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Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends

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This paper shows recent progress in our understanding of climate variability and trends in the Amazon region, and how these interact with land use change. The review includes an overview of up-to-date information on climate and hydrological variability, and on warming trends in Amazonia, which reached 0.6–0.7°C over the last 40 years, with 2016 as the warmest year since at least 1950 (0.9°C + 0.3°C). We focus on local and remote drivers of climate variability and change. We review the impacts of these drivers on the length of dry season, the role of the forest in climate and carbon cycles, the resilience of the forest, the risk of fires and biomass burning, and the potential "die back" of the Amazon forests if surpassing a "tipping point". The role of the Amazon in moisture recycling and transport is also investigated, and a review of model development for climate change projections in the region is included. In sum, future sustainability of the Amazonian forests and its many services requires management strategies that consider the likelihood of multi-year droughts superimposed on a continued warming trend. Science has assembled enough knowledge to underline the global and regional importance of an intact Amazon region that can support policymaking and to keep this sensitive ecosystem functioning. This major challenge requires substantial resources and strategic cross-national planning, and a unique blend of expertise and capacities established in Amazon countries and from international collaboration. This also highlights the role of deforestation control in support of policy for mitigation options as established in the Paris Agreement of 2015.

Keywords: Amazonia, El Niño, climate variability, deforestation, tipping point, moisture transport, rainfall, climate modelling

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INTRODUCTION

In this paper we review some aspects of climate variability and change in the Amazon region in light of new developments. We focus on climate drivers of variability and change, including natural climate variability and land-use changes, their impacts on the length of dry season, the role of the forest on climate and carbon cycles, the resilience of the forest, and the risk of fires. In addition, the "die back" of the Amazon forests when surpassing a "tipping point" and its associated uncertainties are also discussed. Lastly, we also touch on some experiences of adaptation to hydroclimate extremes as well as mitigation options such as reducing deforestation as established in the Paris Agreement of 2015.

This article is organized as follows: Section 1 included the description of how the climate system over Amazonia works, including modes of variability, hydroclimatic extremes, changes in the dry season, moisture transport and moisture recycling; Section 2 shows how climatic changes interact with other on-going processes and the potential effects of different stressors on Amazon forests such as fire, and land use change due to deforestation; Section 3 shows an evolution on model development for climate change studies and explains how the climatic system is changing, as well as shows the future of Amazon forests look like in a "die back scenario" when surpassing the critical threshold on temperature or deforestation, as well as the associated uncertainties in these climate projections. Finally, Section 4 discusses, among other things the grand questions on Amazon climate variability and change that need to be explored in more detail, including strengths and limitations of the current knowledge we have on Amazon climate variability and change, climate modeling, human influences and land use change in the region.

OVERVIEW ON CLIMATE SYSTEM AND CLIMATE VARIABILITY IN THE AMAZON REGION

The Amazon basin covers an area of about 7 million km^2. Amazon forests cover about 5.3 million km^2, which represents 40% of the global tropical forest area (Laurance et al., 2001; Aragão et al., 2014; Nobre, 2014; Weng et al., 2018). Its abundant rainfall of about 2200 mm y^{-1} makes the Amazon basin an important latent heat source for the atmosphere, generating an estimated 210,000 m^3·s^{-1} to 220,000 m^3·s^{-1} of river discharge from the Amazon River, which represents about ~15% of the freshwater input into the oceans (Callède et al., 2012; Marengo and Espinoza, 2016; Nobre et al., 2016). The Amazon River exhibits interannual and long-term climate variability due to rainfall variations and this translates into large variations in downstream discharge (Richey et al., 1989; Zeng et al., 1996; Zeng, 1999; Milly et al., 2005; Cox et al., 2008; Marengo et al., 2008a,b; Espinoza et al., 2009a,b; Marengo and Espinoza, 2016; Sampaio et al., 2018). The Amazon ecosystems host about 10–15% of land biodiversity (Lewinshohn and Prado, 2002; Hubbell et al., 2008) and it stores an estimated 150 billion to 200 billion tons of carbon (Malhi et al., 2006; Cerri et al., 2007; Saatchi et al., 2011).

Since the initial work by Salati et al. (1979), various studies show the importance of the Amazon forests, playing a crucial role in the climate system by means of moisture recycling and contributing to atmospheric circulation and to the water, energy and carbon cycles (Zemp et al., 2014, 2017b; Spracklen and Garcia-Carreras, 2015; Nobre et al., 2016; Sampaio et al., 2018; among others). The spatial and temporal variability of rainfall and hydrology in the Amazon basin have also been discussed, including the influence of El Niño/La Niña or SST anomalies in the Tropical North Atlantic on natural climatic variations (Jiménez-Muñoz et al., 2016; Marengo and Espinoza, 2016; Sorribas et al., 2016), and projections of future climate change for the coming decades (Magrin et al., 2014; Sampaio et al., 2018). These studies build on an already solid scientific basis on the relationship between Amazon forest and climate variations, the impact of land use and land cover change, and how they change the water resources in the region.

Long-Term Climate Trends in Amazonia

The Amazon region is viewed as being at great risk from climate variability and change. The risk is not only due to projected climate change but also through synergistic interactions with other threats, such as land clearance, forest fragmentation, and fire detected in the present. A key question is whether a general long-term trend exists during recent decades toward drought conditions and, if so, whether it is associated with anthropogenic climate change such as deforestation. Furthermore, fire occurrence could increase the vulnerability of tropical forest ecosystems in the Amazon region. Even a single fire can contribute to forest fragmentation and spread of fire prone biomes (Alencar, 2004; Barlow and Peres, 2004, 2008; Brando et al., 2014; Gatti et al., 2014; Alencar et al., 2015; Aragão et al., 2018; Silva C.V.J. et al., 2018). In the following we review some of the evidence of change linked to natural climate variability and to land-use change.

Observational studies show an increase in the mean air temperature in the Amazon region of 0.6°C from 1973 to 2013 (Almeida et al., 2017). Previously, Jiménez-Muñoz et al. (2016) detected a warming of 0.5°C since 1980, with stronger warming during the dry season over the southeastern Amazonia. **Figure 1** shows the observed warming in the region derived from various data sets since 1950. Warming reached 0.6–0.7°C over the last 40 years, with 2016 as the warmest year since at least 1950 (0.9°C + 0.3°C). While there are some systematic differences among the trends, all sources show that the recent two decades were the warmest, with 2016 as the warmest year followed by 1998. Both of these years were El Niño years.

No long-term unidirectional total rainfall trends have been identified (Marengo, 2004; Espinoza et al., 2009a; Satyamurty et al., 2010; Almeida et al., 2017) in the region. However, a positive trend in precipitation detected in northwestern Amazon since 1990 may be a consequence of the intensification of the hydrological cycle in the region (Gloor et al., 2013). Furthermore, Alves (2016) detected a statistically significant negative rainfall trend in southern Amazonia during the pre-rainy season and the peak of the rainy season during 1979–2014. Recent work by Espinoza et al. (2018) shows that while southern Amazonia exhibits negative trends in total rainfall and extremes, the opposite is found in Northern Amazonia.

