones.

The rest of this paper describes how the 27 different climates of Figure 1 (along with the 3 temperature threshold climates) were constructed by de-trending, bias-correcting, and further statistically downscaling the raw RCM output from two

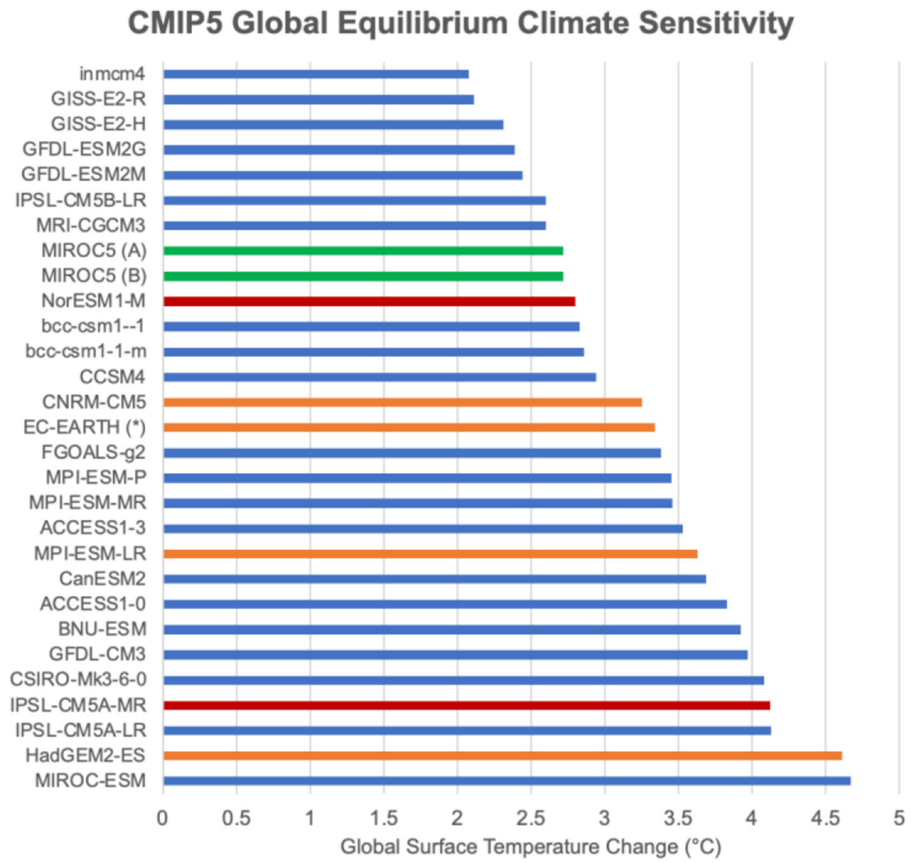

FIGURE 2
Ordered list of CMIP5 model ECS values, aggregated from Table 7.SM.5 of the IPCC AR6 report, Vol. 1: (https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf). The green bars represent models used for RCM downscaling by Nolan and Flanagan (2020), the red bars represent models used for RCM downscaling by EURO-CORDEX, while the orange bars represent models used by both. The blue bars represent models not used by TRANSLATE because no high-resolution RCM-downscaling of them was available over Ireland. (*) EC-EARTH model sensitivity was estimated separately.

separate sets of simulations. Some sample results are provided for illustrative purposes.

2. Methods

2.1. Two different RCM ensembles

The first effort to produce standardized future climate projections for Ireland begins with the separate sets of downscaled ensemble-RCM simulations from Nolan and Flanagan (2020; henceforth N&F), and the EURO-CORDEX project.[3] Both sets of simulations were embedded in CMIP5 GCMs (see Figure 2), with four GCMs used in common. However, both projects used completely different RCMs, different grid spacing, and had different numbers of ensemble members (see Table 1 for a summary of some key differences). Note that we used the EURO-CORDEX simulations with ∼12 km grid spacing; those EURO-CORDEX runs with ∼50 km grid spacing had too few points to capture adequate detail over Ireland. In contrast, the N&F simulations were at 4 km grid-spacing. Thus, both sets of simulations produced what could be viewed as independent versions of the 27 sub-climates depicted in Figure 1.

Regarding the N&F RCMs, the choice of model physics and parameterization schemes was informed by short-term validation experiments and the recommendations of the respective RCM development team. For example, the N&F WRF simulations did not include a convection parameterization scheme (convection resolving) while the COSMO-CLM5 simulations utilized the Mass Flux Tiedtke parameterization scheme (Tiedtke, 1989). An overview of the N&F RCM configurations is provided by Nolan et al. (2017) and Nolan and Flanagan (2020). The N&F RCM configurations were validated by downscaling European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalyzes for multi-decadal time periods and comparing the output with observational data. For an in-depth validation of the RCMs, see Nolan et al. (2017), Flanagan et al. (2019), Werner et al. (2019), Flanagan and Nolan (2020), and Nolan and Flanagan (2020), whose results confirm that the output of the RCMs exhibit reasonable and realistic features, as documented in the historical data record, and consistently demonstrate improved skill over the GCMs and low-resolution RCMs in the simulation of

3 https://www.euro-cordex.net/

TABLE 1 Comparison of how the Nolan and Flanagan (2020) and EURO-CORDEX downscaled ensembles of RCMs are different, and handled differently by TRANSLATE.

	Nolan and Flanagan (2020)	EURO-CORDEX
Native grid-spacing	4 km	12 km
Ensemble size	4–6 members per RCP scenario	19–29 members per RCP scenario
Interpolate to (1.0 km) observational grid?	Yes: interpolate to observational grid from start.	No: Work at native 12 km grid spacing as much as possible before downscaling final fields to observational grid.
	With relatively few ensemble members and grid-spacing not too different, this did not consume excessive compute time or data storage.	Interpolating to fine grid at start would require 144 x more compute time and data storage, which would be both wasteful and prohibitive.
Detrending	On 1.0 km grid	On native 12 km grid—using observations interpolated to this grid.
Bias correction	QDM on 1.0 km grid	QDM on 12 km grid
Downscaling to 1.0 km grid	QDM (effectively done along with bias correction above).	Use degraded observations (interpolated from 1.0 to 12 km grid and back again) subtracted from original observational fields to downscale 12 km fields directly, or with 2nd pass through quantile mapping (Section 2.4.3).
Climate statistics	On 1.0 km grid	On 1.0 km grid
Reconstructed 30-yr daily timeseries (for computing extreme indices, etc.)	On 1.0 km grid	On 12 km grid

multiple fields (e.g., precipitation and near-surface temperature, wind, humidity and radiation). Nolan et al. (2017) analyzed a larger ensemble of RCMs (both COSMO-CLM and WRF) with different grid spacings (18, 7, 6, 4, 2, and 1.5 km) and found that the RCMs demonstrated a general stepwise increase in skill with increased model resolution. Furthermore, it was shown that heavy precipitation events are more accurately resolved by the higher spatial resolution RCM data. However, it was found that although the RCM accuracy increased with higher spatial resolution, reducing the horizontal grid spacing below 4 km provided relatively little added value (Nolan et al., 2017). These results, and the requirement for a large RCM ensemble for analysis of climate projection uncertainty, informed the N&F RCM 4 km experiment setup.

2.2. Historical observations

High-resolution (~1.0 km grid-spacing) gridded observations of daily mean, minimum, and maximum surface air temperature (at 2 m height) for the Republic of Ireland, and daily precipitation over all Ireland were provided by Met Éireann spanning the reference historical period 1976–2005. The production of these datasets is described by Walsh (2016, 2017), while the time-period available has expanded from 1981–2010 to span 1961–2014. The temperature fields were supplemented by temperature observations at 5 km grid spacing over Northern Ireland (the northeastern part of the island and part of the UK) from the UK Met. Office's CEDA archive (Hollis et al., 2018). Standard bilinear interpolation was used to patch the temperature data across the border between the Republic of Ireland and Northern Ireland.

Those 30-year high-resolution gridded observations of daily minimum, maximum and mean air surface temperature and daily precipitation were used to validate the corresponding variables in RCM output for the same historical period (1976–2005), and to facilitate downscaling and bias-correction of all future projections, as described below. Ensembles of reconstructed (i.e., detrended and bias-corrected) 30-year daily timeseries of those four variables provide the basis for each of the 27 representative climates shown in Figure 1.

Note that while all model output included gridded values over both land and sea, the observational temperature data were provided over land only. The discontinuities across the coastline introduced some difficulties when using simple interpolation, since offshore grid-points with "missing data" could then contaminate neighboring onshore points by treating them as "missing" too. The interpolation algorithm was modified to work around this issue by interpolating from available land points only.

2.3. Climate sensitivity decomposition

For any given RCP forcing scenario and for any future time-period, the decomposition of the "climate sensitivity" axis in Figure 1 can be done in different ways. Prior to making a final choice, it is worth considering the "equilibrium climate sensitivity" (ECS) of the different CMIP5 global models, as shown in Figure 2. ECS is the equilibrium global-mean surface temperature change that occurs in response to instantaneous doubling of CO_2 concentrations. The green, red, and orange bars represent models that were used for high-resolution dynamical downscaling with RCMs over Ireland by N&F, EURO-CORDEX, or both, and so are incorporated into TRANSLATE. The models available for use by TRANSLATE are reasonably well-distributed among the different ECS values, although the models with lowest ECS (e.g., the GISS and GFDL models) are not available, since they were not downscaled over Ireland by any RCM with adequate grid spacing. This "low-sensitivity" gap should be remembered when analyzing the distribution of TRANSLATE results.

For the purposes of TRANSLATE, however, the climate sensitivity of each model over Ireland is more relevant than the global ECS. Figure 3 shows the mean surface temperature changes over Ireland from the RCM ensemble means from 3 different future scenarios and time-periods, all relative to 1976–2005. Figure 3A is for the N&F ensemble; Figure 3B is for the EURO-CORDEX ensemble. For all 3 metrics in both ensembles, the HadGEM2-ES model is clearly the most sensitive, while the MPI-ESM-LR model

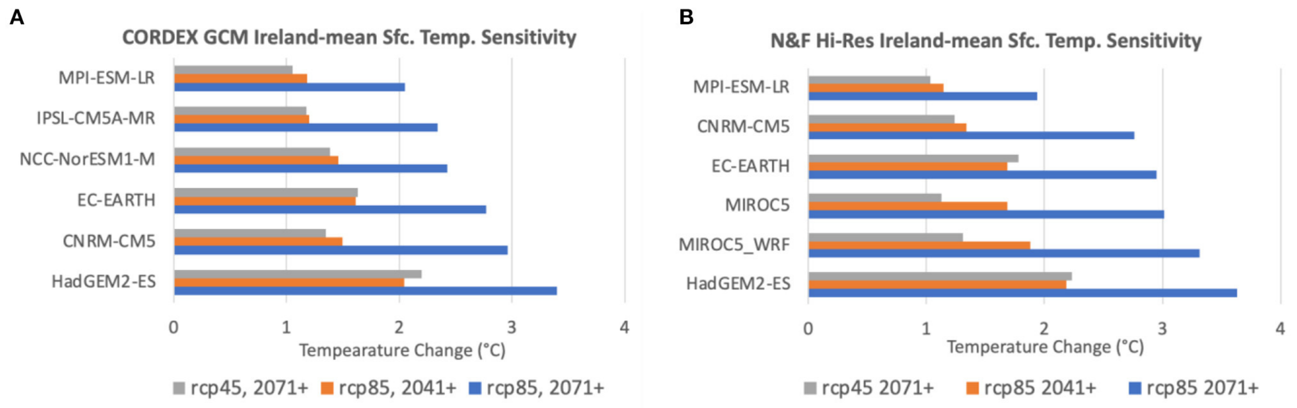

FIGURE 3
CMIP5 global models used by TRANSLATE, ranked by the mean surface temperature change over Ireland from the RCM ensemble-mean under the RCP8.5 scenario for the period 2071–2100 (blue bars). **(A)** is from the Nolan and Flanagan (2020) ensemble; **(B)** from the EURO-CORDEX ensemble. The orange bars in each chart show the ensemble- and area-mean temperature change under RCP8.5 for 2041–2070, while the gray bars show the same temperature change metric under RCP4.5 for 2071–2100. All changes are relative to 1976–2005.

is the least sensitive—even though MPI-ESL-LR is among the *more* sensitive models as measured by the global ECS metric (Figure 2). The difference in the projected mean temperature changes over Ireland under RCP8.5 by the end of the century between the most (HadGEM2-ES) and the least (MPI-ESM-LR) sensitive models is almost 1.7°C (3.63° vs. 1.94°C).

The sensitivity over Ireland of the other global CMIP5 models (those in the 4 middle rows of Figures 3A, B) is somewhere in between, but more mixed. However, if all of these models are combined as the "mid-range" ensemble on the climate sensitivity axis of Figure 1, then the ordering among them doesn't matter. Figures 3A, B are consistent in showing HadGEM2-ES to be the most sensitive model when downscaled over Ireland; MPI-ESM-LR is the least sensitive, while the other 3 (N&F ensemble) or 4 (EURO-CORDEX ensemble) or 5 (combined ensembles) are somewhere in between.

Decomposition along the climate sensitivity axis of Figure 1 is then relatively straightforward: all RCMs nested in the HadGEM2-ES global model make up the "high-sensitivity" ensemble; all RCMs nested in the MPI-ESM-LR model make up the "low-sensitivity" ensemble, and all RCMs nested in any of the other GCMs constitute the "medium-sensitivity" ensemble. Thus, the low- and high-sensitivity ensembles are each based on just one GCM simulation (as downscaled by several different RCMs). This means that the uncertainties due to differences among GCMs are not well-sampled in these sub-ensembles. The low and high-sensitivity sub-ensembles are really just the tails of the full ensemble comprising all GCM simulations.

Note that this measure of climate sensitivity is based on the mean surface temperature over Ireland; other variables may not display the same relative sensitivities. Note too that this leads to ∼70% of all simulations being placed in the mid-sensitivity ensembles of Figure 1, and about 15% in each of the low and high-sensitivity ensembles. Thus, the three sensitivity ensembles shown in Figure 1 should not be considered as equally likely, but as a rudimentary histogram of model uncertainty. A more fine-grained picture is shown in Supplementary Figure S2, which charts model sensitivity, as measured by surface mean temperature change over Ireland by 2071–2100 relative to 1976–2005 under RCP8.5 for each of the 26 GCM/RCM combinations that were available from EURO-CORDEX. The partitioning of all available simulations among the three sensitivity ensembles is summarized in Supplementary Table S2.

2.4. Detrending, bias-correcting, and downscaling RCM output

2.4.1. Detrending

Each member of the 27 different ensembles represented in Figure 1 is in principle an independent climate instance, and as such, should represent a stable climate with no background trend. However, the different RCP scenarios typically generate clear trends in many variables as the climate changes in response. Thus, a simple detrending is performed on all RCM 30-year output timeseries (and on observed 30-year timeseries) before any other adjustments are made. Detrending distills the changing climate over a century or so into just a few representative time-periods, and allows each future projected 30-year period to be treated statistically just as recently observed 30-year climate normals are (Gutman, 1989). With the climate change signal removed, internal climate variability, extreme events, and other indices can all be calculated more reliably over 30-years of a statistically stable climate than year-by-year of a changing climate.

In the case of interval variables like temperature, detrending can be done by subtracting the linear trend from the original timeseries. In the case of ratio variables such as precipitation, the linear trend is calculated, but cannot be simply subtracted from the original timeseries since that can introduce distortions such as negative precipitation, or turning dry days into wet ones. Precipitation detrending must be done multiplicatively. If $P_{orig}(t)$ is the original time-series, P_{mean} is its mean, and $P_{linear-trend}(t)$ is its linear trend value at time t (with zero mean), then a detrended timeseries $P_{detrended}(t)$ is:

$$\mathbf{P_{detrended}}\ (\mathbf{t})\ = \mathbf{P_{orig}}\ (\mathbf{t})\ \times [\mathbf{1} + \frac{(\mathbf{P_{mean}} - \mathbf{P_{linear-trend}}\ (\mathbf{t})\ )}{\mathbf{P_{mean}}}]$$

This has the desired characteristics that dry days stay dry $(\mathbf{P_{detrended}} = \mathbf{P_{orig}} = \mathbf{0})$, and no negative precipitation is possible $[\mathbf{P_{linear-trend}}\ (\mathbf{t})\ \leq \mathbf{2} \times \mathbf{P_{mean}}]$. However, it does not preserve the original mean value P_{mean}. That is recovered by computing the mean of the $P_{detrended}$ series, then scaling all $P_{detrended}(t)$ values by multiplying them by the factor $\frac{\mathbf{P_{mean}}}{\mathbf{P_{detrended-\ mean}}}$.