The forest has an important role in maintaining local and regional rainfall, contributing to the hydrological cycle by means of recycling and transport of moisture inside and outside the

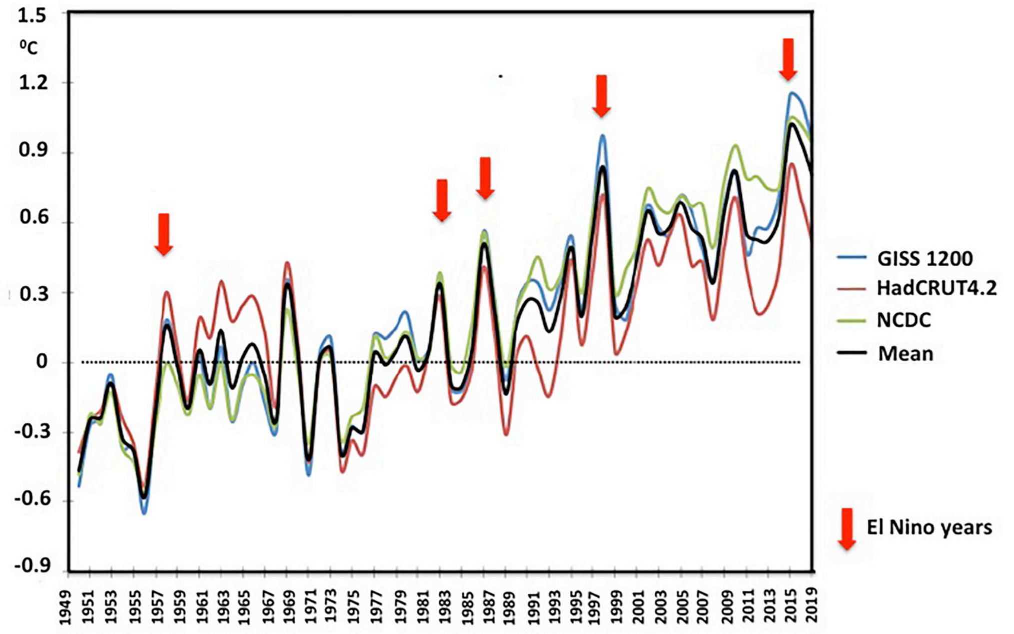

FIGURE 1 | Average surface air temperature anomalies (°C) over the Amazon region for 1949–2017 relative to 1961–1990. Red arrows indicate El Niño years. Sources of data are: GISS-NASA Goddard Institute for Space Studies, EUA (blue line); NCDC-National Climatic Data Center, EUA (green line); HadCRU-Hadley Centre-Climate Research United Kingdom (red line); average over all data sets (black line).

region. Moisture is transported from Amazonia to regions such as Southeastern South America by means of the low level jet to the east of the Andes that forms part of the regional circulation (Marengo et al., 2004; Arraut et al., 2012). Although climate change can affect this moisture flux from Amazonia (Soares and Marengo, 2009), deforestation resulting from intensive land-use activities poses a more immediate threat to the Amazon forests (Aragão et al., 2018; Sampaio et al., 2018). Climate modeling studies simulating Amazon deforestation show significant reductions in rainfall in Amazon forests, affecting regional hydrology and thus increasing the vulnerability of ecosystem services for the local and regional population in and outside the Amazon region (see next sections). This highlights the connection between the Amazon forests, rainfall and human well-being.

Satellite measurements, field observations and climate models suggest that the impact of deforestation on climate on longer time scales may depend on: a threshold of forest area converted by deforestation; the spatial arrangement of forests surrounded by deforested area, i.e., its matrix effect; different land-use practices; and external forcing caused by global-scale climate change (Lawrence and Vandecar, 2015). At the global scale, Haddad et al. (2015) show that deforestation generates habitat fragmentation that can reduce biodiversity by 13–75%, and impair key ecosystem functions by decreasing biomass and altering nutrient cycles. Various studies (Nobre and Borma, 2009; Marengo et al., 2010a,b, 2011; Davidson et al., 2012; Anadon et al., 2014; Duffy et al., 2015; Nobre et al., 2016; Lovejoy and Nobre, 2018) suggest changes in climate and climate variability may affect parts of the Amazon basin that are susceptible to biome shifts (Lapola et al., 2009), biodiversity loss and depletion of carbon storage. Sampaio et al. (2007) suggest that a threshold value of 40% regional deforestation could be a "tipping point" followed by a sudden change of climate in the region to a warmer and drier climate. For small patches of deforestation in extensive forest areas, studies point to increased precipitation in deforested areas and "small" changes in local climatic conditions, i.e., evapotranspiration, mean temperature, rainfall frequency (D'Almeida et al., 2006, 2007). However, such small-scale deforestation does not predominate in the region (Ewers and Laurance, 2006; Rosa et al., 2012).

Recent extreme climatic events in the region, such as droughts and floods, changes in the rainy and dry seasons, increased fire risk with associated their impacts on climate, health, and biodiversity are examples of what could happen in Amazonia as a consequence of climate change (Espinoza et al., 2011, 2012a,b; Jiménez-Muñoz et al., 2013, 2016; Gatti et al., 2014; Duffy et al., 2015; Erfanian et al., 2017; Aragão et al., 2018). Three "mega-droughts" in 2005, 2010 and 2016 (Jiménez-Muñoz et al., 2016; Marengo and Espinoza, 2016; Zou et al., 2016) were events classified at the time of their occurrence as "one-in-100 year event". Past mega-droughts were registered in 1925–1926, 1982–1983, and 1997–1998 due to El Niño (Tomasella et al., 2011, 2013; Marengo and Espinoza, 2016). In contrast, "mega-floods" were detected in 2009, 2012, and 2014 (Chen et al., 2010; Vale et al., 2011; Marengo et al., 2012a,b; Sena et al., 2012; Coelho et al., 2013; Espinoza et al., 2013, 2014; Satyamurty et al., 2013a,b) pointing to increased climate variability. Their observed impacts on natural and human systems in the region demonstrate the vulnerability of population and ecosystems to the occurrence of such hydro-meteorological extremes in the region. Moreover, climate-induced changes in the extent or character of the forest could themselves exert a feedback on climate change, both through effects on the regional climate and on global warming itself via the carbon cycle (Betts et al., 2004). In addition to being a major driver of global warming, increasing concentrations of carbon dioxide could impact the regional climate of the Amazon by reducing the return of moisture to the atmosphere by evapotranspiration (Betts et al., 2004).

The attribution of these droughts or floods and their impacts on nature and society are still not totally resolved. For drought, the risk of subsequent ire depends on the timing of the beginning and demise of the rainy season and on the length of the dry season. Droughts can have natural causes via changed climate-ocean interactions and lead to climate extremes (2005, 2010, 2016). However, human activities related to deforestation can cause high fire years (2004 and 2016), and coincide with extreme dry years (2016) as shown by Aragão et al. (2018). Deforestation, increases in greenhouse gasses and changes in land-surface characteristics associated with human-caused fires leads to the release of more aerosols which in combination with urban pollution may influence precipitation formation, thus affecting variability in the region's rivers (Summers et al., 2004; Magrin et al., 2014; Spracklen and Garcia-Carreras, 2015; Marengo and Espinoza, 2016). Initial work by Andreae et al. (2004) suggests that biomass-burning aerosols in the Amazon region can delay the onset of the rainy season in southern Amazonia. Later on, Gonçalves et al. (2015) pointed out that regional climate over the region can be significantly affected by aerosol particles. Recent work by Esquivel-Muelbert et al. (2018) show that within the Amazon region, the increase in atmospheric CO2 is driving a shift within tree communities to large-statured species and that climate changes to date will impact forest composition,

Climate Variability and Hydroclimatic Extremes

The annual cycle of precipitation varies across the region. As shown in Figueroa and Nobre (1990) and Fisch et al. (1998), rainfall in southern Amazonia peaks during austral summer while in central Amazonia and near the Amazon delta it peaks in the autumn, and north of the Equator it peaks in austral winter. The physical cause is the meridional migration of the Intertropical Convergence Zone (ITCZ). While Northwest Amazonia is the wettest and shows no dry season, rainfall in southern Amazonia shows months during the austral winter with rainfall that can be lower than 100 mm. As a consequence of the seasonal cycle in rainfall, the Amazon River main stem and tributaries show the peak of river levels few months after the peak rainfall season. The river level and discharge both depend on the precipitation in the rainy season during the previous wet season. Rivers that extend over southern Amazon basin (e.g., Solimões, Madeira) peak in April-May while rivers with basins in the central Amazon basin (e.g., Rio Negro) peak in May-June. For more details about rainfall and river regimes in the Amazon basin, please refer to Marengo et al. (2014) and Marengo and Espinoza (2016) and references therein.