2.4.2. Bias-correction with quantile delta mapping

The RCMs nested in the GCMs provide downscaled projections that represent the best that can be achieved using the laws of physics, as expressed numerically in the various models. Beyond the physics, however, there remains an opportunity for statistics to contribute useful information by adjusting the model projections to correct for systematic biases that can be identified during well-observed historical periods. Without bias-correction, raw model projections are usually shown as "change" fields between a simulated future and a simulated past, in which the biases are assumed to cancel out. Change fields alone may suffice for some purposes, but most practical applications eventually need to match projected changes with recent observations, which amounts to bias-correction, however implicit. For example, it is not enough to tell engineers that events with 10-year return periods currently will have 5-year return periods in the future; they also need to know the magnitude of such events, and bias-correction is required to more reliably estimate that information.

TRANSLATE adopted the quantile delta mapping (QDM) method, as described by Cannon et al. (2015), and who also show how it is superior to the other quantile mapping variants considered by virtue of explicitly preserving relative changes in (e.g.,) precipitation quantiles. By now, QDM has been widely tested and validated, e.g., by Fauzi et al. (2020) or Xavier et al. (2022). The method is applied to each grid-point independently, and so is easy to parallelize. However, this suggests a potential weakness of the method, which is that dynamical consistency between fields (e.g., temperature and precipitation) is not enforced and so may be lost, as explored by Rocheta et al. (2014). Indeed, consistency within a single field may also be lost (Maraun, 2013), especially insofar as the method is applied for downscaling purposes. More fundamentally, QDM assumes that biases remain statistically stable from the observed historical period to the end of the future projected period. This is usually a valid assumption, as discussed by Maraun (2012), but still, should not be pushed too far. TRANSLATE developed its own implementation of QDM, but third-party software implementations are also available.[4] The nature of the changes made by QDM can be seen in Supplementary Figure S3, which shows the modifications made to the Ireland-mean daily precipitation timeseries for the period 2071–2100 under RCP4.5 for each of the 6 members of the N&F ensemble.

4 E.g., https://github.com/topics/quantile-delta-mapping.

2.4.3. Downscaling (EURO-CORDEX) using degraded observation corrections

Ultimately, we want to produce final projection fields on the finest possible grid, which in our case is the observational grid, with ~1.0 km grid spacing. Meanwhile, the N&F output fields are on a native grid with ~4 km spacing, while the EURO-CORDEX output fields are on a native grid with ~12 km spacing. In principle, all fields could have been interpolated to the 1.0 km grid from the beginning. Even though interpolation from coarse to fine grids provides no real gain of information, such interpolation allows QDM to effectively function as a downscaling as well as a bias-correction tool, since real information from every observational grid-point is used to adjust the model projections. As stated in Table 1, it was convenient and practical to do this with the N&F RCM output, but not with the EURO-CORDEX output, since that would have consumed over 2 orders of magnitude more computing time and storage resources.

Instead, as also listed in Table 1, QDM on the EURO-CORDEX RCM output was performed on the native 12 km grid for bias-correction purposes only. However, once the ensembles of reconstructed 30-year timeseries were condensed into annual cycles of mean, percentile, and other statistical fields, they were then downscaled onto the high-resolution observational grid as well. "Downscale" is used advisedly here rather than "interpolate," since downscaling adds extra information to the physical fields whereas interpolation does not.

Fields on the 12 km EURO-CORDEX grid can be interpolated onto the 1.0 km observational grid (with some extra care needed around coastlines, as mentioned in Section 2.2, and as shown in Figures 4A, B), but this provides no real gain in information. The real downscaling step involves taking the corresponding *observational* field on the high-resolution grid, interpolating it to the coarser EURO-CORDEX grid (thus losing some information), then interpolating it back again to high-resolution (without recovering the lost information). The difference between that (degraded) observational field on the high-resolution grid and the original observational field on the same grid (e.g., Figure 4C) mimics the information that is potentially missing from the projected field on the same grid. Downscaling is then achieved by simply adding that information to the projected field (e.g., Figure 4D).

If $\boldsymbol{T}$ represents temperature or similar variable, and subscripts *OBS* and *PROJ* represent observations and projections, resp., the process can be described symbolically as:

$$\begin{aligned}
\mathbf{T_{PROJ}}\ (\mathbf{CORDEX_grid}) &\rightarrow \mathbf{T_{PROJ}}(\mathbf{hires_grid}) \\
&\quad [\textit{by low to hi} - \textit{res interpolation}] \\
\mathbf{T_{OBS_ORIG}}\ (\mathbf{hires_grid}) &\rightarrow \mathbf{T_{OBS}}\ (\mathbf{CORDEX_grid}) \\
&\quad [\textit{by standard interpolation}] \\
\mathbf{T_{OBS}}\ (\mathbf{CORDEX_grid}) &\rightarrow \mathbf{T_{OBS_DEG}}(\mathbf{hires_grid}) \\
&\quad [\textit{by low to hi} - \textit{res interpolation}] \\
\mathbf{T_{PROJ_FINAL}}\ (\mathbf{hires_grid}) &= \mathbf{T_{PROJ}}\ (\mathbf{hires_grid}) \\
&\quad + \mathbf{T_{OBS_ORIG}}\ (\mathbf{hires_grid}) \\
&\quad - \mathbf{T_{OBS_DEG}}(\mathbf{hires_grid})
\end{aligned}$$

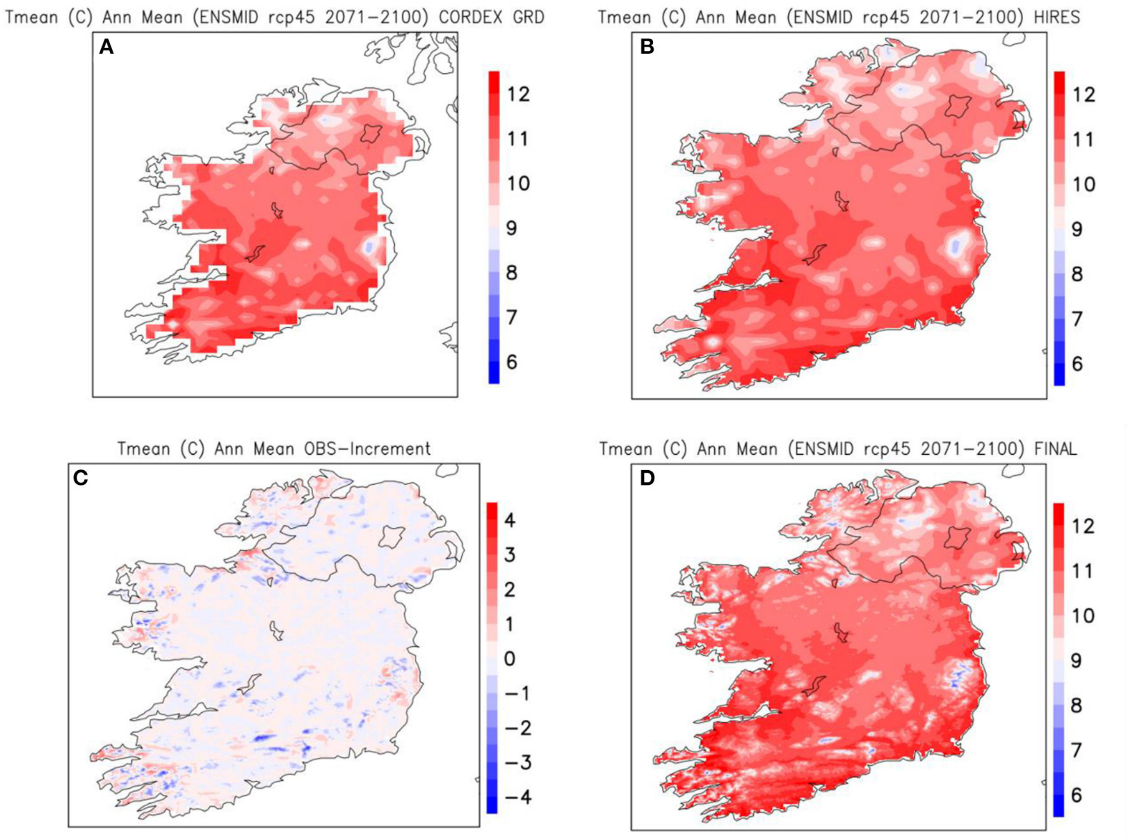

FIGURE 4
Illustration of the downscaling of EURO-CORDEX projections post quantile mapping, in this case for the annual mean of daily mean temperature from the mid-sensitivity ensemble under RCP4.5 for 2071–2100. The projected field on the EURO-CORDEX grid **(A)** is interpolated to the high-resolution observational grid **(B)**. The adjustments derived from interpolating the historical observed field to the EURO-CORDEX grid and back again **(C)** are added to the field in **(B)** to give the final projected downscaled field in **(D)**.

Here, $\mathbf{T_{OBS\_DEG}(hires\_grid)}$ represents the degraded observational field on the high-resolution grid. For a ratio variable like precipitation, the process is similar, only the final equation is multiplicative instead of additive:

$$\begin{aligned}\mathbf{P_{PROJ\_FINAL}}\left(\mathbf{hires\_grid}\right) &= \mathbf{P_{PROJ}}\left(\mathbf{hires\_grid}\right)\\ &\quad\times\ \mathbf{P_{OBS\_ORIG}}\left(\mathbf{hires\_grid}\right)\\ &\quad/\mathbf{P_{OBS\_DEG}}\left(\mathbf{hires\_grid}\right)\end{aligned}$$

Figure 4D shows the result $\mathbf{T_{PROJ\_FINAL}(hires\_grid)}$ of such a process in the case of the annual mean field of daily-mean temperature from the mid-sensitivity ensemble under RCP4.5 for 2071–2100. Overall, Figures 4A–D illustrates the process described symbolically above. The large-scale features don't change between Figures 4A, D, but the process does provide extra local detail.

EURO-CORDEX fields based on histograms of occurrence frequency are downscaled slightly differently. They are interpolated from the EURO-CORDEX grid to the observational grid as above, but being frequency distributions, they lend themselves naturally to application of a second round of quantile mapping—this time not to correct biases based on historical performance, but simply to downscale. The role played by the historical simulations in "normal" quantile mapping is now played by $T_{OBS\_DEG}(hires\_grid)$, i.e., the degraded observations after interpolation to the EURO-CORDEX grid and then back to the high-resolution grid again. Otherwise, the quantile-mapping algorithm runs much as before.

3. Results

3.1. Integrating the EURO-CORDEX and N&F projections

Once both the EURO-CORDEX and N&F ensembles are detrended, bias-corrected, and downscaled to the same high-resolution observational grid, how much relative weight should then be given to each individual (coarse-resolution) EURO-CORDEX simulation relative to each individual (high-resolution) N&F simulation when combining them into a single integrated ensemble? In practice this question is mostly moot, since the final projections for all the fields we have compared from both sets of ensembles are so similar as to be climatically identical. It makes almost no difference whether 80% weight is given to one and 20% to the other, or vice versa. For simplicity, then, the two sets of ensembles were combined into a single final set by giving equal weight to each individual ensemble member.

An example is shown in Figure 5, for the 99th percentile of daily precipitation amounts during autumn (Sept.-Nov.), from the middle-sensitivity ensemble under RCP4.5 for the period 2071–2100. Since autumn tends to be the wettest season in Ireland, these charts indicate what the wettest days during the wettest season would be like under that scenario. The top row (Figures 5A–C) shows the fields from the N&F ensemble, the EURO-CORDEX ensemble, and the combined ensemble, resp. The differences between the fields in Figures 5A, B are very small and difficult to see, so not surprisingly their combination in Figure 5C looks much the same again. The bottom row (Figures 5D–F) shows the ratios of the top row fields to the corresponding observed field from 1976 to 2005, and here the differences between the N&F ensemble (Figure 5D) and the EURO-CORDEX ensemble (Figure 5E) are more apparent, though still small. Their combination in Figure 5F shows a relatively simple pattern of rainy autumn days becoming wetter over most of the country by slightly more than 10% relative to the end of the 20th century.

3.2. Some illustrative sample results

3.2.1. Climate means

The projected end-century annual mean temperature fields under the three different emission scenarios and three different sensitivity ensembles are shown in Figure 6. Each map shows a lot of spatial detail, most of which corresponds to local elevations. All the main mountain ranges in Ireland can be easily identified. In each map, temperatures tend to be slightly cooler in the midlands and north, and slightly warmer around the coasts and toward the south, much as they are today. There is also a clear gradient across the nine maps shown, with temperatures increasing from left to right as the climate sensitivity increases, and from top to bottom as the emission scenarios increase from RCP2.6 to RCP8.5. Note that "absolute value" maps like this that have been bias-corrected are much more credible than raw RCP output, whose biases can be quite misleading.

The differences between each map in Figure 6 and the annual mean temperature during the reference period 1976–2005 are shown in Figure 7. Projected temperature changes relative to the reference period are all relatively uniform and smooth, with just a slight increasing gradient from west to east in each map. This gradient is likely due to the moderating influence of the Gulf Stream extension in the Atlantic acting most strongly on that part of Ireland closest to it. The inter-map differences are larger, with temperature changes increasing between maps from left to right as climate sensitivity increases, and from top to bottom as the emissions forcing increases. Of course, annual mean temperature is precisely the field that was used to define climate sensitivity, so the gradient from left to right in Figure 7 is pre-determined by that choice. Even so, it is apparent in Figure 7 that projected climates are more sensitive to the changes in RCP scenario than to the differences between the model responses (as measured by their climate sensitivity).

The cross-section through Figure 1 for the annual mean of daily precipitation during the late- century 2071–2100 is shown in Figure 8. There is very little difference between any of the maps in Figure 8: they all show higher precipitation (up to 8 mm day^{-1}) over the higher elevations and along the western seaboard, with lowest values (2–3 mm day^{-1}) over the midlands and eastern regions. However, the difference between the 9 maps in Figure 8 become more apparent when shown in Figure 9 as percentage changes relative to observations during the reference period 1976–2005. Figure 9 shows that any precipitation increases tend to be largest (in percentage terms) in the midlands and east.

Even the annual mean precipitation changes shown in Figure 9 mask significantly different behavior between the summer and winter seasons. Figure 10 shows projected precipitation changes during the end-century period as in Figure 9, but for the summer months June to August, while Figure 11 shows the corresponding change maps for the winter months December to February. Figures 9–11 all use the same contour intervals and the same color palette. The clear message is that summers are projected to become drier, while winters are projected to be wetter. Those patterns are amplified as the emission scenarios increase from RCP2.6 through RCP4.5 to RCP8.5. In contrast, the (temperature-based) climate sensitivity dimension does not show much variation, or any clear pattern. This is probably because there is only a weak relationship between temperature sensitivity and precipitation sensitivity over Ireland, where variable synoptic-scale circulation patterns can easily overcome the more direct Clausius-Clapeyron scaling between temperature and precipitation. See e.g., Houghton and O'Cinnéide (1976), Kiely (1999), or McCarthy et al. (2015) for evidence of how the Irish climate depends on large-scale circulation patterns in both the atmosphere and Atlantic ocean.

Much as the annual mean precipitation projections (Figure 9) can mask large changes of opposite sign from summer and winter seasons (Figures 10, 11), so too can the individual ensemble-mean maps shown in Figures 9–11 mask large variability within each ensemble, as well as interannual variability within each ensemble member. This is illustrated in Supplementary Figure S4, which is analogous to Figure 9, but instead of the ensemble *means*, shows the ensemble *range* in each map, i.e., ensemble-maximum percentage change minus ensemble-minimum percentage change, for daily precipitation on each day of the year, then averaged over the annual cycle. The ranges are large, reflecting the fact that, e.g., if the projected ensemble minimum on each day is 1 mm day^{-1} less than the observed amount while the ensemble maximum is 3 mm day^{-1} more, at a point where the observed mean value is 4 mm day^{-1}, then the ensemble range of percentage change will be 100%. The sequence of Figure 8–11 and Supplementary Figures S4 shows how future precipitation projections can be deconstructed from a pattern of relative uniformity to reveal ever more variability as the projections are explored in more detail. This helps to distinguish those projected characteristics that are relatively robust from those that are more uncertain.

3.2.2. Projected frequency distributions

Frequency histograms were computed for each of the four main variables (T_{mean}, T_{min}, T_{max}, and precipitation), and for each 30-year climate instance (or ensemble member) of each projected climate. Temperature frequencies were binned in 1°C increments

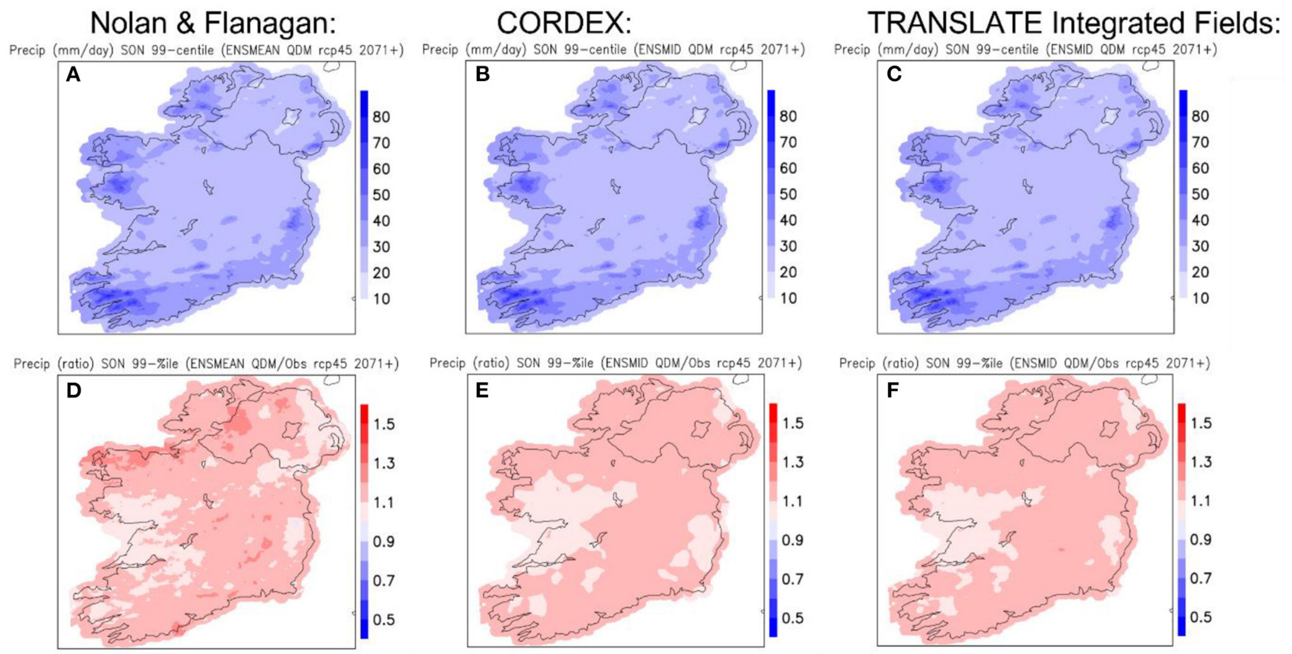

FIGURE 5
(A–C) Show the 99th percentile of daily precipitation amounts projected for the Sept.-Nov. season, by the mid-sensitivity ensembles under the RCP4.5 scenario for the period 2071–2100. **(A)** Shows the field from the Nolan and Flanagan (2020) ensemble; **(B)** from the EURO-CORDEX ensemble, while **(C)** is from the combination of the two, with equal weight assigned to each ensemble member. **(D–F)** Show the projected change signals as ratios of the fields in a-d relative to the corresponding observed field from 1976 to 2005, i.e., the (future projected value)/(historical observed value) at each grid-point.

from −10 to 35°C, while precipitation frequencies were binned in increments of 2 mm day^{-1} up to 80 mm day^{-1}.

Figure 12A shows annual and seasonal T_{min} histograms for 2071–2100 under RCP4.5 from the mid-sensitivity ensemble (solid curves) and for the observed reference period 1976–2005 (dashed curves), with local (grid-point) frequencies averaged over both the ensemble and the island of Ireland. The shading around each solid curve spans the range from minimum to maximum within the ensemble. The simplest interpretation of Figure 12A is that all the frequency curves retain much the same shape over time, but are shifted about 2°C to the right from the reference period to the end of the 21st century. The most dramatic changes thus occur near the tails. E.g., winter season T_{min} values of −5°C occurred with a frequency of about 0.02 (i.e., once every 50 winter-time days) during the reference period, as shown by the dashed blue curve in Figure 12A, but the frequency of similar cold nights by 2071–2100 under this scenario is projected to drop by a factor of 5 to about 0.004 (i.e., once every 250 winter days, only every 3 years or so). At the other extreme, summer nights with T_{min} values around 17°C are projected to occur up to 10 times more frequently than in the past. "Tropical nights" with T_{min} not falling below 20°C did not occur at all during the reference period but are projected to occur with a small but finite frequency in the future under this scenario.

Precipitation is distributed differently to temperature, and so the precipitation frequency histograms in Figure 12B have a logarithmic y-axis. As in Figure 12A, the biggest differences between the past and projected future precipitation distributions are at the high-rainfall low-frequency tails. Thus, the wettest days are projected to get wetter in all seasons as well as for the year as a whole (all the solid curves at the tail of Figure 12B are to the right of the corresponding dashed curves). Spring-time rainfall events of 60 mm day^{-1} that had a nominal occurrence frequency of 0.00001 (or a return period of 100,000 days) in the past (green dashed curve) are projected to occur about 3 times more often by the end of the century under this scenario (green solid curve).

The low frequencies of extreme events in Figure 12B are referred to as "nominal" above, because in reality they are relatively high-frequency localized events whose frequency value is reduced by the all-Ireland averaging. The curves in Figure 12 result from computing local frequencies and ensemble averaging first, and then doing all-Ireland averaging, instead of the other way round. This ordering doesn't really matter in the case of temperature (Figure 12A), since temperature anomalies tend to span wide areas, but in the case of precipitation (Figure 12B) it has the effect of expanding the sample size by several orders of magnitude before averaging it down again. Instead of ∼20 ensemble members each with a single 30-year timeseries of daily data from which to compute event frequency, each ensemble member has 30 years of such data for each of about 2,000 (EURO-CORDEX) grid-points, or 30 years for each of hundreds of effectively independent locales where intense precipitation can occur. This sample multiplier effect is how return periods of up to 100,000 days (∼275 years) can be plotted in Figure 12B. Even so, it is notable that most curves in Figure 12B have such smooth trajectories all the way down to the lowest frequencies and could reasonably be extrapolated further if desired. Plots like Figure 12B that are restricted to individual grid-

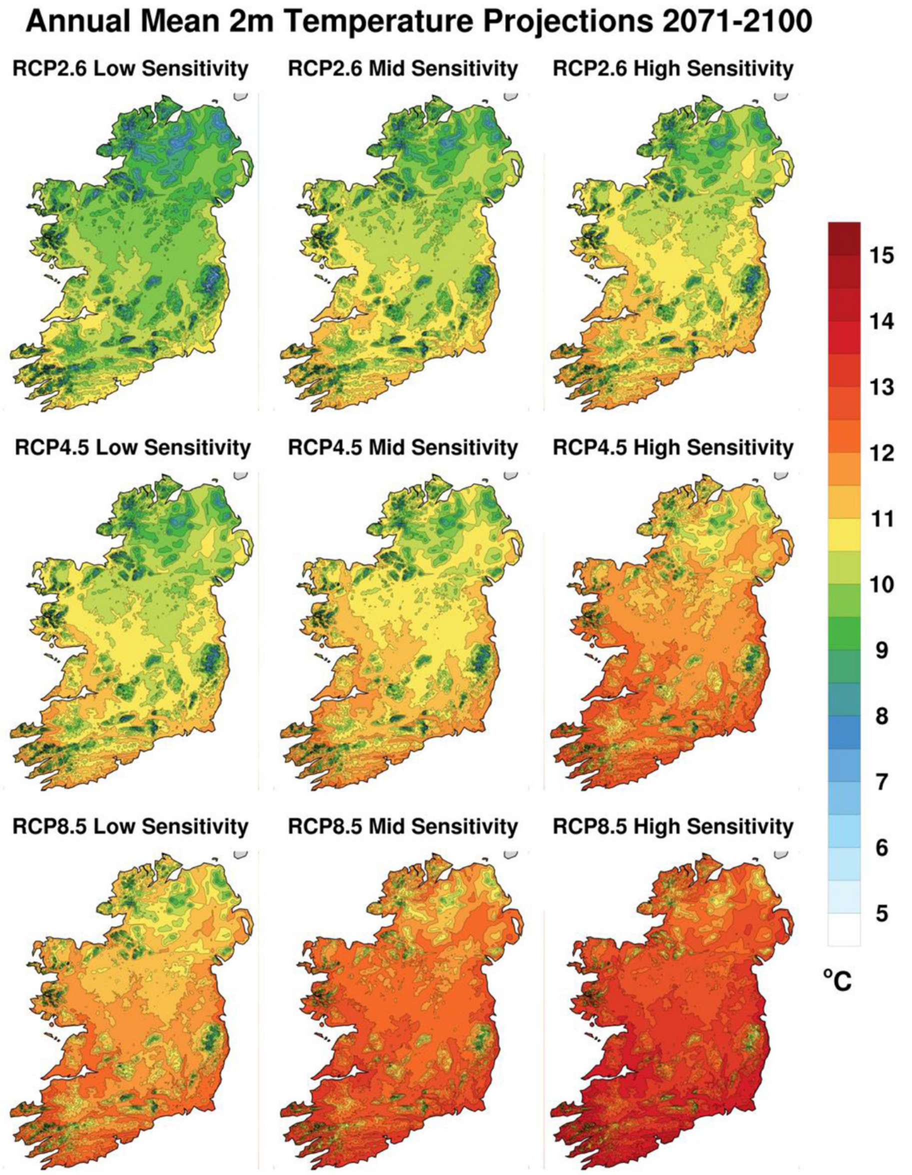

FIGURE 6
Projected annual mean surface temperature fields (°C) for the 2071–2100 period under the three different forcing scenarios and for the three different sensitivity ensembles.

points or small regions of just a few points only extend smoothly to frequencies of 0.001 (return periods of 3 years or so) before becoming noisy and non-monotonic (i.e., reporting isolated very wet events at the extreme tails of the distributions).

3.2.3. Temperature threshold-based projections

As mentioned in the Introduction, future climate ensembles were constructed from timeseries of 20-year periods centered on the year when the annual and global mean temperature from each underlying GCM used by TRANSLATE reached a specified threshold value above the pre-industrial mean from the same GCM. Three threshold values were considered, namely 1.5, 2.0, and 2.5°C. Table 2 shows the threshold- crossing dates for each RCP scenario for each of the CMIP5 GCM runs that were downscaled by either N&F or by EURO-CORDEX and further post-processed by TRANSLATE. Even the higher 2.5°C threshold was crossed by 16 different CMIP5 GCM simulations used by TRANSLATE, and most of those were further downscaled by multiple RCMs. This produced large ensemble sizes (>50 members) for each threshold climate. Each individual 20-year timeseries was then detrended, bias-corrected and further downscaled to the high-resolution observational grid, as was done for each of the 30-year timeseries underlying the different climate ensembles of Figure 1. One assumption behind assembling these large ensembles at different global warming levels is that the "path" to each level matters less than simply reaching and crossing that level. This assumes that the climate can adjust relatively quickly to a particular

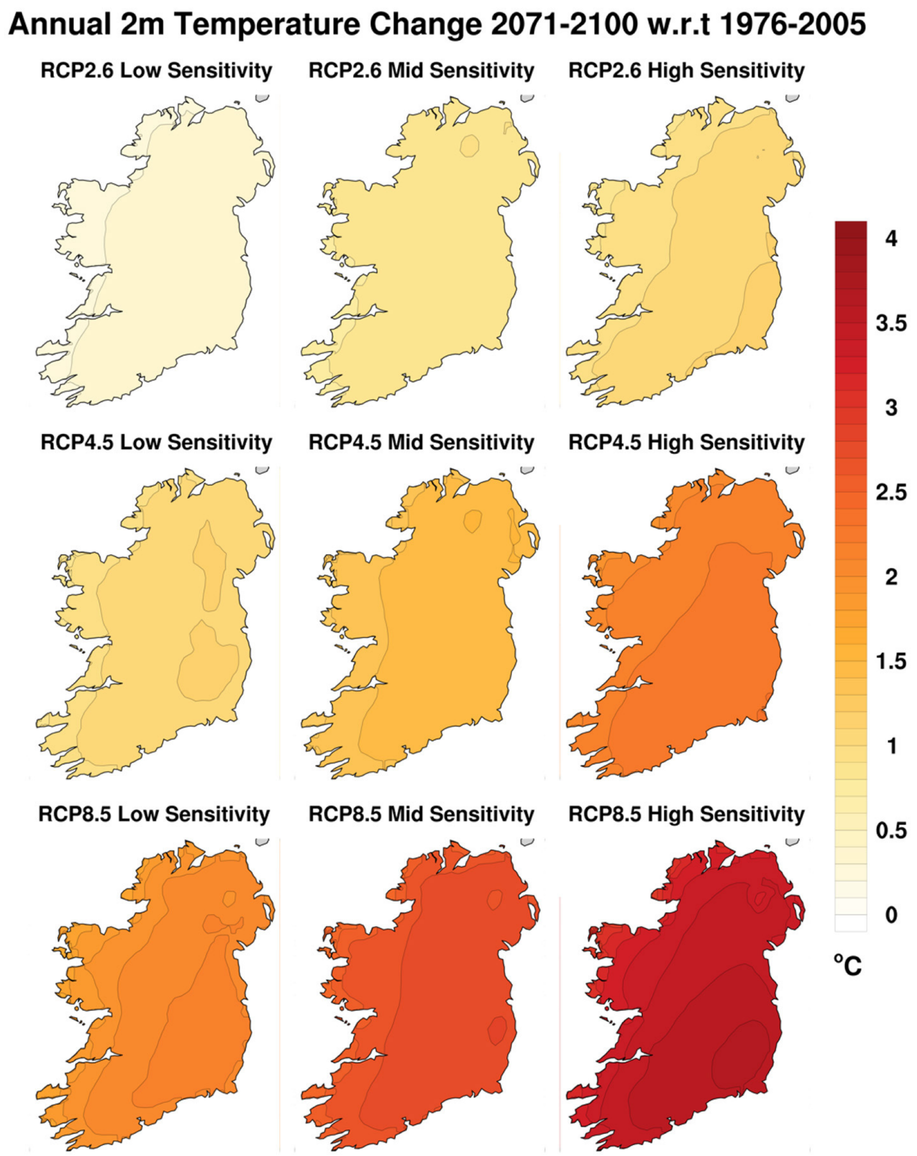

FIGURE 7
Differences between projected annual mean temperatures from the end-century period 2071–2100 and the reference period 1976–2005, under the forcing scenarios RCP2.6, RCP4.5, and RCP8.5, and the three different sensitivity ensembles.

RCP forcing as time goes by. Experiments conducted by Ricke and Caldeira (2014) suggest that the timescale needed to adjust to an impulsive emission event is about 10 years, so the response time to more gradual forcing (as in the RCP scenarios) is presumably somewhat less than that.