Observations of evapotranspiration (ET) vary from 3.5 $mm \cdot d^{-1}$ to 4 $mm \cdot d^{-1}$ (105 $mm \cdot mo^{-1}$ to 120 $mm \cdot mo^{-1,}$ respectivelly) as shown by Shuttleworth (1988). This value is lower than rainfall in the dry months, where precipitation is below 100 $mm \cdot mo^{-1}$, value that defines a dry month by Sombroek (2001). If ET exceeds incoming precipitation P the forest is in water deficit and drought conditions can be identified. Several studies have documented droughts in the Amazon region in the past, and they have been related to negative rainfall anomalies, in some cases as a direct consequence of El Niño events, such as in 1912, 1926, 1983 and 1997–1998 and recently in 2016 (Williams et al., 2005; Jiménez-Muñoz et al., 2016; Marengo and Espinoza, 2016; Panisset et al., 2017). However, the severe droughts in 1964 and 2005 were related to a warmer than normal tropical North Atlantic Ocean (Uvo et al., 1998; Marengo et al., 2008a,b; Zeng et al., 2008). In addition, intense floods have happened in Amazon basin during the last decades, as in 1989, 1999, 2009, 2012 and 2014 (See reviews in Marengo and Espinoza, 2016 and references therein).

These drought and flooding events have produced impacts such as increased risk of forest fires, extreme warming, floods and inundations, which can affect the human population and flora and fauna on land as well as in lakes and rivers (e.g., Davidson et al., 2012; Marengo et al., 2013; Brando et al., 2014; Doughty et al., 2015). While droughts increase the risk of tree mortality, the combination of severe droughts and floods can put additional stress on Amazon forests, especially if the flooding regime of regularly inundated areas are perturbed outside of their natural range (Langerwisch et al., 2013). It also affects riverine carbon balance via outgassing of carbon from the Amazon River and the amount exported to the Atlantic Ocean, with non-linear effects to be expected if deforestation is also considered (Langerwisch et al., 2016). It is important to mention that the perception of drought and flood by the population may be different in Amazonia compared to other regions, and low or high river levels are better indicators of drought or floods, respectively compared to rainfall anomalies. Through their close dependency on water levels, local people are well placed to detect variability in both climate and hydrological regime and are able to respond to early warning signals to cope with potential impacts on their activities (Pinho et al., 2015).

Teleconnections patterns involving changes in SST anomalies in both the tropical Pacific and tropical Atlantic Ocean and changes in rainfall in Amazonia are shown in **Figure 2**. Driest years, when Amazonia experienced record droughts (1987, 1998, 2010, 2016) occurred during El Niño years, while the drought in 2005 occurred during a neutral year. Wet years (1989, 1999, 2009, and 2012), which produced floods, occurred during La Niña Years. Considering the SST forcing in the tropical Atlantic, dry years (2005, 2010, 2016) occurred during the period with a warmer Tropical North Atlantic Ocean (Shukla et al., 1990; Satyamurty et al., 2013a).

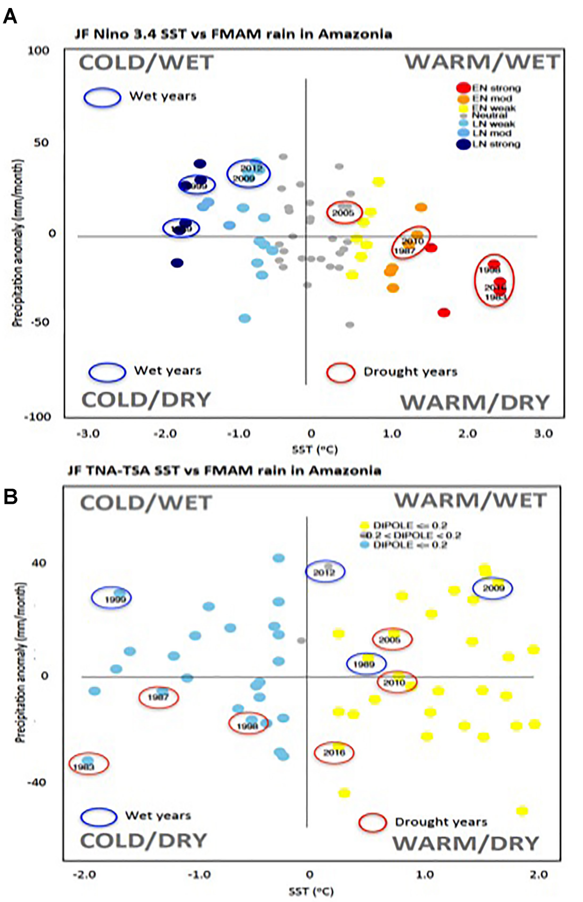

FIGURE 2 | Scatter diagrams of anomalies in the SST anomalies (°C) in the tropical Pacific (Nino 3.4) **(A)** and the SST dipole in tropical Atlantic (SST tropical North Atlantic–SST tropical South Atlantic) **(B)** during January–February and GPCC rainfall anomalies (mm/month) during the FMAM peak season in Amazonia. Base period for the SST and rainfall anomalies is 1961–1990. Drought and wet years in Amazonia are shown by numbers and the stronger events appear inside circles (Modified from Marengo et al., 2013, © American Meteorological Society. Used with permission).

Early work by Sternberg (1987); Meggers (1994), and Williams et al. (2005) reports that during the drought in 1926 an intense heat wave killed fish, and favored fires lasting several months which killed thousands of rubber gatherers. Later on, 2005 and 2010 drought-induced water stress was so intense that it killed large trees, increasing the number of forest fires and releasing large amounts of carbon to the atmosphere (Marengo et al., 2008a,b; Lewis et al., 2011; Marengo et al., 2011; Dos Santos et al., 2017).

The 2015–2016 El Niño saw record-breaking warming in the Amazon region (**Figure 1** and Jiménez-Muñoz et al., 2016), as well as the most extensive area under extreme drought with up to 13% of the rainforests undergoing extreme drought in February-March 2016 (Aragão et al., 2018). Erfanian et al. (2017) show that the ecohydrological consequences from the 2016 drought were more severe and extensive than the 2005 and 2010 droughts. They suggested that warmer-than-usual SSTs in the Tropical Pacific and Tropical Atlantic were not able to explain the severity of the 2016 drought, and pointed out that land cover change in the form of deforestation and human-induced warming may have strongly influenced it. The drought of 2016 also reduced forest net primary productivity and increased canopy tree mortality, thereby altering both the short- and the long-term net forest carbon balance (Leitold et al., 2018).