While the temperature thresholds were computed relative to the pre-industrial period 1850–1900, only relatively sparse station observations are available from that period in Ireland. Such data as do exist were collected from hand-written records and transcribed to digital format by Mateus et al. (2020), and are available from the Met Éireann web-site.[5] From this collection, 9 stations were selected for their geographical distribution around the country, and because each has relatively long and continuous observations of T_{mean}, T_{min}, and T_{max} from the pre-industrial period. Long-term mean values from these stations are shown in Supplementary Table S3, along with comparable data from the well-observed reference period 1976–2005 (The "pre-industrial" period is extended to 1914 or 1913 for a couple of stations for the sake of a longer continuous timeseries). For most stations, the 3 temperature variables increased from pre-industrial to modern times, on average by 0.51, 0.43, and 0.51°C for T_{max}, T_{min}, and T_{mean}, resp. However, there is large variation between stations, and even a couple of temperature decreases (shown in red font in Supplementary Table S3). The numbers are also sensitive to arbitrary choices, such as whether the Malin Head station data (from the northernmost tip of Ireland) are taken from 1885 to 1914, or from 1885 to 1900. Nevertheless, it seems reasonable to add an extra 0.5°C to any temperature change field that is

5 https://www.met.ie/climate/available-data/long-term-data-sets

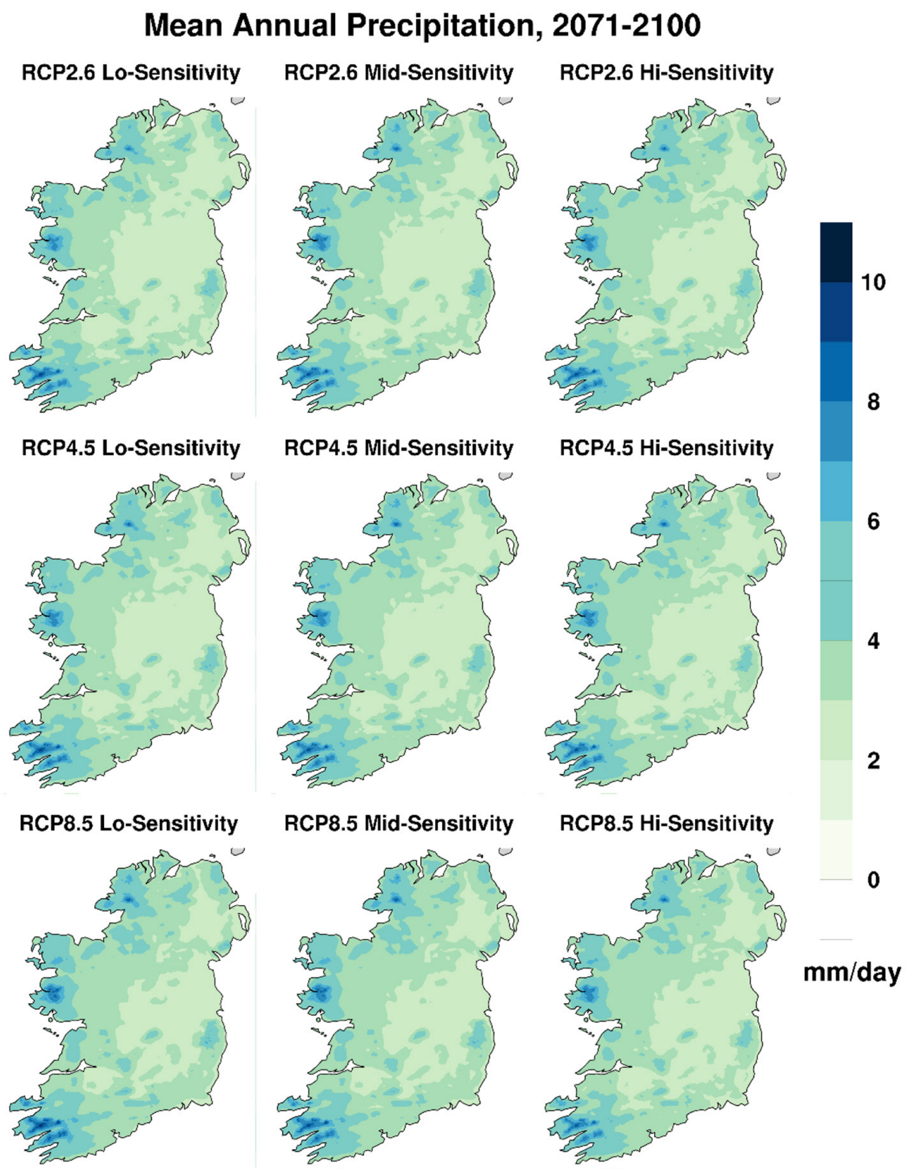

FIGURE 8
Projected annual mean daily precipitation fields (mm day^{-1}) for the 2071–2100 period under the three different forcing scenarios and for the three different sensitivity ensembles.

computed relative to 1976–2005, in order to obtain an estimate of temperature change relative to 1850–1900. Moreover, this analysis was repeated using CRU temperature data over Ireland and obtained very similar results.

Figure 13 shows the T_{mean} changes (relative to 1976–2005) for each of the three threshold climates, and for the 10th percentile, mean, and 90th percentile of each threshold ensemble. As discussed above, a further 0.5°C should be added to each field in Figure 13 to approximate the projected changes relative to 1850–1900. In that case, the means of each ensemble (middle column in Figure 13) show changes over Ireland very close to, but perhaps slightly less than, the global mean change (i.e., 1.5, 2.0, and 2.5°C). As in the time- and scenario-dependent projections (e.g., Figure 7), the change fields are remarkably uniform and featureless, with relatively weak internal gradients across the country. Once again, the global change signal is very straightforwardly manifested in the projections over Ireland too. Of more significance, perhaps, is the relatively large spread within each ensemble, shown by the ~2.0°C differences between the 10th percentile fields (leftmost column of Figure 13) and the 90th percentile fields (rightmost column of Figure 13). This intra-ensemble spread reflects quite a large range of uncertainty that can be attributed mainly to differences between the models—both GCMs and RCMs. Analyses like this can be used to assign confidence levels to the projections, especially given the large ensemble sizes behind them. Thus, there is ~80% chance that temperature changes over Ireland (relative to 1976–2005) will

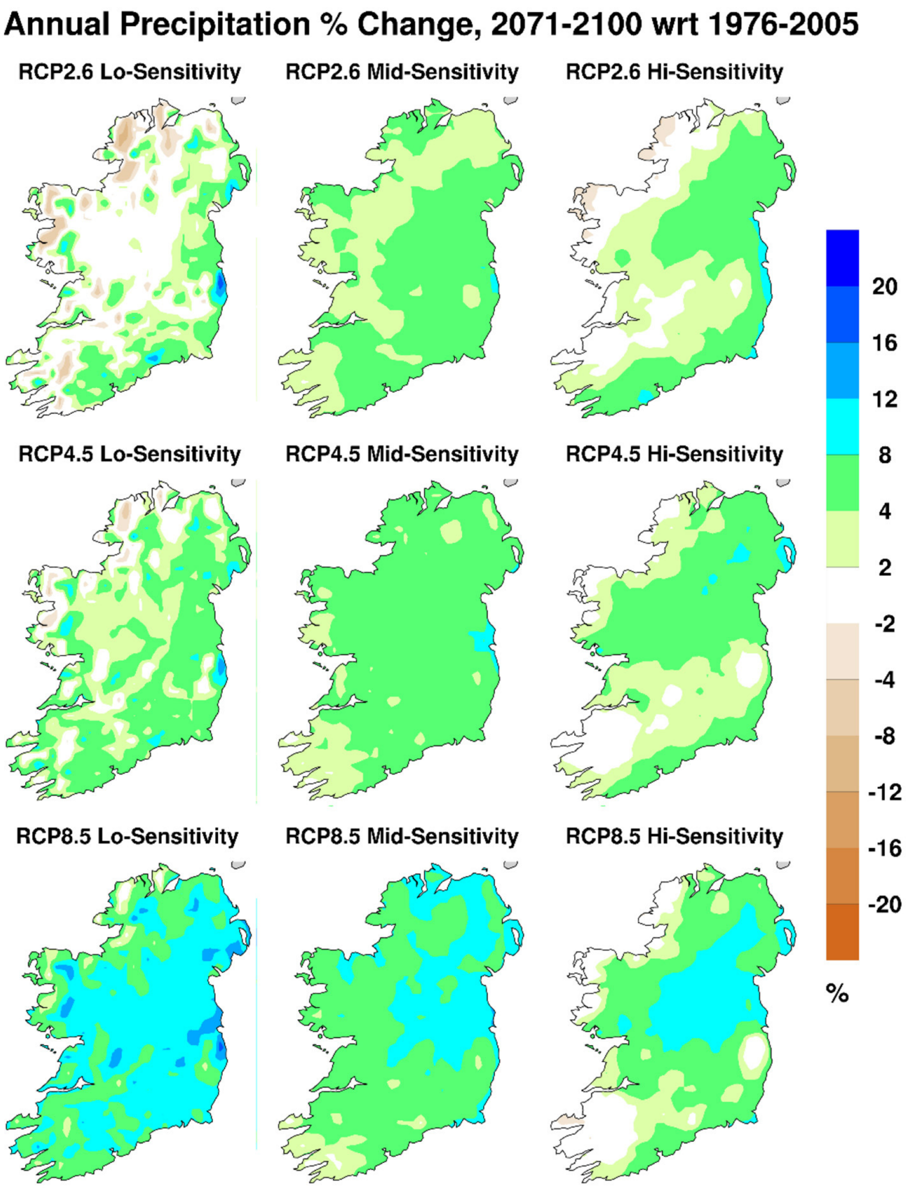

FIGURE 9
Differences between projected annual mean daily precipitation from the end-century period 2071–2100 and the reference period 1976–2005, under the forcing scenarios RCP2.6, RCP4.5, and RCP8.5, and the three different sensitivity ensembles.

be somewhere between the leftmost and rightmost columns of Figure 13 whenever any of the (global) temperature thresholds shown are reached.

3.2.4. Climate indices

A total of 27 standard climate indices are defined by the Expert Team on Climate Change Detection and Indices (ETCDDI).[6] Most of the indices measure different aspects of climate extremes. They can all be easily computed from the (detrended and bias-corrected) 30-year timeseries files for each ensemble member in each ensemble shown in Figure 1, or from the 20-year timeseries for each ensemble member of each temperature threshold climate. TRANSLATE saves each such (reconstructed) timeseries so that any ETCDDI index, or indeed other custom indices (e.g., "growing season duration") can be computed on demand. Typically, an index is computed for each year, then averaged over the duration of each timeseries; finally, the ensemble median is computed as the representative index value for that particular climate (e.g., each of the 27 sub-blocks in Figure 1). For reference, a regional breakdown of several such extreme climate indices using CMIP6 global model projections is provided by Almazroui et al. (2021). The changes in selected indices (TXx, TNn, R99p) relative to 1976–2005 are shown in Supplementary Figures S5–S7, as cross-sections through Figure 1 for the end century period 2071–2100.

6 ETCI indices are listed at http://etccdi.pacificclimate.org/list_27_indices.shtml.

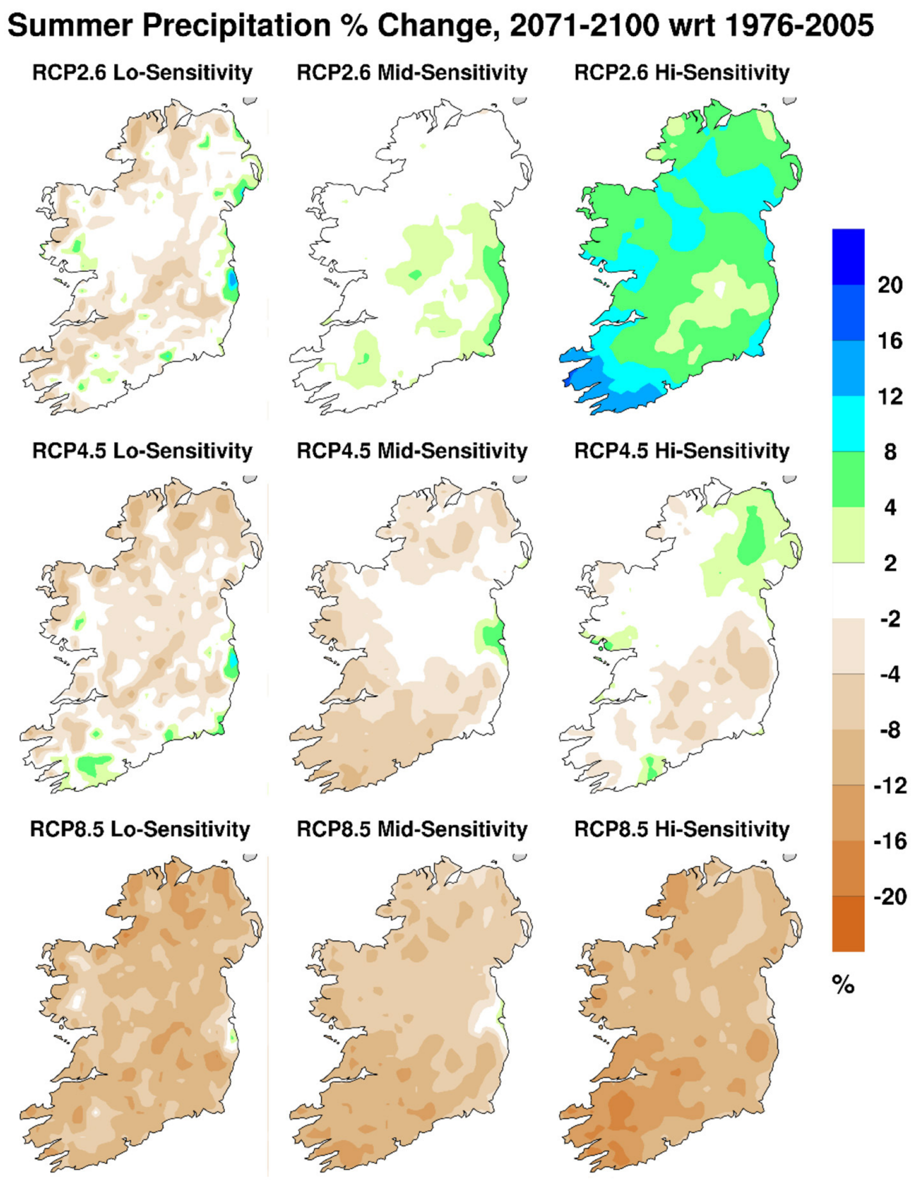

FIGURE 10
Percentage change in end-century projected daily precipitation, as in Figure 9, but for the summer months June to August.

4. Discussion and conclusions

A paradox of various national standards for future climate prections (e.g., UKCP18, CH2018, and KNMI'14 in the UK, Switzerland and the Netherlands, resp.) is just how different they all are from each other, each reflecting different national circumstances. This is also true of more recent projections for Central America by Tamayo et al. (2022). Nevertheless, it is clear from those projects that any standard future projection for Ireland should be based on high-resolution dynamical downscaling of global CMIP models. They should include a range of forcing scenarios to accommodate future emissions uncertainty, and a range of climate sensitivity responses to accommodate model uncertainty.