Changes in the Length of the Dry Season

Various studies have shown evidence of lengthening of the region's dry season, primarily over the southern Amazon region (see Marengo et al., 2017 and references therein). The reasons for this lengthening are still not clear. This tendency can be related to large-scale influence of SST gradients of the North and South Atlantic, or a strong influence of dry season ET in response to a seasonal increase of solar radiation (Fu and Li, 2004; Li et al., 2006; Butt et al., 2011; Lewis et al., 2011; Dubreuil et al., 2012; Fu et al., 2013: Alves, 2016; Marengo et al., 2017). However, current data show that the dry season has increased by about 1 month in southern Amazon region since the middle 1970's up to present day (**Figure 2**).

In the drought years 2005, 2010 and 2016, as well as in previous droughts, the rainy season started late and/or the dry seasons lasted longer (Marengo et al., 2011; Alves, 2016). Fu et al. (2013) quantified this apparent lengthening of the dry season, with an increase of about 6.5 ± 2.5 days per decade over the southern Amazon region since 1979. During the 2016 drought, the onset of the rainy season in 2015 occurred 2–3 pentads later than normal (Marengo et al., 2017). Furthermore, the length of the dry season also exhibits interannual and decadal-scale variations linked either to natural climate variability (**Figure 3**), or as suggested by Wang et al. (2011) and Alves et al. (2017), the influence of land-use change in the region.

A longer dry season and thus, late onset of the rainy season may have direct impacts on the risk of fire and on the hydrology of the region, enhancing regional vulnerability to drought. Wright et al. (2017) highlight the mechanisms by which interactions among land surface processes, atmospheric convection, and biomass burning may alter the timing of wet season onset. Furthermore, they provide a mechanistic framework for understanding how deforestation and aerosols produced by late dry season biomass burning may alter the onset of the rainy season, possibly causing a feedback that enhances drought conditions. Recent work by Agudelo et al. (2018) shows that longer dry seasons in southern Amazonia also relate to enhanced atmospheric moisture content over the Caribbean and northern South America regions, mainly due to increased contributions of water vapor from oceanic regions and the increase of surface moisture convergence over the equatorial region.

Moisture Recycling and Moisture Transport in and Out of the Amazon Region

On the local and regional scales, the Amazon forest exerts control on rainfall and temperature through ET, in a process

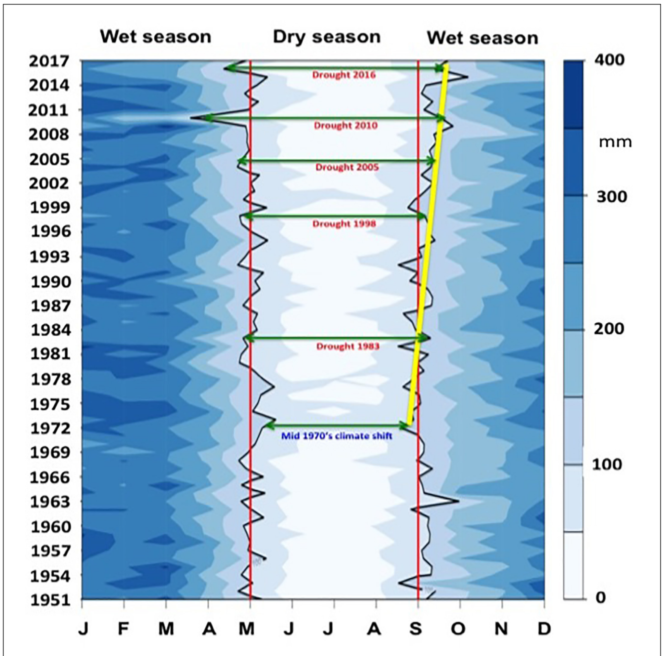

FIGURE 3 | Hovmoller diagram showing monthly rainfall from 1951 to 2017 for Southern Amazonia (mm/month). The isoline of 100 mm/month is an indicator of dry months in the region (Sombroek, 2001). Drought years are indicated with green lines. Red lines show the average onset and end of the rainy season (Adapted from Marengo et al., 2011 and updated to 2017). Yellow line shows the tendency for a longer dry season after the mid 1970's climate shift (Modified from Marengo et al., 2011, © American Geophysical Union. Used with permission).

known as "moisture recycling." Several studies have quantified the water balance in the Amazon basin, and despite uncertainties due to different measuring techniques, estimates of ET widely range from about 35% to over 80% of the precipitation (Lettau et al., 1979; Salati et al., 1979; Salati and Vose, 1984; Dickinson and Henderson-Sellers, 1988; Lean and Warrilow, 1989; Nobre et al., 1991; Salati and Nobre, 1991; Dickinson and Kennedy, 1992; Brubaker et al., 1993; Henderson-Sellers et al., 1993, 2002; Eltahir and Bras, 1994; Marengo et al., 1994; Polcher and Laval, 1994a,b; Sud, 1996; Vorosmarty et al., 1996; Zeng et al., 1996; Hahmann and Dickinson, 1997; Lean and Rowntree, 1997; Costa and Foley, 1999, 2000; Trenberth, 1999; Marengo, 2004, 2005, 2006; Voldoire and Royer, 2004; van der Ent et al., 2010, 2014; van der Ent and Savenije, 2011; Zemp et al., 2014). Furthermore, van der Ent et al. (2010) estimated that 70% of the water resources of the La Plata River basin depend on evaporation over the Amazon forest.

Basin-wide and long-term water balances based on observations of precipitation and Amazon River discharge constrain the ET/P ratio to about 0.45–0.60 (e.g., Salati and Vose, 1984; Nobre et al., 1991, among others). van der Ent et al. (2010) estimated this fraction as 48% for the Amazon region. This aspect is even more relevant considering that in some areas ET in the dry season tends to be equal to or higher than wet-season ET (e.g., Shuttleworth, 1988). The high water vapour flux generated by the forest's evapotranspiration during the dry season would therefore play an important role in the onset of the rainy season (Fu and Li, 2004).

In addition to the *in situ* contribution to the moisture transport, during the wet summertime season, the moisture from the Amazon basin is exported out of the basin via the South American low-level jet along the east flank of the Andes to the La Plata River basin in Southeastern South America. This low level jet is also referred to as "flying river" – Nobre (2014) or "aerial river" – Arraut et al. (2012) as an analogy to surface rivers, and contributes to precipitation over the La Plata basin (Marengo et al., 2004; Marengo, 2005; Arraut and Satyamurty, 2009; van der Ent et al., 2010; Arraut et al., 2012; Satyamurty et al., 2013b; Zemp et al., 2014).

Work by Bosilovich and Chern (2006), Drumond et al. (2008, 2014), van der Ent et al. (2010), and Sorí et al. (2018) has identified continental and oceanic moistures sources for rainfall in the Amazon region and its sub-basins, and they conclude that the tropical Atlantic is the most important remote moisture source for the Amazon Basin. Inside the Amazon region, Sorí et al. (2018) confirms the moisture contribution from the Tropical North Atlantic region modulates the onset and demise of the rainy season in the Rio Negro Basin. For the Madeira River Basin, the most important moisture contribution comes from the basin itself and surrounding regions of Tropical South America. The intensification of the hydrological cycle in the Amazon region has been observed in the last decades by Gloor et al. (2013) and is partly explained by changes in moisture transport coming from the tropical Atlantic, caused by SST-induced northward displacement of the ITCZ (Marengo et al., 2008a,b, 2013). Angelini et al. (2011) have also shown that rainfall in the Amazon region comes primarily from large-scale weather systems from the tropical Atlantic and that it is not directly driven by local evaporation.

It is still difficult to attribute changes in regional circulation and moisture transport to deforestation. Zemp et al. (2017b) states that the self-amplifying drying effects lead to forest loss in 11–19% of the forest area due to intensified dry season and drought events. This means that when the links from moisture transport into the Amazon basin are cut, drying intensifies and increases forest loss further. However, while this analysis explains a link between moisture transport and deforestation, it cannot be used as an explanation of the intensification of the hydrological cycle.

The fundamental role of the forest in the regional moisture transport and balance has been discussed in the context of a novel theory – the "biotic pump" – that suggests that local evaporation and condensation can exert a major influence over atmospheric dynamics (Makarieva and Gorshkov, 2007, 2009, 2010; Makarieva et al., 2013; Sheil, 2018). This theory proposes that high rainfall can be maintained within those continental landmasses that are sufficiently forested, and suggests that the water vapor delivered to the atmosphere via evaporation from forests represents a store of potential energy available to accelerate air and thus drive winds. Therefore, following this theory, cutting atmospheric moisture transport and respective recycling of precipitation due to deforestation in climate-critical regions may induce a self-amplified drying process which would further destabilize the Amazon forests in downwind regions, i.e., the south-western and southern Amazon region, but also influence moisture arriving at the La Plata basin (Zemp et al., 2017a). With 40% of the area of the Amazon deforested, local annual precipitation would be reduced by 5–10% in the Amazon basin (Zemp et al., 2017b).

Following Arias et al. (2018), understanding the interplay between climate variability and land cover is fundamental to the conservation and sustainable management of tropical river basins, where forests play an important role in regional water and carbon cycles. This is particularly true in the Amazon region, where deforestation and climate variability threaten to cause major environmental and hydrological changes at regional, continental, and global scales (Malhi et al., 2008; Davidson et al., 2012; Coe et al., 2013).

POTENTIAL EFFECTS OF DIFFERENT STRESSORS (LAND USE CHANGE, FIRES) ON AMAZON NATURAL AND HUMAN SYSTEMS

Land Use Change: Deforestation as a Socio-Climatic Problem

Development in the Amazon region has pushed the agricultural frontier, resulting in widespread land-cover change. As agriculture in the region has been of low productivity and unsustainable, the loss of biodiversity and continued deforestation will lead to high risks of irreversible change of the Amazon forests (Ometto, 2011; Nobre et al., 2016). In the Amazon countries, at an underlying level, deforestation is caused by multiple factors acting synergistically, e.g., economic factors such as low internal costs (for land, labor, fuel or timber), and the increase in the price of products (especially cash crops or timber). Institutional factors include formal measures that favor deforestation, land use policies and economic development programs associated with colonization, transport, and subsidies for land-based activities (RAISG, 2015). Existing land-tenure systems and failed policies (like the corruption or mismanagement of the forestry sector) are also important drivers of forest loss (Geist and Lambin, 2002). For the entire Amazon region, the Rede Amazonica de Informacion Socio Ambiental Georeferenciada-RAISG (RAISG, 2015) shows that deforestation rates in the entire Amazon from all Amazon countries region reached 118,530 km^2 in 2000–2005; 77,809 km^2 in 2005–2010 and 47296 km^2 in 2010–2015, and Brazil is the country with the highest loss in absolute terms, both in historical and recent deforestation (**Table 1**). Work by Kalamandeen et al. (2018) identify hotspots of Amazonian forest loss are moving away from the southern Brazilian Amazon to Peru and Bolivia.

The PRODES (Monitoramento do Desmatamento na Amazônia Legal por Satélite) program provides annual estimates of deforestation for the entire Brazilian Amazon since 1988 based on 30m-resolution Landsat satellite images (Instituto Nacional de Pesquisas Espaciais [INPE], 2015). There has been a marked decline in deforestation in the Brazilian Amazon over the last decade, where deforestation was reported to have fallen from a record 27,772 km^2 in 2004 (consequence of cattle ranching) to 4,571 km^2 in 2012 (**Figure 4**). Meanwhile, a rebound of the deforestation rate has been observed since 2013 (Hansen et al., 2013; Aragão et al., 2018) and in 2015–2016, during the El Niño-related drought the clearing reached about 8,000 km^2 (higher than in 2014–2015) of primary forests. The combination of law enforcement, close monitoring and the soy and beef moratoria were contributing to the decline in deforestation rates in the Brazilian Amazon (Nepstad et al., 2004, 2008, 2014, Godar et al., 2014). In fact, land-use change and shifts in land-uses after deforestation show spatial heterogeneity in the Amazon region (Müller-Hansen et al., 2017). These findings point to an important interplay of governance, monitoring and policy-making requiring the involvement of all important actors to reach, for example, a zero-deforestation goal or reduce forest degradation. These estimates are somewhat different pattern from the PRODES data for Brazil due mainly to differences in methodologies to calculate deforested areas.

Deforestation within the Amazon region is one of the driving forces for climate change in the region (Aragão et al., 2018; Sampaio et al., 2018). Spracklen and Garcia-Carreras (2015) suggest that considering deforestation rates prior to 2004, this could lead to a 8.1 + 1.4% reduction in the annual mean Amazon basin rainfall by 2050, which is greater than the natural variability. Recent work by Spracklen et al. (2018) reviews the current understanding of the processes through which tropical land-cover change affects rainfall, and they show that tropical deforestation leads to reduced evapotranspiration, increasing surface temperatures by 1–3°C and causes boundary layer circulations, which in turn increases rainfall over some regions and reduces it elsewhere.

Land-use change has affected 1.4 million km^2, around 20% of the Amazon basin so far (Castello and Macedo, 2016). The peak of deforestation in the Amazon (around 2004), when

TABLE 1 | Deforestation in Amazon countries (km^2) (RAISG, 2015, updated to 2015).

Amazon country	Cumulative deforestation until 2000 (km^2)	Deforestation rate 200–2005 (km^2)	Deforestation rate 2005–2010 (km^2)	Deforestation rate 2005–2010 (km^2)
Bolivia	14,035	4,614	3,733	3,035
Brazil	458,500	101,138	57,399	30,003
Colombia	34,673	3,446	6,167	3,360
Ecuador	9,343	487	424	957
Guyana	3,097	785	821	1,138
French Guyana	1,539	295	257	354
Peru	55,649	6,680	7,225	5,164
Suriname	5,664	194	263	500
Venezuela	8,914	890	1,521	2,781
Total Amazonia	591,414	118,530	77,809	47,296