Ideally, future projections should be based on as large an ensemble as practically possible, with each ensemble member providing an independent climate instance of daily values of relevant variables for periods long enough to provide stable statistics (i.e., 20–30 years). Aggregated projections based on the modeled temperature crossing key thresholds are also worthwhile. The timeseries of each variable in each climate instance should be detrended, bias-corrected, and downscaled to the best possible grid-spacing to provide a stable climate reconstruction, which can then be queried for a wide range of statistics and climate indices. As shown in Section 2.4.3 and by Figure 4, statistical downscaling can add meaningful spatial information to climate projection fields that have coarser grids, just as dynamical downscaling by RCMs can provide more spatial detail than the low-resolution GCMs

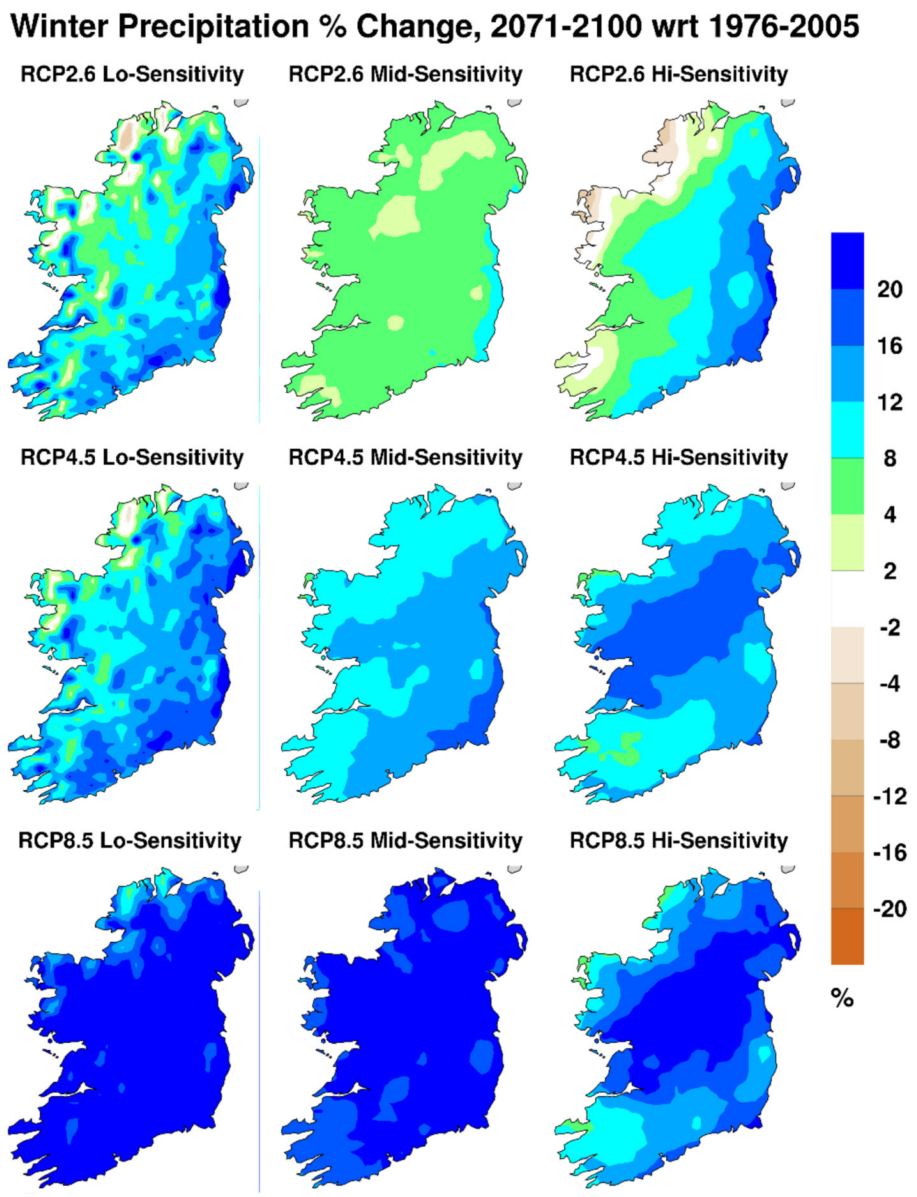

FIGURE 11
Percentage change in end-century projected daily precipitation, as in Figure 9, but for the winter months December to February.

that drive them. Nevertheless, downscaling does not fundamentally alter or feedback on the climate change signal that is passed down from the coarser model grid.

An initial set of standardized climate projections for Ireland was produced, based on the dynamical downscaling work already done by N&F, and by the EURO-CORDEX project. These two sets of downscaled ensembles are nested in the same global CMIP5 models but are very different in the RCMs they use and in their native grid spacing. Given their different grid spacings and ensemble sizes, their post-processing by TRANSLATE to provide detrended, bias-corrected and fully downscaled output was done somewhat differently (Table 1). Nevertheless, the final projected output fields from both sets of ensembles tend to look remarkably similar (Figure 5). The future projected fields e.g., Figure 6 tend to include local details that reflect the main geographical features of Ireland, but the difference fields with respect to the reference 1976–2005 climate tend to be smooth and bland, reflecting the large-scale pattern of the underlying climate change signal (e.g., Figure 7). The similarity in the final future projections between the N&F fields and the EURO-CORDEX fields tends to serve as a cross-validation between them, increasing confidence in the validity of both.

Under the TRANSLATE project, initial standard projections for Ireland were built along the three separate axes of the cube shown in Figure 1, namely future forcing scenarios (as defined by the CMIP projects), future time periods, and climate sensitivity (as defined by the mean surface temperature response of the different ensemble members). Three further scenarios were based on 20-year time-periods around the 1.5, 2.0, and 2.5°C threshold warming

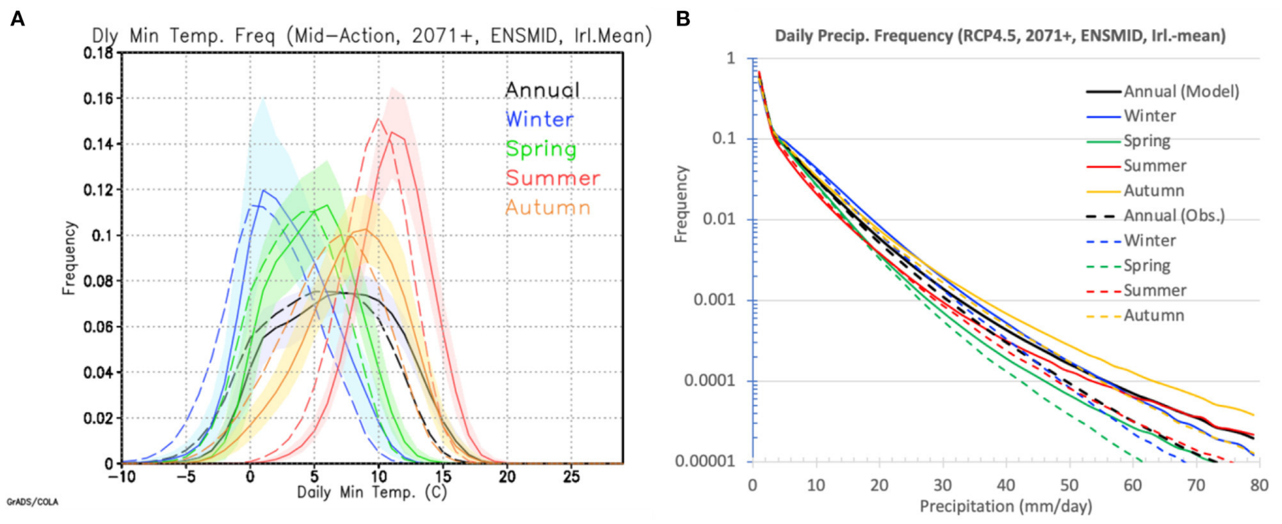

FIGURE 12
(A) Frequency distribution of projected daily minimum temperature (T_{min}) under the RCP45 (mid-range) forcing scenario for the end-of-century (2071–2100) from the mid- sensitivity ensemble, averaged over all Ireland, for each season and the annual cycle (solid curves). Shaded areas around each projected curve span the range from minimum to maximum value within the ensemble. The corresponding observed T_{min} values from the reference period 1976–2005 are shown as dashed curves. The temperature "bins" are 1°C wide; a frequency of 0.1 means that temperatures within that 1°C bin occur once every 10 days on average. **(B)** As in **(A)** except for daily precipitation, with frequency on a logarithmic scale, and for precipitation bins 2 mm day^{-1} wide. No shading is shown as in **(A)** to avoid confusing the plot, but as the frequency decreases to 0.0001 (i.e., once in 10,000 days), the range of daily precipitation spans up to 50 mm day^{-1} from ensemble minimum to ensemble maximum.

TABLE 2 The year at which the smoothed timeseries of global and annual mean surface temperature for the different CMIP5 GCM simulations listed crossed the 1.5, 2.0, and 2.5°C thresholds above their pre-industrial (1850–1900) mean.

CMIP5 Model	1.5°C			2.0°C			2.5°C		
	RCP26	RCP45	RCP85	RCP26	RCP45	RCP85	RCP26	RCP45	RCP85
CNRM	2042	2037	2030		2058	2045		2085	2057
EC-EARTH r1		2023	2021		2047	2027		2077	2052
EC-EARTH r12	2027	2021	2017		2045	2035		2073	2049
IPSL-LR	2012			2036					
IPSL-MR		2017	2015		2031	2031		2056	2042
MPI-ESM-LR r1	2024	2025	2014		2043	2037		2094	2050
MPI-ESM-LR r2	2017	2021	2020		2039	2034		2073	2045
HadGEM2-ES r1	2022	2030	2023	2049	2043	2035		2059	2048
NCCNorESM1-M		2038	2033		2071	2049			2062
MIROC5 r1	2051	2039	2033		2069	2051			2060

The cells with no data are either from simulations that were not available to TRANSLATE, or because a simulation did not cross a particular threshold. See Supplementary Figure S1 for an illustrative example of how each date was determined.

levels as they are reached by simulations under different forcing scenarios. All the raw projected timeseries were detrended (using different methods for temperature and precipitation) and bias-corrected using quantile delta mapping, leading to completely reconstructed timeseries for each variable. The relatively coarse EURO-CORDEX fields were further interpolated and downscaled to the high-resolution observational grid by using the information lost as the observations themselves are interpolated to the coarse grid and back again. A second round of quantile mapping was applied to the EURO-CORDEX frequency fields, with the degraded observational field substituting for the historical simulation in the quantile mapping process.

An initial set of standardized climate projections for Ireland has already been produced by the TRANSLATE project using the principles and specific methods described above, and more complete results from these projections will become publicly available by summer 2023. Ultimately, our intent is to provide as complete and accessible quantitative information

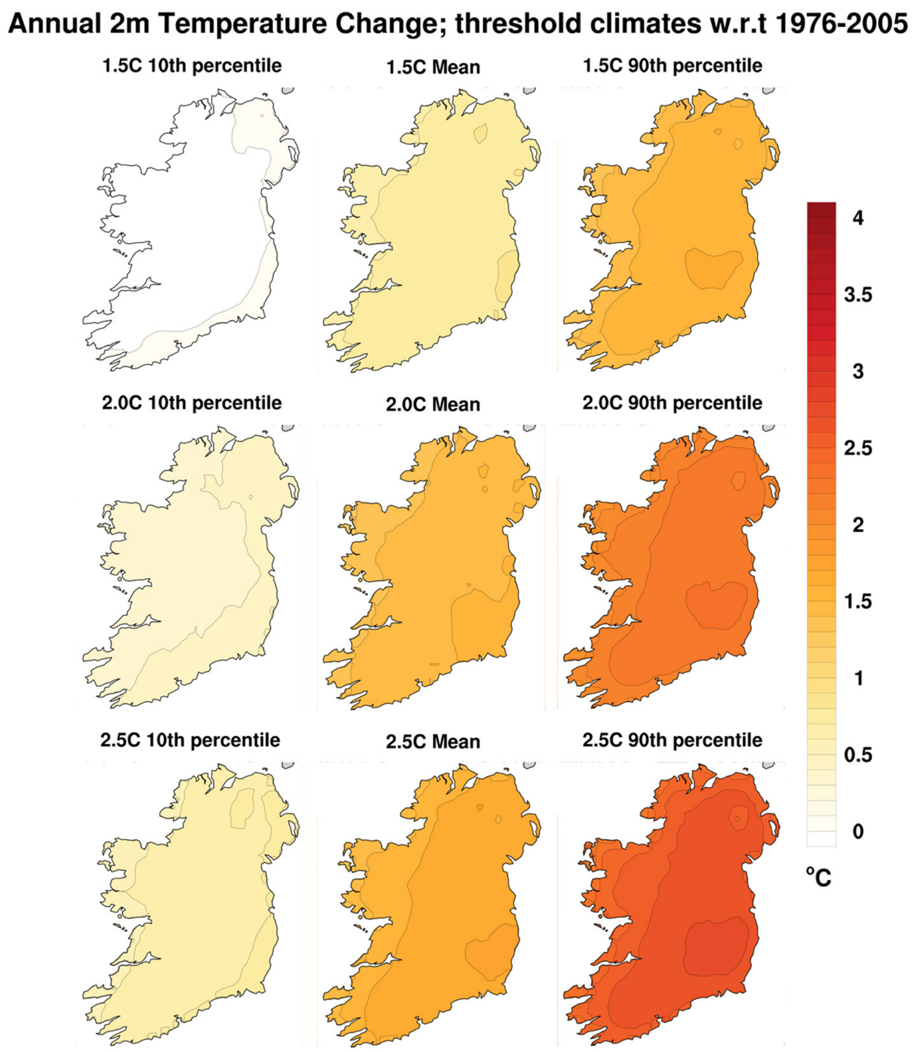

FIGURE 13
Projected annual daily mean temperature (T_{mean}) changes from the 1976–2005 reference period to a climate nominally 1.5, 2.0, and 2.5°C warmer than the pre-industrial period. The rows show the T_{mean} change fields for each threshold value, while the columns show the change fields for the 10th percentile, the mean, and the 90th percentile of each threshold ensemble.

as practically possible about likely future climates in Ireland to meet the needs of those whose job is to plan and manage the national infrastructure out to the end of the 21st century.

Data availability statement

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

Author contributions

EO'B and PN are jointly responsible for the ideas behind this work and wrote the text. PN provided all the RCM output data. The RCM post-processing software was written and run by EO'B, in collaboration with PN. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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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.2023.1166828/full#supplementary-material

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Distortion of sectoral roles in climate change threatens climate goals

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The longstanding method for reporting greenhouse gas emissions—carbon dioxide equivalence (CO_2e)—systematically underestimates methane-dominated economic sectors' contributions to warming in the coming decades. This is because it only calculates the warming impact of a pulse of emissions over a 100-year period. For short-lived climate forcers that mostly influence the climate for a decade or two, like methane, this method masks their near-term potency. Assessing the impacts of future greenhouse gas emissions using a simple climate model reveals that midcentury warming contributions of sectors dominated by methane—agriculture, fossil fuel production and distribution, and waste—are two times higher than estimated using CO_2e. The CO_2e method underemphasizes the importance of reducing emissions from these sectors, and risks misaligning emissions targets with desired temperature outcomes. It is essential to supplement CO_2e-derived insights with approaches that convey climate impacts of ongoing emissions over multiple timescales, and to never rely exclusively on CO_2e.

KEYWORDS

climate change, climate metrics, greenhouse gas emissions, climate modeling, methane, climate goals, climate policy, economic sectors

Introduction

Quantification of sectoral contributions to future warming is critical for guiding climate change mitigation priorities. However, the current method for evaluating the contributions of economic sectors to temperature increases is distorting their relative magnitudes. This distortion is most salient in the coming decades but persists for over a century. Given that sectoral emissions include a variety of greenhouse gases, aggregating their impacts without a climate model requires a metric for intercomparison. Sectoral contributions are almost always quantified using current annual greenhouse gas (GHG) emissions in carbon dioxide equivalence (CO_2e) which employs global warming potentials with a 100-year time horizon (GWP100). A long-term calculation from 1 year's emissions overlooks the near-term potency of short-lived climate forcers such as methane. This is problematic because several sectors are dominated by methane emissions and therefore their impacts (and thus sectoral share) in the near-term would be greater. While the time dependency of the calculation is therefore critical to the statistic, it is continually left out of reporting. The result is a simplified statistic (sectoral share) devoid of its more nuanced meaning (sectoral share over a particular period). In other words, it doesn't mean what people think it means.