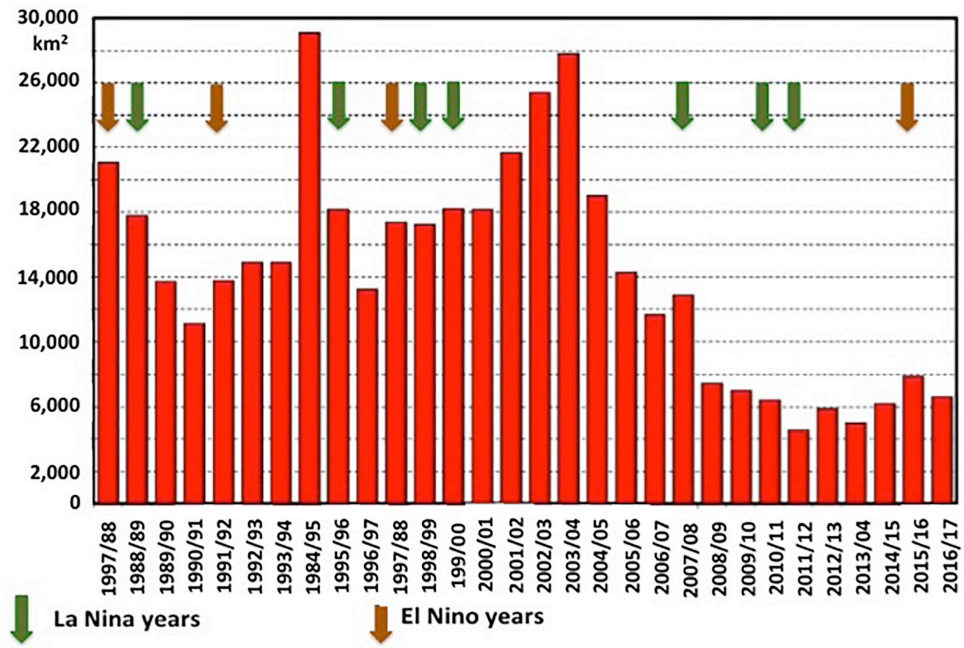

FIGURE 4 | Deforestation rates in the Brazilian Amazon region from 1988 to 2017 (Source: data from PRODES-INPE). Years with strong and very strong El Niño and La Nina events are depicted by brown and green arrows, respectively (Source: : ggweather.com/enso/oni.htm).

approximately 28,000 km^2/yr^{-1} was being cleared (Aragão et al., 2018), was primarily the result of cattle ranching (Nepstad et al., 2006), but soybean production has also been expanding (Barona et al., 2010; Settele et al., 2014; Silvério et al., 2015). Palm oil is one of the main biofuel crops, and while its current use is still relatively small, Brazil has the largest potential for expansion in South America and around half of the Amazon is suitable for its cultivation (Butler and Laurance, 2009; Magrin et al., 2014) but with the risk of higher sedimentation rates, and thus implications for riverine ecosystems (Silva C.V.J. et al., 2018).

Fires and Biomass Burning

The impacts of deforestation are greater under drought conditions, as fires set for forest clearance can become uncontrollable and burn larger areas, especially forests that have been previously logged (Cochrane et al., 1999; Asner et al., 2005; Soares-Filho et al., 2006; Alencar et al., 2015). Forest fires, drought, and logging increase susceptibility to further burning through fragmentation, flammability and ignition, while deforestation and smoke can inhibit rainfall, exacerbating fire risk. Therefore, the increase in the risk of forest fires represents an additional environmental driver of change in the Amazon region.

Almost all modern fires in the Amazon region are caused by human activities. However, natural fires have long played a critical role in determining the forest–savanna transition. Hirota et al. (2010) showed that for current climate conditions the tropical forest would penetrate 200 km into the savanna domain in the absence of fires. Drought-related mortality can result from other mechanisms, such as desiccation, reduced pest-defense mechanisms and fires (Brando et al., 2014), which may further reduce the forest resistance to droughts (Longo et al., 2018).

During the recent drought of 2015–2016 in Amazonia, Anderson et al. (2018) estimated that 46% of the Brazilian Amazon biome was under severe to extreme drought, compared with 16% and 8% for the 2010 and 2005 droughts, respectively. They suggest that forests in the twenty-first century are becoming more vulnerable to droughts, with larger areas intensively and negatively responding to water shortage in the region.

The potential effects of fire as stressor on Amazon climate and forests depend on the rainfall distribution mainly in the "dry season." De Faria et al. (2017) identify major fires occur in different parts of the Basin, and they are more likely to occur in southern Amazonia, where deforestation is more intense (eg., the arc of deforestation located on that region), and also to water stress and higher temperatures due to a longer dry season as shown in previous sections. This is in agreement with recent rainfall and extreme rainfall trends identified in Amazonia by Espinoza et al. (2018), where l has been increasing on the recent decades in northern Amazonia, while in southern Amazonia, where and the rate of deforestation is relatively higher than in northern Amazonia, rainfall has been diminishing in time, consistent with a longer dry season as previous discussed.

For many years, fire was highly correlated with areas of deforestation in the Amazon. However, recent analysis by Cano-Crespo et al. (2015) showed that area burnt and deforestation now follow different trends, with 75% of forest fires that occur along forest periphery resulting from fires that escaped from neighboring pasture land. While there is a 76% decline in deforestation rates over the past 13 years, fire incidence increased by 36% during the 2016 drought compared to the preceding 12 years. The cumulative deforested area still play important roles in burned area, either by increasing the surface of flammable edges or decreasing fuel connectivity, this was the case of 2010 where much of the material that burned was due to the drought of 2005 (Gatti et al., 2014). The 2016 drought in the Amazon region had the largest ever ratio of active fire counts to deforestation, with active fires occurring over an area of 799,293 km^2, and extending beyond the arc of deforestation, impacting areas in central Amazon region that were barely affected by fires in the past (Aragão et al., 2018).

Any increase in fire frequency, whether associated with climate variability (e.g., El Niño), climate change, logging, or road construction is likely to trigger positive feedback mechanisms that promote establishment of fire-dominated, low-biomass forests (Barlow et al., 2003; Aragão et al., 2018). Conversely, deliberate limitation of deforestation and fire may be an effective intervention to maintain the resilience of Amazon forests in the face of imposed 21st Century climate change. This is technically and economically viable with intensification of cattle ranching and improved soil management in croplands, which does not require fires and clearing new forests to increase beef and crop productivity (Latawiec et al., 2014; Gibbs et al., 2015; Moutinho et al., 2016).

EVOLUTION OF MODEL DEVELOPMENT FOR SIMULATING LAND USE EFFECTS ON CLIMATE IN THE AMAZON REGION

Evolution of Climate and Land Use Modeling in Amazonia

Deforestation changes the energy, carbon and water balance, and the interaction between atmosphere and forest, and atmosphere and agricultural area. Such changes have been investigated in the Amazon region using global and regional climate models. The initial deforestation experiments in the 1980s using global climate models assumed unrealistically large perturbations, with scenarios of complete deforestation of the Amazon basin. These projections mostly resulted in warming and drying of the entire Amazon region in most of the models, although a few models showed warmer and wetter conditions in the region, suggesting that projections may depend also upon model parameterizations (See reviews in Zhang et al., 2001; Lawrence and Vandecar, 2015; Marengo and Espinoza, 2016; Chambers and Artaxo, 2017; Sampaio et al., 2018). These models have also been used to simulate scenarios of climate change, considering low and extreme conversion of forests by deforestation and an increase in greenhouse gasses concentration (Feddema et al., 2005; Badger and Dirmeyer, 2016).

Climate model experiments since that time have allowed the simulation and estimation of the difference in energy balance of forest areas caused by deforestation at various space-scales. Model experiments by D'Almeida et al. (2006, 2007) and Pitman and Lorenz (2016) indicate that deforestation impacts at other scales, i.e., local, regional, and meso-scale, would be significant. The scenario of complete loss of forest by deforestation is unlikely, but serves as a warning to society and decision-makers about the potential risks of deforestation under climate change. Kalamandeen et al. (2018) found that small scale (<1 ha) low-density forest loss expanded markedly in geographical extent during 2008–2014. Recent findings show a substantial proportion of tropical forests being fragmented and following a power law, where approx. 11% of the Amazon forest area are forest fragments smaller than 10000 ha (Taubert et al., 2018). These findings shift presents an important and alarming new challenge for forest conservation, despite reductions in overall deforestation rates. Additionally, forest degradation caused by selective logging, forest fires and forest fragmentation may reduce forest resilience to climate change (Malhi et al., 2009; Davidson et al., 2012; Brando et al., 2014; Castanho et al., 2016), which still needs to be investigated using climate models to capture feedbacks between climate, land and ocean.

When considering only the results of global climate models on a regional scale, i.e., on the Amazon scale, the impact of deforestation on climate is more severe. Studies reported by Magrin et al. (2014) derived from IPCC CMIP3 models point to an increase in annual mean temperature ranging from 0.1 to 3.8°C, and a reduction of 10–30% in annual precipitation, which would lead to changes in the climatic seasons both locally and regionally or the A1 scenario (high emissions). Spracklen et al. (2012) found that clearing 40% of the Amazon results in a 12% reduction in wet-season rainfall and a 21% reduction in dry-season rainfall across the Amazon basin. In any case, the magnitude of rainfall reduction and the location of the most affected regions are still uncertain (Joetzjer et al., 2013). Analyzing the water balance in the Amazon region, Llopart et al. (2018) shows that under the deforestation scenario the land surface processes play an important role by driving precipitation changes in western Amazonia.

Projected changes in annual rainfall for the region's 21st century climate show uncertainties, although results from multiple model predictions generally indicate reductions in eastern Amazonia and longer dry seasons, particularly in Southern and Eastern Amazonia (Malhi et al., 2008; Fu et al., 2013; Intergovernmental Panel on Climate Change [IPCC], 2014; Peripheral Blood Mononuclear Cell [PBMC], 2014; Boisier et al., 2015; Longo et al., 2018). This may increase the risk of recurrence of intense droughts and fires and would jeopardize the biome in the long term. This is explored in previous sections.

Based on CMIP5 models, warming projected for the entire Amazonia for RCP8.5 by 2100 reaches about 6°C (varying from 4°C to 8°C). At regional levels, **Figure 5** shows by the end of the century an increase in temperatures can reach even higher levels and reach approximately 6–7°C in eastern and southern

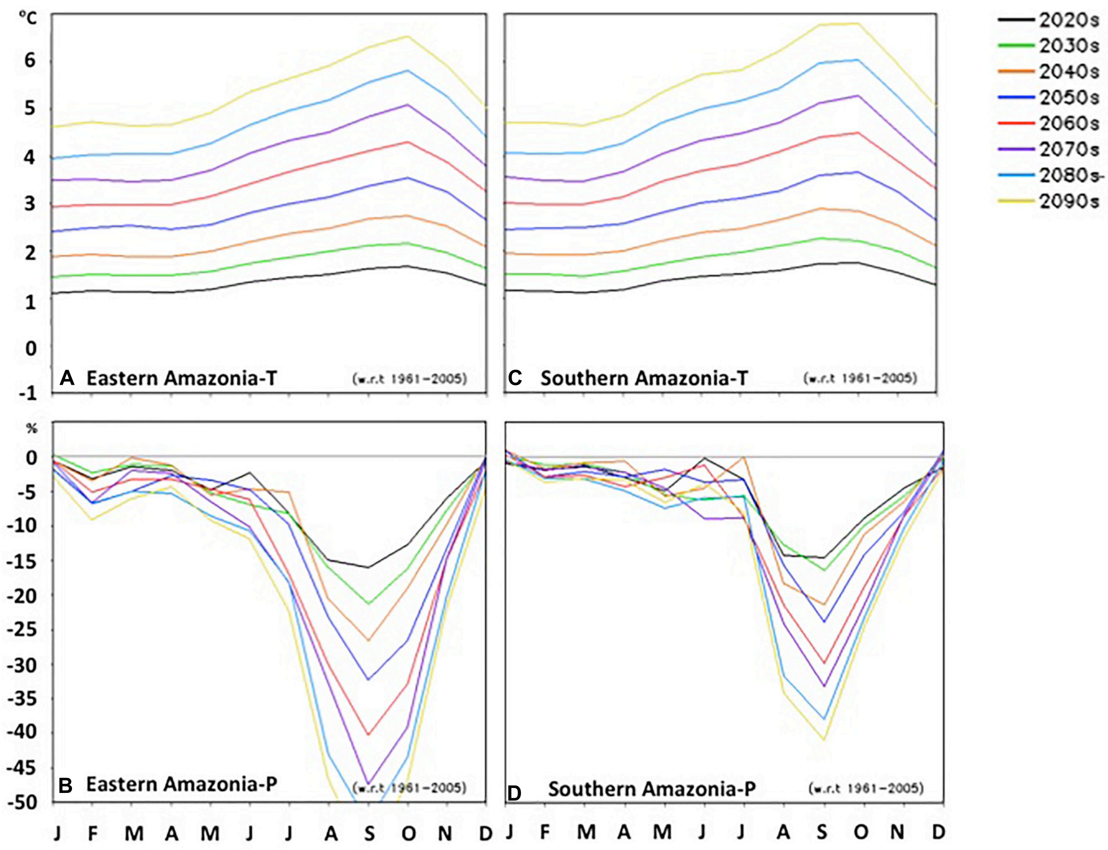

FIGURE 5 | CMIP5 multi-model ensemble projected air temperature (°C) and rainfall change (%) in annual cycle of precipitation in eastern (60°W – 48°W/10°S – 0°S) and southern Amazonia (70°W – 50°W/14°S – 5°S) under the RCP8.5 scenario for decadal time slices for the period 2020–2100 relative to the 1961–2005 baseline.

Amazon for the RCP8.5. The first decades of the twenty-first century also follow the tendency of increase according to the projections, but with a smaller magnitude, with an increase of up to 1°C already from the 2020 decade. For rainfall, they found that rainfall shows a reduction in precipitation for all months, and it is more pronounced during dry and transition season of July–November in southern Amazonia, which modifies the annual cycle. During the transition from dry season to wet season August–October, the projections show the sharpest proportional decline in precipitation, varying from 15% in 2020 to 40–55% by 2100 in both southern and eastern Amazonia for the RCP8.5, and implying a progressive prolongation of the dry season, resulting in a reduction in the length of the rainy season and possibly increasing the risk of fire. As shown **Figure 3**, a tendency for a lengthening of the dry season has been already observed in southern Amazonia since the 1970's.

Land use change in the future depends heavily on socio-economic factors, as reflected in the various IPCC RCP scenarios from CMIP5. High emission scenarios such as RCP8.5 project high land use conversion for agriculture, and high mitigation scenarios including RCP2.6 suggest high land use conversion for biofuels. Middle emissions scenarios such as RCP4.5 show reforestation across Brazil as a climate mitigation measure (**Figure 6**). Approaching zero-deforestation would reduce carbon emissions to a level that could be compensated by forest productivity until 2050 although uncertainties on the role of degraded forests and regrowth of secondary forests remain large (Aguiar et al., 2015; Aguiar et al., 2016).

Future scenarios of complete deforestation in the region result in a 10–20% decrease of the annual rainfall in the entire Amazonia (Moore et al., 2007). On larger scales, deforestation leads to reductions in moisture recycling, reducing regional rainfall by up to 40% (**Figure 5**). Results from projections of climate change scenarios from CMIP5 models with hydrological models from Abe et al. (2018) suggest that an increase in deforestation will intensify floods and low-flow events.

Using a Carbon and Land Use Change dynamic carbon model, De Faria et al. (2017) found that creased air temperature was the primary driver of changes in simulated future fire intensity, while reduced precipitation was secondary, particularly in the eastern portion of the Basin. As a consequence, fire-drought interactions strongly affect live carbon stocks and that future climate change, combined with the synergistic effects of drought on forest flammability, may strongly influence the stability of tropical forests in the future.