Employing a climate model can more accurately convey the relative roles of economic sectors by considering impacts of multiple climate forcers with varying radiative potencies and atmospheric lifetimes over all timescales and accounting for ongoing emissions. In this perspective, we use a reduced-complexity climate model to show that GWP100/CO_2e vastly undervalues methane-dominated sectors' contributions to mid-century warming for both "no further climate action" and "strong mitigation" scenarios. Further, we discuss the policy implications of the resulting distortion and offer recommendations to improve accuracy.

A more accurate representation of sectoral contributions

As our indicator of "true" temperature impacts from future sectoral greenhouse gas emissions, we use a reduced-complexity climate model (MAGICCv6) (Meinshausen et al., 2011). Though models are not without uncertainties (see Supplementary material for how uncertainties influence our analysis), they are more accurate than simplified metrics because they consider interacting chemistry and physics along with climate feedbacks and treat changing climate forcer emissions and resulting atmospheric concentrations with more sophistication.

We consider two global GHG emissions scenarios: a "no further climate action" reference pathway and a "strong mitigation" pathway designed to limit global mean temperature increase to 1.5°C (Keramidas et al., 2018) (Supplementary Figure S1). We use these two scenarios to investigate both the breakdown of global sectors' contributions to absolute warming, as well as their contributions to avoided warming from potential emissions reductions. The reason for this is to determine how standard metrics can influence the perception of sectors in not just contributing to the climate change problem, but in contributing to climate change solutions as well. For example, it is important that we not only understand the full extent in which different sectors cause warming, but also the full extent in which their mitigation can avoid warming. We evaluate the impacts of future emissions from 2021 to 2100 for the three major GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); we do not evaluate changes in hydrofluorocarbons (HFCs) because their current contributions to warming are relatively small and are already covered under a global phaseout agreement (The Kigali Amendment, 2016). Though sectoral emissions also include other warming and cooling climate forcers, as analyzed in Unger et al. (2010), we limit our focus to the main GHGs included in net-zero targets.

We categorize emissions into nine global economic sectors, three dominated by methane—agriculture; fossil fuel production & distribution (FFPD); and waste—and six dominated by CO_2–power generation; industry; transport; buildings; land-use, land-use change, and forests (LULUCF); and Other CO_2 (e.g., energy losses, transfers, etc.). For all sectors, the dominant gas accounts for more than two-thirds of emissions as weighted by GWP100 and a GWP with a shorter time horizon of 20 years (GWP20) (Supplementary Figure S3). We evaluate the global mean temperature responses to sectoral emissions through midcentury to convey near-term warming on policy-relevant timescales, as well as through the end of century to convey long-term warming and relevance for temperature targets.

For the "no further climate action" scenario, the climate model suggests that around half (53%) of additional warming in 2050 due to future GHG emissions, and slightly less than half (44%) in 2100, will be attributed to the three methane-dominated sectors (Figure 1). Methane sectors' contributions are substantial because methane is a potent gas with emissions expected to increase throughout most of the century in the absence of further action (Ocko et al., 2021). In fact, our analysis suggests that around 60% of warming over the next decade from future GHG emissions will come from methane-dominated sectors. Increases in methane emissions will continue to reinforce its near-term potency, even as the warming share of methane-dominated sectors decreases over time due to the accumulation of CO_2 in the atmosphere from the CO_2-dominated sectors.

The methane-dominated fossil fuel production and distribution (FFPD) and agriculture sectors, along with the CO_2-dominated power generation sector are the three largest contributors—amounting to 59% of warming in 2050 with no further climate action. This broadly aligns with previous findings that the highest contributing sectors in the near-term are energy sectors (including FFPD and power generation) and agriculture (Lund et al., 2020).

For the "strong mitigation" scenario consistent with a 1.5°C target, emissions reductions from methane-dominated sectors could contribute half (52%) of the total avoided warming by 2050 (avoided warming relative to absolute warming in the "no further climate action" scenario; note that this is different than the absolute warming analyzed under the reference scenario and thus not directly comparable), and at least a third (36%) of avoided warming in 2100 (Figure 1). While the modeled mitigation scenario in this paper is just one of many potential pathways to achieve 1.5°C, it illustrates the substantial impact that methane mitigation efforts can have on reducing near-term, as well as longer-term, warming.

Misleading metrics and a distorted climate problem

The metric almost always chosen to convert GHGs into their CO_2e is GWP: a measure of the relative potency (in terms of cumulative radiative forcing) of 1 year's (pulse) non-CO_2 emissions as compared to a pulse of CO_2 emissions over a specified time horizon. While the time horizon is an arbitrary choice, 100 years has become the standard. GWP100 is used in Nationally Determined Contributions (NDCs), corporate climate targets (Net Zero), state and company level emissions reporting (Greenhouse Gas Protocol)[1], and widely used emissions inventories such as WRI's Climate Watch platform, EPA's annual greenhouse gas inventory, and the European Commission's annual JRC GECO report.

Decades of literature have illustrated the shortcomings of GWP100 (Lynch et al., 2021) and a prominent issue is that it does not convey the near-term impacts of short-lived gases (Balcombe et al., 2018). This is significant because, of the two GHGs responsible for most of current warming—CO_2 and methane—CO_2 can last for centuries in the atmosphere whereas methane is a potent but short-lived gas that on average remains in the atmosphere for around a decade (IPCC, 2021). When GWP100 is used to convert methane emissions into CO_2e, the result is a skewed perception of methane's impact because the metric relies

1 https://ghgprotocol.org/

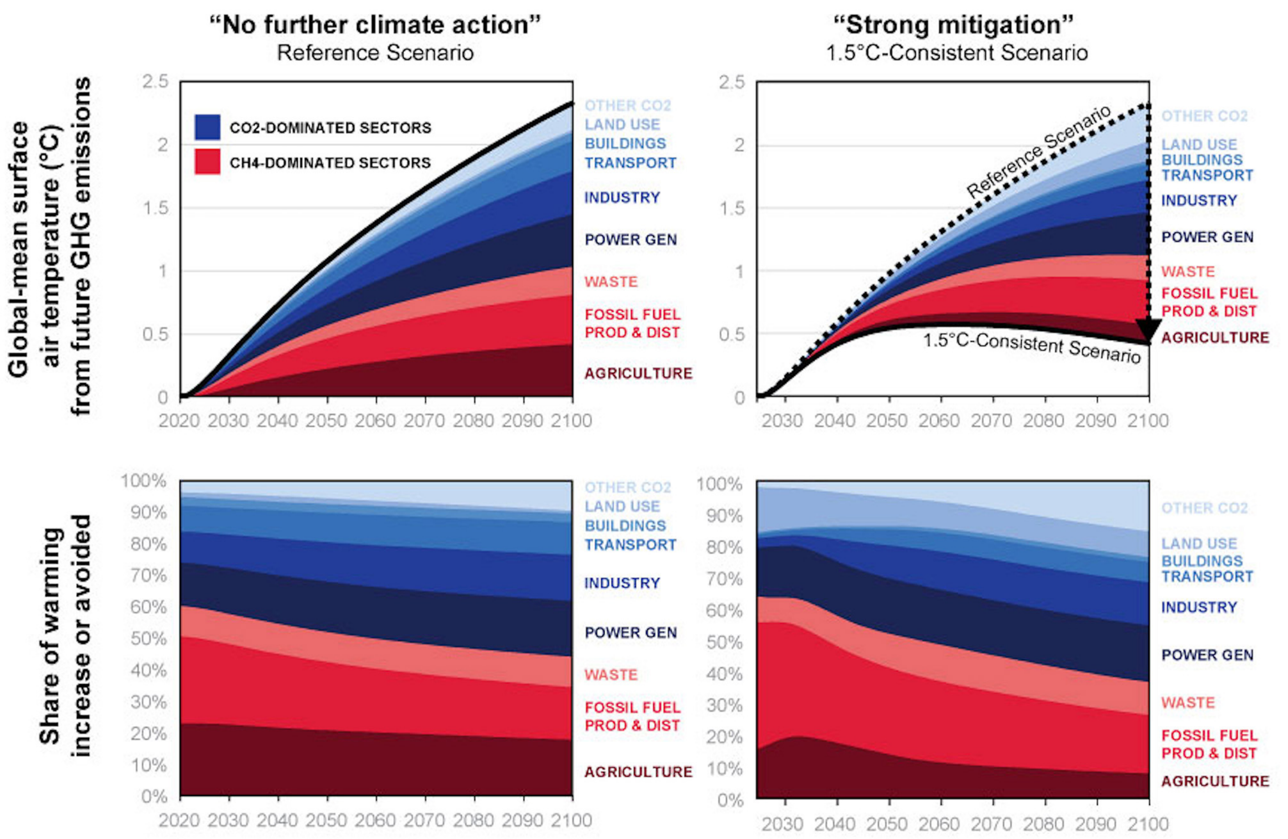

FIGURE 1
Global temperature contributions of continuous 2021–2100 emissions of CO_2, CH_4, and N_2O using a simple climate model. Left panels show warming under one possible reference scenario that includes all climate and energy policies implemented as of 2017, and right panels show avoided warming under a scenario that limits global warming to 1.5°C. Both scenarios are taken from Keramidas et al. (2018). CO_2-dominated sectors are in shades of blue, methane-dominated sectors are in shades of red. "Land use" refers to "land use, land-use change, and forestry." "Other CO_2" includes emissions from losses of the energy transformation industry (excluding power and heat generation).

on averaging the warming impact of a pulse of methane over multiple decades when the pulse has substantially decayed and is not considerably influencing the atmosphere. A continuing flow of methane will maintain a corresponding elevated atmospheric concentration, and warming impact; but again, this is not well reflected via GWP100.

Our analysis illustrates the inadequacy of relying solely on GWP100. While the climate model makes it clear that methane-dominated sectors could account for around half of (1) warming from future GHG emissions in the absence of climate action and (2) avoided warming from a strong mitigation scenario, using the standard GWP100/CO_2e approach leads to vastly different results.

For example, cumulative CO_2e using GWP100 practically halves the role of methane-dominated sectors over the 2021–2050 period relative to the model results (53% model; 28% metric; Figure 2). While GWP100 performs better in the long-term, as the period from 2021 to 2100 more closely matches a 100-year time horizon, the results in 2100 over this time period are still distorted, with the methane-dominated sectors' role cut by around a third when using the metric relative to the model (44% model; 30% metric).

Similarly, GWP100 obscures the importance of emissions reductions from methane-dominated sectors—cutting their avoided warming potential almost in half in 2050 (52% model; 24% metric) and by almost a third in 2100 (36% model; 22% metric). This yields a misrepresentation of the relative potentials of economic sectors to mitigate additional warming (Figure 2).

While alternative metrics for comparing GHGs with different lifetimes have been proposed (e.g., Ocko et al., 2017), there is no single simplified metric that can capture impacts over all timescales. Nevertheless, we test the accuracy of two other popular climate metrics: GWP20 and GWP* [a metric that evaluates the relative climate impact of a change in the emission rate of a short-lived climate pollutant compared to a pulse of CO_2 (Cain et al., 2019)]. In 2050, both GWP20 and GWP* can provide sectoral shares that are consistent with the climate model (Supplementary Figure S4). In 2100, neither metric replicates the climate model as closely; GWP20 slightly overvalues the contributions of methane-dominated sectors and GWP* slightly overvalues the contributions of CO_2-dominated sectors (Supplementary Figure S4). However, both can perform better than GWP100 out to 2100. We also note that the specific distortion of methane's contributions assessed via cumulative GWP is highly dependent on the methane emissions pathway under consideration in addition to the chosen time horizon.

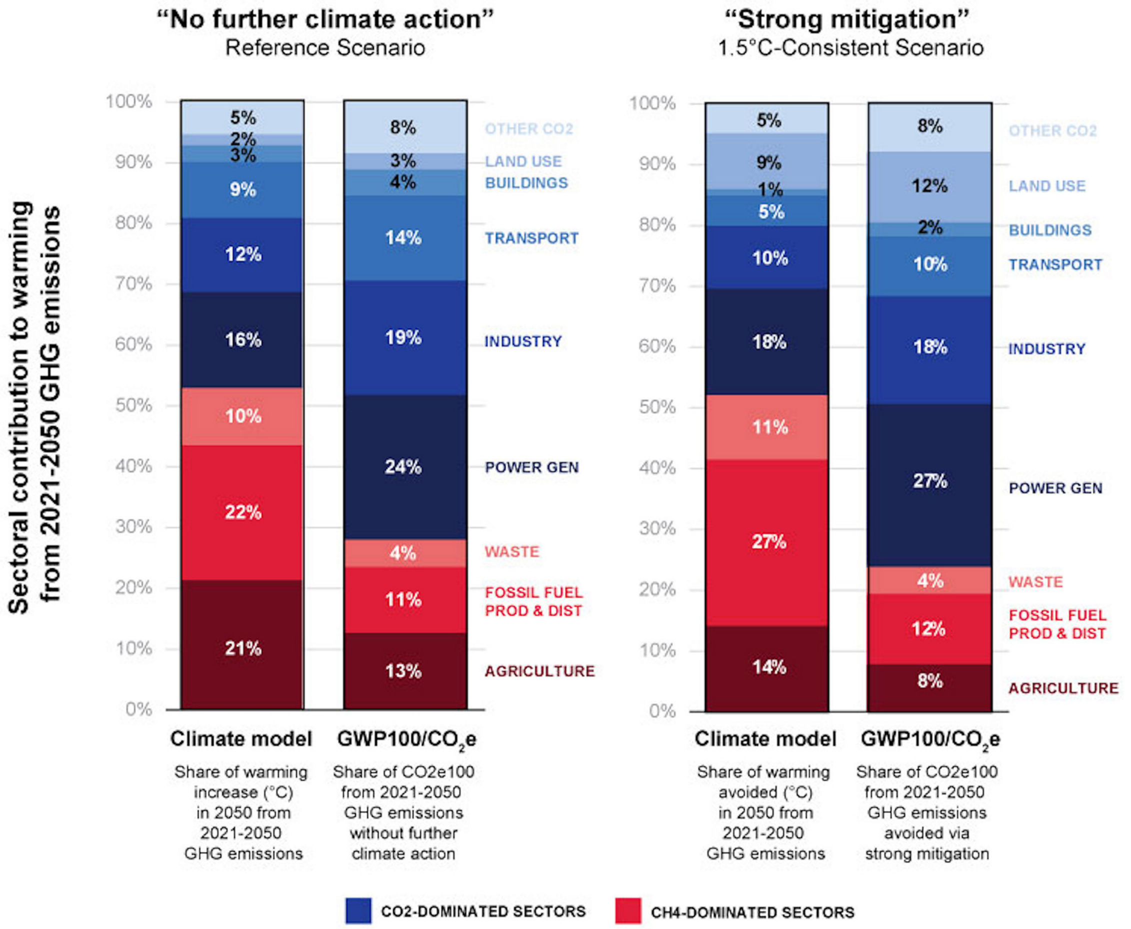

FIGURE 2
Comparison between a climate model and GWP100 of sectoral warming and avoided warming contributions in 2050 from continuous 2021–2050 emissions of CO_2, CH_4, and N_2O. Left panel shows one possible reference scenario that includes all climate and energy policies implemented as of 2017, and right panel shows avoided warming (relative to the reference scenario) under a scenario that limits global warming to 1.5°C. Both scenarios are taken from JRC GECO (2018). CO_2-dominated sectors are in shades of blue, methane-dominated sectors are in shades of red. "Land use" refers to "land use, land-use change, and forestry." "Other CO_2" includes emissions from losses of the energy transformation industry (excluding power and heat generation).

Climate decision making must adopt new standard practices

Given how GWP100-based CO_2e calculations distort the roles of economic sectors in contributing to future warming, relying solely on GWP100 can lead to suboptimal policies and priorities by misleading climate actors from the top levels of government (e.g., U.S. NDC)[2] to grassroots organizations. This is because the importance of methane emissions in several sectors is systematically underestimated by GWP100.

The prominent role of methane in climate change and its mitigation has been increasingly recognized (UNEP, 2021), culminating in the recent Global Methane Pledge. However, GWP100/CO_2e in isolation continues to be pervasive in climate policy, advocacy, and education. Yet there are examples of acknowledgment of the metric issue by stakeholders (such as work by the Irish Climate Change Advisory Council to establish multi-gas GHG budgets, as well as the State of New York publishing their emissions inventory using GWP20). Given that prioritizing sectoral mitigation efforts is often necessary under cost and political constraints, the current sectoral share distortion imposed by GWP100/CO_2e risks mis-prioritizing sectors for emissions reductions, undervaluing the benefits of methane-sector mitigation—especially in the near-term—and potentially overlooking important abatement measures. This can have implications for the temperature outcomes of climate policies. For example, if CO_2-dominated sectors are regularly prioritized for mitigation, the realized temperature benefits in the near-term will be lower than anticipated because the remaining warming impact from methane-dominated sectors will be underestimated.

The bottom line is that GWP100 should never be singularly relied upon for emissions assessments. Fortunately, myriad alternative or supplemental metric strategies have been proposed.

2 https://unfccc.int/NDCRE

These include dual-reporting of emissions using two metrics to capture both the near- and long- term climate impacts, (Ocko et al., 2017) separately indicating contributions of short- and long-lived pollutants to a total CO_2e target, (Allen et al., 2022) or defining metric time horizons according to global temperature goals (Abernethy and Jackson, 2022). While there is no "one-size-fits-all" metric for climate decision making (IPCC, 2021), this should not be a reason to always defer to the status quo. We urge the climate policy community to recognize the necessity for additional metrics or methods that can adequately convey the impacts of GHG emissions in both the near- and long-term. Furthermore, we recommend that:

1. All emissions accounting start by breaking down emissions by gas in units of mass. This is an essential practice for ensuring that the most appropriate evaluating method and time horizon can be used by making the underlying information available. Too often emissions are presented—whether for a company, a sector, or an entire country—only as a combined CO_2e. Without the breakdown by gas, it is impossible to convert the emissions to any other metric or input accurately into a model. The UNFCCC is a prime example of requiring emissions inventories to be broken down by gas, and we strongly recommend this practice be widely adopted.
    a. We also recommend that this method of emissions accounting by gas be extended to emissions projections and commitments, such as those included in countries' NDC targets.
2. Data tools, inventories, and reports allow users to see GHG emissions according to different metrics, side by side. This means reconfiguring the way we present sectoral emissions data to better account for varying sectoral contributions to warming over time. This would introduce a user-oriented decision-making process regarding which metric is most appropriate for the application at hand.
3. Emissions totals and percentage contributions that combine multiple greenhouse gases using a specific time-horizon in the aggregation should never be reported without explicitly stating the time-horizon of the climate metric used to calculate them. This would bring the time-dependency of the information to the forefront.

These new standard practices must become embedded across the climate science and policy communities if we want to secure the best chance at reducing emissions and mitigating the worst of climate change over all timescales.

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.

Author contributions

IBO designed the study. NC-S carried out the experiments with help from TS. NC-S analyzed the results. IBO and NC-S prepared the visuals. All authors wrote the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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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.2023.1163557/full#supplementary-material

TABLE 1
Data Appendix; emissions data and GWP calculations.

DATA SHEET 1
Model Parameters; used to run MAGICCv6 in this study.

DATA SHEET 2
Supplementary Material; including supplemental figures, experiment descriptions, and tabular data.

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How to provide actionable information on weather and climate impacts?—A summary of strategic, methodological, and technical perspectives

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Climate change will result in more intense and more frequent weather and climate events that will continue to cause fatalities, economic damages and other adverse societal impacts worldwide. To mitigate these consequences and to support better informed decisions and improved actions and responses, many National Meteorological and Hydrological Services (NMHSs) are discussing how to provide services on weather and climate impacts as part of their operational routines. The authors outline how a risk framework can support the development of these services by NMHSs. In addition to the hazard information, a risk perspective considers the propensity for a given hazard to inflict adverse consequences on society and environment, and attempts to quantify the uncertainties involved. The relevant strategic, methodological and technical steps are summarized and recommendations for the development of impact-related services are provided. Specifically, we propose that NMHSs adopt an integrated risk framework that incorporates a hazard-exposure-vulnerability model into operational services. Such a framework integrates all existing forecast and impact services, including the underlying impact models, and allows for flexible future extensions driven by the evolving collaboration with partners, stakeholders and users. Thereby, this paper attempts to unify existing work streams on impact-related services from different spatial and temporal scales (weather, climate) and disciplines (hydrology, meteorology, economics, social sciences) and to propose a harmonized approach that can create synergies within and across NMHSs to further develop and enhance risk-based services.

KEYWORDS

climate service, weather and climate risk, extreme weather and climate, National Weather Service, impact assessment, co-design, user needs, hazard-exposure-vulnerability

1 Introduction

Weather and climate events pose a multitude of risks to societies (WMO, 2020). Providing effective decision support services concerning these risks is a challenge for research institutions, service providers and users alike. Here we address National Meteorological and Hydrological Services (NMHSs) in identifying common strategies and best practice guidelines for the integration and provision of impact information into weather and climate services. NMHSs' primary objective is the provision of actionable decision support service with respect to meteorological, climatological and hydrological information (Mosley, 2001; WMO, 2015; Göber et al., 2023). Ultimately, these services should increase preparedness, activate swift response and prevent/reduce negative impacts of the hazard.

In recent years, an increasing number of NMHSs have begun to provide not only information on the hazard itself, but also information on the potential impact (Uccellini and Ten Hoeve, 2019; Kaltenberger et al., 2020; WMO, 2020). This shift is motivated by the fact that the ideal basis for risk-reducing actions is knowledge of the potential societal impacts. It is challenging to evaluate potential adverse impacts based on weather and climate information alone (Anderson-Berry et al., 2018; Uccellini and Ten Hoeve, 2019; Kaltenberger et al., 2020; Potter et al., 2021). Moreover, besides information on the potential impacts, other measures (e.g., preparedness planning, mitigation works) can influence the decision-making process (Potter et al., 2018; Taylor et al., 2018). In accordance with the IPCC, we refer to impacts as the consequences of realized risks on natural and human systems (IPCC, 2023). Risks result from dynamic interactions between the hazard (a spatio-temporally constrained weather or climate event) with the exposure (the geographical distribution of points of interest, e.g. infrastructure, persons) and vulnerability (the susceptibility of these points of interest to the hazard) (Reisinger et al., 2020). Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, thereby contributing to the probabilistic nature of risks (Kropf et al., 2022).

To provide actionable climate and weather services, we propose the implementation of a risk framework by NMHSs that includes the hazard-exposure-vulnerability (HEV) dimensions as building blocks in a model to calculate impacts and risks of extreme weather and climate events (Birkmann et al., 2013; IPCC, 2021). In comparison to traditional representations of risk modeling where hazard, exposure and vulnerability are discrete building blocks, e.g., using the famous IPCC risk propeller (O'Neill et al., 2022), we here propose a continuous representation of risk modeling in a smooth risk plane (Figure 1). The mechanics of this modeling approach allows for a gradual increasing interaction of these three building blocks, starting with hazard only information up to a full risk assessment (Röösli et al., 2021). We therefore refer to the full risk triangle as shown in Figure 1 as the "larger picture" into which the traditional hazard modeling activity of a NMHS is naturally embedded. By increasing the complexity of the provided exposure and vulnerability information (from uniform over categorical to more sophisticated levels), the model generates the impact-related output as required by the user (numbered items in Figure 1, Table 1 for detailed examples). In addition, existing HEV-models are also capable of integrating cost/benefit perspectives on specific risk reduction and adaptation measures, e.g., CLIMADA (Bresch and Aznar-Siguan, 2021) and the Oasis Loss Modelling Framework (n.d.).

An integrated HEV-model (operated at a NMHS or in collaboration with other organizations), that flexibly incorporates the existing NMHS service landscape and the various impact-related services requested, resembles the first of two pillars of a NMHS' impact strategy. The second pillar is transdisciplinary collaboration, as implementing an impact strategy does not only involve research and development but also an increased exchange with existing but also new public and private actors. The implementation of impact-related services in cooperation with so-called boundary organizations is therefore key. We refer to boundary organizations (BO) as all downstream users, service providers or consultancies that can independently access the hazard event and impact information to produce additional impact and risk assessments either for their own purposes or for other specific users and applications. The provision of a modular, open-source and -access HEV-model will support this co-design process. Potential services might comprise purely physical (e.g., hydrological impacts), social (e.g., lives threatened), economic (e.g., economic damages) but also environmental, cultural or institutional assessments. In another dimension, the model can provide either qualitative (e.g., impact-oriented warnings or forecasts) or quantitative assessments (e.g., potential economic damage, potentially affected people, data-driven impact-based decision support services for specialized users) (Table 1).

The implementation of such a process at a NMHS requires strategic, methodological and technical considerations, which are further detailed below and complemented by a discussion with recommendations and practice-oriented steps.

2 Strategic perspectives of impact-related services

Many NMHSs are currently revising their strategies triggered by changing user requirements, budgetary or legal constraints, novel technical developments and as a response to rapid climate change (WMO, 2020).

NMHSs respond to changing user preferences by refining both their products and services as well as the product's design procedure, e.g., following the value chain approach (Nurmi et al., 2013; Golding et al., 2019). From the outset, the design process ideally involves potential users through interdisciplinary expertise and co-design strategies. As a result, the usability of the NMHS' portfolio increases, which in turn may result in favorable behavioral changes, support individual and especially institutional decision making and render socioeconomic benefits for society.

Providing impact-related services represents one way of responding to changing user preferences toward individualized and decision-relevant services. Recent advances in method development and data availability have resulted in model improvements that allow NMHSs already today to generate and provide impact-related warnings and forecasts fully probabilistically and seamlessly from the nowcasting to the

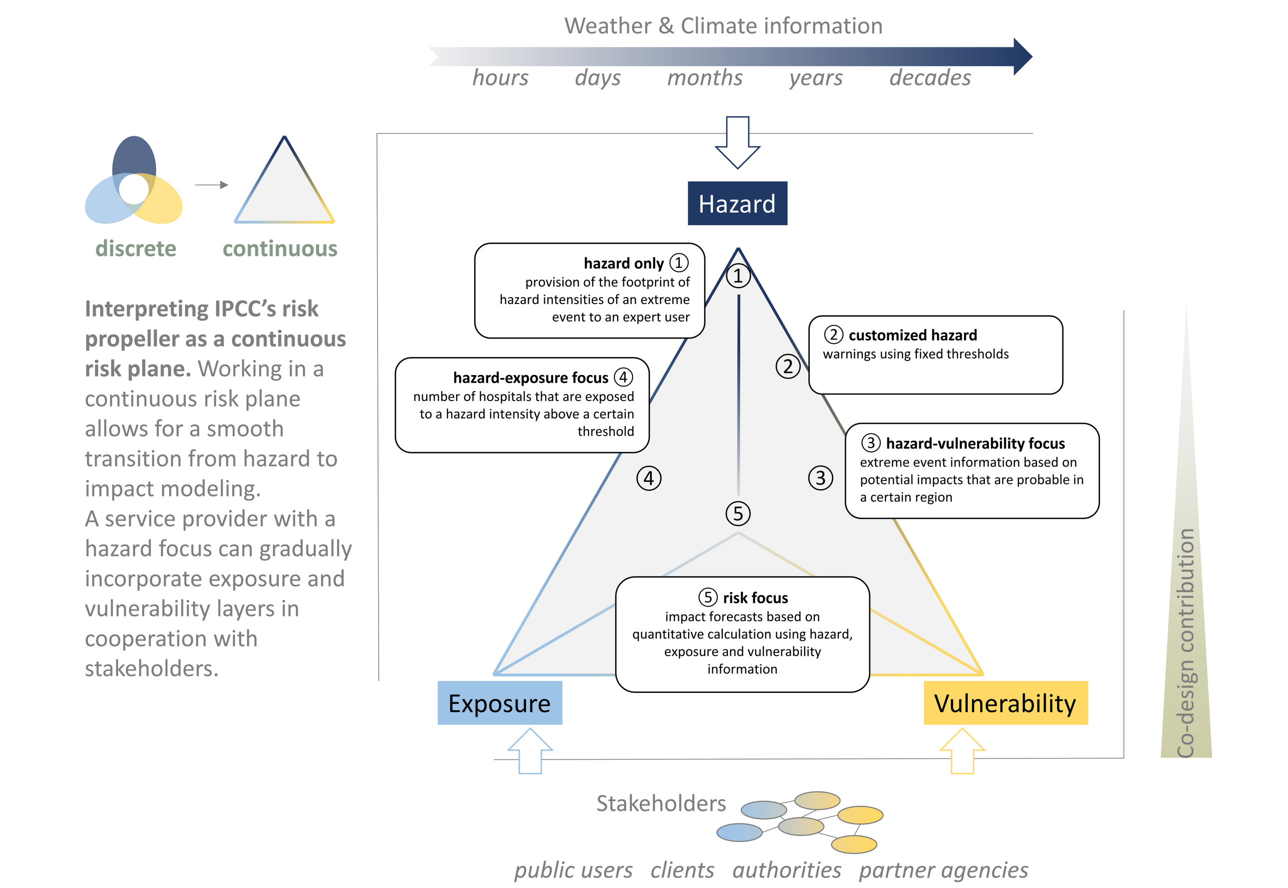

FIGURE 1
Modeling impacts for weather and climate services in a continuous risk plane. A hazard-exposure-vulnerability (HEV)-model uses the building blocks hazard (a spatio-temporally constrained weather or climate event), exposure (the geographical distribution of points, lines or polygones of interest) and vulnerability (the susceptibility of these points of interest to the hazard) to calculate impacts and risks of extreme weather and climate events. Traditionally, risk modeling is done using discrete HEV building blocks (IPCC risk propeller, left of figure). Here, we propose continuous risk modeling in a HEV-plane (risk triangle, center of figure). The risk triangle displays different weather and climate services (numbers ①-⑤) as potential realizations in the HEV-plane. As a common first step the desired weather or climate information (top of figure) is transformed into a spatio-temporal hazard event, e.g., containing the hazard's intensities ①. Moving down, exposure and/or vulnerability information is included to a varying degree into the risk assessment (②-⑤), with a full risk assessment reached at ⑤. Concrete examples for the five realizations in the HEV-plane are listed in Table 1. Co-design requirements and interaction with boundary organizations (BO), e.g., stakeholders, partners and users, increases from top to bottom (bottom and lower right of figure).

climate forecast scale (Röösli et al., 2021). Therefore, impact-related services are in line with other key strategic developments (probabilistic and seamless forecasts) and, if produced by an integrated HEV-model (Figure 1), can help to unite existing NMHS products within a single framework.

Individual NMHSs might argue that they lack the legal mandate to act in this field, because the responsibility (and related expertise) lies with other governmental bodies or private service providers (Kaltenberger et al., 2020). While this might be the case today, the situation might change in the future, e.g., due to adapted legal requirements and/or increasing risks driven by climate change. Adopting an integrated HEV-model now allows one to fulfill the current mandate, but also to move toward impact-related services in partnership with others in the future (Figure 1).

Another NMHS's concern might be liability. To avoid that false alarms could undermine the provider's reputation or even cause liability issues, it is again of utmost importance to co-develop the impact-related services with the users from the start and to reiterate that these services do not replace decision making. Moreover, starting out with more qualitative impact advisories instead of impact warnings (see Methodological Perspectives) will help to avoid false expectations and to circumvent potential liability issues.

3 Methodological perspectives of impact-related services

"Understanding disaster risk and forecasting hydrometeorological[1] impacts are generally beyond the remit of meteorologists and hydrologists. However, since the risks and impacts are often triggered by extreme hydrometeorological

1 While our present discussion refers mostly to meteorological hazards, we acknowledge that our reasoning also holds true for hydrometeorological hazards and related impact assessments not in the focus here, as highlighted in the WMO report (WMO, 2015).

TABLE 1 Examples of actionable impact information as obtained from a HEV-model.

Product type (cf. Figure 1)	Forecast range	Actionable information	Intended users	Representation in HEV-plane			Details
				Hazard-event	Exposure	Vulnerability	
Hazard only ①	Short / medium	Wind speed	All users	Storm footprint based on wind speed	-	-	Wind footprint, e.g., ensemble mean of daily max wind, as provided by numerical weather model. **Use case**: Tropical cyclone track forecasting
Customized hazard ②	Short / medium	Wind warning level	All users	Storm footprint based on wind speed	-	Fixed official warning thresholds	Categorization of wind footprint by warning level. **Use case**: Warning of tropical cyclone occurrence by Saffir-Simpson scale
Hazard-vulnerability focus ③	Short / medium	Probability of sewage system failure	Local infrastructure managers	Maps with hourly precipitation sums	-	Sensitivity of sewage system to extreme precipitation	Risk map with hot spots for sewage system failure. **Use case**: Coordination of rapid response teams
Hazard-exposure focus ④	Short / medium	Number of vacant hospital beds exposed to heatwave	Hospital managers, emergency services	Map with multi-day heatwave extent	Location of hospitals and their number of vacant beds	-	Risk map with potential hospital bed shortage. **Use case**: Cancelation of non-emergency hospital services to free staff and beds
Risk focus ⑤	Short / medium	Map with expected building damages	Emergency services, post-event assessment teams	Map with daily max wind forecast	Location and value of buildings	Sensitivity of building damage to max wind	Impact map for building damage hotspots. **Use case**: Planning of personnel for post-event insurance claim services
Hazard only ①	Extended / long	Sunshine duration	All users, energy sector, tourism	Map of monthly expected sunshine duration	-	-	Regional aggregation of sunshine duration as direct model output. **Use case**: Solar energy generation potential
Customized hazard ②	Extended / long	Map with wildfire danger	Planners in fire departments, tourism managers	Map with wildfire index	-	Fixed official warning thresholds	Categorization of forecasted wild fire index by warning levels, that are associated with certain behavioral restrictions. **Use case**: Outside leisure activity planning in tourist regions
Hazard-vulnerability focus ③	Extended / long	Map with expected crop yield losses by crop type	Farmers, local decision makers	Map with high probability of prolonged drought conditions	-	Sensitivity of specific crop variety to drought conditions	Translation of drought conditions into potential crop yields. **Use case**: Pre-sowing decision support for crop choice
Hazard-exposure focus ④	Extended / long	Map combining riverine traffic and forecasted river discharge	Hydrological experts, water traffic authorities	Map of forecasted weekly min/max river discharge at specific gauge stations	Daily number of shipping vessels at specific gauge stations	-	Interacting forecasted river extreme discharge with usual shipping activity to anticipate potential impacts of decision-making. **Use case**: Optimization of decision timing for efficient logistics
Risk focus ⑤	Long / projections	Guidance for future health care requirements by region	Political decision makers, public health experts	Maps of changes in severity of heatwaves in a warming climate	Maps of demographic changes of population	Sensitivity of heat-related mortality by age cohorts	Quantification of local heat-related deaths for future scenarios. **Use case**: Adaptation of building standards of health care facilities, e.g., retrofitting of air-conditioning systems

Illustration of concrete impact-related applications as represented by the individual numbers (cf. column 1) in Figure 1, their representation in the HEV modeling plane (cf. columns 5–7) and intended users (cf. column 4). An exemplary use case is provided in the last column. The applicability from the weather to the climate forecast range (cf. column 2) is illustrated by the following lead times: short range (≤2 days), medium range (≤15 days), extended range (≤6 weeks), long range (months to years), projections (decades).

events, it may be argued that NMHSs are best equipped to forecast their impact in partnership with others" (WMO, 2015).

This quote highlights two aspects: (i) NMHSs possess substantial expertise, both, with respect to the hazard and technically in the provision of operational services, (ii) impact-related services require interdisciplinary and transdisciplinary (user engagement and co-design) partnerships. Working with BO from the start will bring together the interdisciplinary expertise, will ensure the usefulness of the services to be developed and share the burden of developing, providing and communicating the service. As a matter of fact: the more the services focus on impacts, the more tailor-made the services become, and the more such partnerships are required (Figure 1). At the same time, the provision of tailor-made products for a range of users remains only feasible if the underlying service architecture is strictly modular and flexible and/or supported by stakeholders or BO.

Another important aspect concerns the metrics to be provided, which range from qualitative metrics (e.g., text-based, based on forecasters' judgment, simple impact indicators) to quantitative assessments (e.g., economic damages, affected people). Depending on the metric requirements, less complex impact advisories (potentially derived from non-public impact forecasts) can be a good starting point in place of actual impact warnings or forecasts. Impact advisories are also less strict on data availability and quality or on output evaluation, verification and uncertainty assessments. Quantitative assessments, on the other hand, will benefit from standardized and generalizable metric definitions that are clearly defined and communicated and comparable across impacts, e.g., people affected or monetized damage.

The successful development of any impact-related service will rise and fall with data availability across the full risk plane (Kaltenberger et al., 2020). Data on hazard, exposure and vulnerability are prerequisites for impact estimates (Table 1). In addition, impact observations are needed ex-ante to calibrate vulnerability functions and ex-post to validate impact-related services (Themessl et al., 2022). Alternatively, NMHSs should be prepared to provide their hazard event data to BO to allow for impact assessments with their bespoke exposure and vulnerability information, e.g., to meet user requirements best or to comply with confidentiality.

Accounting for uncertainty throughout the impact-modeling chain is a crucial part of developing impact-related services. This amounts to fully probabilistic risk assessments that combine present probabilistic weather and climate forecasts with suitable uncertainty considerations for the exposure and vulnerability component (Kropf et al., 2022). The associated quality or skill of the impact-related service will strongly depend on the hazard type and the time scale considered. E.g., impacts of an extreme wind event might only be forecasted with sufficient accuracy few days in advance, while temperature-related impacts can be skillful on seasonal time scales and beyond (Merz et al., 2020; Domeisen et al., 2022; Delgado-Torres et al., 2023). Therefore, hazard-specific decision protocols and communication guidelines that clearly name the target group, how to interpret and deal with associated uncertainties, probabilities and the forecast skill must accompany each impact-related service (see Technical Perspectives). This is needed to avoid false accuracy and false expectations.

4 Technical perspectives of impact-related services

Moving toward impact-related services requires specific technical steps. The focus lies on technical steps that are independent of the scope of the service, e.g., the weather or climate scale. This opens up the possibility for synergies in tackling these steps.

Implementing impact-related services at a NMHS for the first time usually requires introducing new concepts, methods and data sources into the operational setting (Röösli et al., 2021). Using a common approach like a HEV-model does not avoid this effort, it only provides a reusable framework for new concepts and its elements, especially if provided open-source and free to use. To facilitate the initial implementation of this framework, it needs to be attached to a strong use case and priority should be given to a generalizable structure. In this way the concepts become part of an operational setting and the efforts for subsequent developments building on the same concepts are reduced considerably. It is generally recommended to start small in terms of implementing the HEV-model at a NMHS and grow with collected experiences.

In the rapidly expanding field of impact-related services, transparent collaboration is a powerful catalyst to bring new concepts to widely used applications. Whilst some methodologies for calculating impact-related information are established, several extensions like compounding events and time-dependent exposure and vulnerability are currently being researched and developed. Different organizations using the same open-source software for their HEV-model allows sharing of new solutions quickly. This supports not only a quick transition from research to application, but also synergies among NMHSs in this common undertaking. At the same time, successfully launched impact-related services by NMHSs supported by a flexible, modular and open-access framework would allow BO, consultancies and other service providers to build upon the same framework and existing interfaces and to create additional services and products that are beyond the mandate of NMHSs. Examples of such services are listed in Table 1, where additional services could be iteratively improved using the same HEV model.

Integrating impacts requires an (extreme) event perspective. In both weather and climate services, the standard for meteorological information is continuous weather data in time and space. On the other hand, observed impacts are normally associated with a specific event, e.g., aggregated precipitation in 24 h within a specific region or spatio-temporal extension of a drought defined by soil moisture indices. Derived statistical evidence, like calibrated damage functions, will require the hydrological and meteorological data to share the same event definition. This requirement calls for an event-based strategy that transforms continuous weather and climate data according to definitions of extreme weather and climate events. While this sounds like a strong limitation at first sight, the event definition is very flexible and is usually defined by the context. On spatial scales, an event can cover anything from a single grid cell to a huge region, e.g., a continent. On temporal scales, an event can be as short as a lightning and as long as a multi-year drought. Sometimes the events can be derived from continuous data using thresholds (e.g., Beusch et al., 2023), sometimes meteorological features are identified and tracked in model data (e.g. Hodges, 1995). Using harmonized event definitions within and across NMHSs will not only make the extreme weather and climate services consistent but also ensures the reusability of impact-related methodologies between the different services and beyond. This automatically ensures a truly seamless handling of impact information.

Having implemented and operationalized an HEV-model is part of the solution, the other part being evaluated model configurations for specific hazard and impact types. These model configurations contain all specifications for the elements hazard, exposure and vulnerability to produce meaningful results in the form of quantitative impact estimates or qualitative impact advisories. These model configurations can be a result of data analysis of past events or of transdisciplinary efforts including stakeholder and expert knowledge. To speed up the generation of new and reliable model configurations, establishing structures for evaluating published model configurations from the scientific literature or the development of new model configurations is important. Here, the interaction of NMHSs with BO in identifying, defining and applying these model configurations is again key.

Another important aspect of HEV-model configurations is the metric on how to measure the quality of the implementation. This aspect should be thought of from the beginning and actively monitored. As such a new service requires resources, it will be important to evidence the success and skill of the new implementation. As observations of impacts are rare, available with a delay and sometimes uncertain, the methodologies normally applied to measure the quality of meteorological and climatological services will have to be adapted. First concepts on comparing impact data with meteorological services are being conceived (e.g., Wyatt and Robbins, 2023). In particular, one should consider that a successful implementation might affect the quality measure under consideration, e.g., behavioral responses affecting the forecasted impact (Scolobig et al., 2022).

Finally, a disclaimer for impact-related products and services needs to be provided with any operational impact service. The role and liability of each stakeholder must be established by actively communicating the disclaimer during the delivery of impact-related products and services. Such a document provides information on the intended use of the product and its uncertainties and shortcomings and can help to address liability concerns raised in the strategic perspectives part of this document. Collaborating with other NMHSs on the elaboration and establishment of such disclaimers could speed up this process.

5 Discussion

Based on the strategic, methodological and technical perspectives raised above we here provide four general recommendations on how to integrate impact information into weather and climate services. These recommendations specifically address applied scientists, senior forecasters and strategic decision makers within NMHSs but also practitioners within the community of stakeholders and BO:

i) First of all, be bold: although risk assessments and impact forecasts seem to be beyond the remit of meteorologists and hydrologists, there are very few others that hold expertise in hazard modeling and in running operational services. Collaborating in inter- and transdisciplinary teams with external partners and users will get the job done.
ii) Use a hazard-exposure-vulnerability mindset: when working with weather and climate data in any project, try to be aware of the potential risks, i.e., the exposure and vulnerability components, even if you are only interested in the hazard for now (Table 1). The weather and climate information should be considered as a potential hazard (in terms of structure) so it can be (re)used in an impact model outside your project or even outside your organization.
iii) Use an integrated HEV-model: a HEV-model is not an add-on of your current activities, it is a way of integrating your current activities into a larger picture. A suitable model integrates your current hazard forecast and warning system and allows you to switch seamlessly between hazard and impact/risk forecasts and warnings–if desired. A HEV-model also works seamlessly from the weather to the climate scale (Table 1).
iv) Think about (strategic) collaborations early on, as BO matter in providing products and services to public and private actors. Research institutions can help, but it will ultimately be BO who can deliver the required services.

How to start - first steps:

1) How to create a basic running HEV-system? Look around for existing HEV-models, see refs. (Bresch and Aznar-Siguan, 2021; Oasis Loss Modelling Framework, n.d.). Pay attention to their usability (open-source code/license of usage, comprehensive documentation, compatibility with your system, potential collaboration with other NMHSs), applicability (relevant use cases/demonstrators available incl. scientific publications, possibility for extension) and reliability (broad and active developer and user community, active code maintenance, helpdesk available). Check the requirements needed to integrate the code on your system? Has someone integrated this model under similar circumstances before? Install the model and try to reproduce existing use cases and adapt them to your needs.
2) First impact assessments: Impact assessments become useful if done in collaboration with accredited partners, relevant agencies, or users. Look around for relevant partners and engage in a co-design process from the very start. Only then will the product be useful and used.
3) Extending your impact portfolio: as many studies, use cases or data sources already exist in the global impact model community, you need a strategy of how to build on this knowledge without starting from scratch every time. E.g., the CLIMADA model (Bresch and Aznar-Siguan, 2021) provides running use cases solely based on open-source data that can be adapted to your needs. This guideline of if and how to use certain knowledge or expertise should revolve around following questions: how to evaluate published studies/use cases for usability? Do their output

metrics coincide with your user requirements? Have the studies/use cases been validated? Do you have access to relevant validation/verification data for your application? Do you have access to relevant exposure/vulnerability data? Has the use case been operationalized? What is the outcome?
4) Make robust, future-ready decisions: integrating impacts into a NMHS is a new and rapidly developing field. To make a robust decision now means to establish concepts and technological solutions that can be flexibly adjusted to the yet unspecified requirements of the future.
5) Spread the word: talk about your experiences, share your developments open-source, publish your work and thereby help others.
6) Carefully assess the potential of existing collaborations (e.g., with emergency services) to build on and new ones to establish (e.g., with engineering consultancies serving their clients managing risks).

6 Conclusion and outlook

Prospectively, operating a HEV-model and integrating it into operational warning and climate services of a NHMS requires adaptations in the well-established procedures. Operational forecasters have always been using a HEV-mindset implicitly, especially when issuing warnings. Having an objective HEV-system in operation still poses a great change for forecasting operations and also for the structures and mindsets of the recipients of the HEV products and forecasts. This is especially valid with respect to communication and further processing of HEV products instead of processing traditional hazard information.

By gathering hands-on recommendations and a set of first steps from the authors' experiences, we hope to provide an insightful contribution to a timely discussion on an international level.

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.

Author contributions

TG: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Supervision. TR: Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. DB: Conceptualization, Writing – review & editing. BE: Methodology, Writing – review & editing. AF: Conceptualization, Writing – review & editing. DI: Methodology, Writing – review & editing. SK: Conceptualization, Methodology, Writing – review & editing. LM: Writing – review & editing. GM: Conceptualization, Writing – review & editing. RS: Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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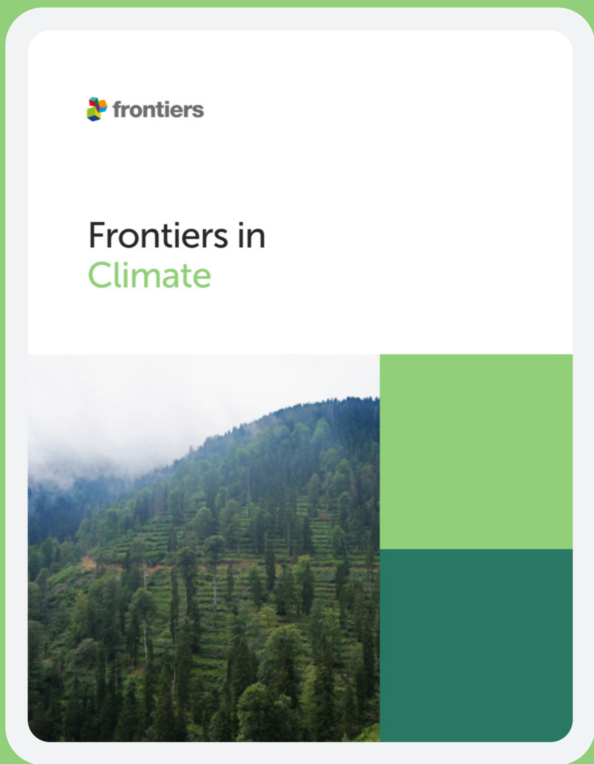

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