The Tipping Point and Die Back Scenario in the Amazon Region, Projections and Uncertainties

Drought impacts alone could be harmful enough for the maintenance of ecosystem integrity. Studies have pointed out that further deforestation and forest degradation will lead to dramatic biodiversity loss, increasing the risk of irreversible change of tropical forests (Barlow et al., 2016; Nobre et al., 2016). Previous studies on a partial rainfall exclusion and drought induced experiment suggested that the trees in a central Amazon forest avoided drought by absorbing deep soil moisture, but they also delayed the onset of drought through hydraulic redistribution of soil moisture and foliar uptake of dry season rainwater and dew (Nepstad et al., 2007; Brando et al., 2008; Da Costa et al., 2010; Rowland et al., 2014).

The combined effects of drought and deforestation, in combination with fire, have the potential to strongly amplify these impacts and potentially cause a collapse of the tropical rainforest ecosystem (Cox et al., 2000, 2004, 2008; Nobre et al., 2016). Model experiments using the CPTEC climate model by Oyama and Nobre (2003); Salazar et al. (2007), and Sampaio et al. (2007) have shown a transformation of the Amazon forest into a drier savanna-like biome. This suggests a threshold value of changes in temperature, CO_2 concentration or deforested area ("tipping points") to induce these changes in vegetation (the Amazon "dieback"). It has been suggested that the Amazon may have two "tipping points," namely, (1) a critical threshold of drought linked to global warming, or (2) deforestation exceeding 25% of forest area (Nobre et al., 2016; Lovejoy and Nobre, 2018) to 40% (Lenton et al., 2008).

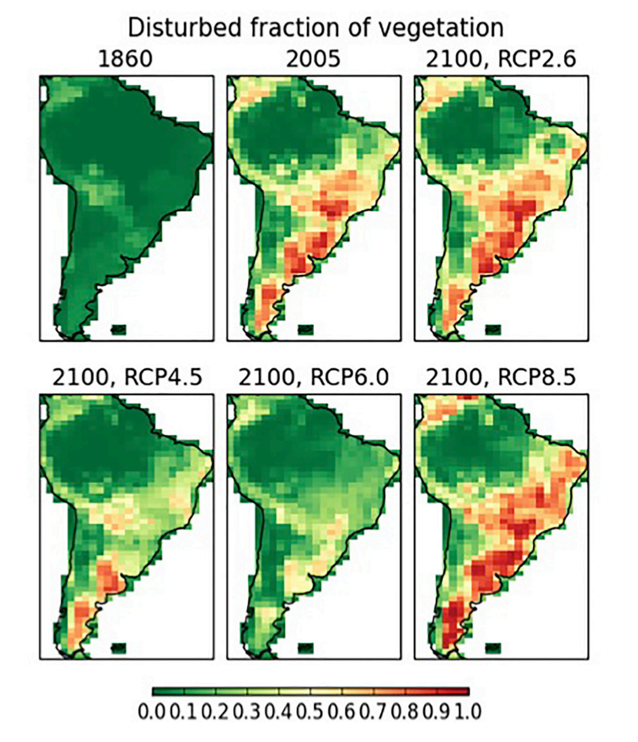

FIGURE 6 | Disturbed fraction of vegetation across South America simulated by the HadGEM2-ES Earth System Model, at 1860, 2005, and four future scenarios at 2100: RCP2.6 (high mitigation), RCP4.5, RCP6.0, and RCP8.5 (high emissions).

Recently, there have been discussions around the limits of deforestation, where beyond a certain threshold the forests may no longer be able to sustain their climate, and the biome could enter a state of collapse. Lovejoy and Nobre (2018) suggest that this threshold could be as low as 25% of deforestation, above which the forest may stop functioning. Today we have reached about 20% deforestation.

If these tipping points are crossed, large-scale transition to savanna vegetation in the southern and eastern Amazon region may take place (Nobre et al., 2016 and references quoted in). The possible "die-back" of the Amazon region would potentially have large-scale impacts on climate, biodiversity, and people in the region. The studies of Cox et al. (2004) and Betts et al. (2004, 2008), using the HadCM3 model have also projected this future dieback. The level of global warming associated with critical drought levels is extremely uncertain (Betts et al., 2004). After that point is reached, the forest collapses and is replaced by secondary or degraded forests. With the establishment of savanna-type vegetation, the soils continue to dry and lose carbon in a process that has been referred as "savannization" of the Amazon region (Cox et al., 2000). This savannization can be interpreted as the deforested analog of the Amazon forests, with the deforested area covered by pastures and agricultural fields of a savanna-equivalent vegetation. The resilience of the forest to the combined pressures of deforestation and climate change is therefore of great concern.

Although the Amazonian forest persisted during moderate to extreme droughts in the recent past (Bush et al., 2016), it is uncertain whether or not future climate change and other anthropogenic stressors will trigger rapid forest dieback in the Amazon basin (Davidson et al., 2012; Diffenbaugh and Giorgi, 2012; Parsons et al., 2018). Therefore the possibility of this dieback scenario occurring is still an open issue and the uncertainties are still very high (Huntingford et al., 2004; Rammig et al., 2010; Shiogama et al., 2011; Good et al., 2013; Boulton et al., 2017). The dieback depends specifically on the ability of the tropical rainforest to increase carbon uptake in scenarios of increasing atmospheric CO_2 concentrations (Rammig et al., 2010), and on the impact that an interruption of the moisture recycling would have on forest stability (Zemp et al., 2017b).

Work by Malhi et al. (2009) with CMIP3 models used the evaporation value at 3.33 mm day^{-1}, or 100 mm month^{-1} in their simulations to define a dry month in the Amazon (Sombroek, 2001), and show that the models do not allow large water deficits to develop, thereby constraining the extent of the dieback. In that sense, an analysis from CMIP3 models combined with alternative models of plant physiological processes by Huntingford et al. (2013) shows that, despite the considerable uncertainties, the likelihood of dieback could be altered, suggesting that there is evidence of forest resilience in the Amazon region.

The dieback projections were also based on an oversimplified representation of the biodiversity of Amazon forests, representing the tropical rainforests with a maximum of two plant functional types. Longo et al. (2018) incorporate ranges of tree age and size into an analysis of Amazon forest resilience and find that three quarters of the Amazon would not become critically dry by the end of this century, but they note that nutrient limitation and leaf and hydraulic trait diversity are not taken into account. When incorporating observed plant trait diversity into a dynamic global vegetation model, tropical forests still collapsed under severe climate change conditions and constant atmospheric CO_2 (unlike in Rammig et al., 2010), but were more resilient than low-diverse forests (Sakschewski et al., 2016). These changes would still impact biodiversity of other organism groups, put moisture recycling at risk and affect ecosystem services provided to people in the region.

Rising atmospheric CO_2 concentrations also lead to stomatal closure and increased water use efficiency, which reduces evapotranspiration (Field et al., 1995; Sellers et al., 1996). This is known as physiological forcing or the physiological effect (e.g., Betts et al., 2007, 2011, 2012). Models suggest that physiological forcing has the effect of increasing runoff (Gedney et al., 2006; Betts et al., 2007; Magrin et al., 2014) and altering the surface energy balance in favor of sensible heat (e.g., Good et al., 2015; Lemordant et al., 2018), which then increases warming, reduces relative humidity and in turn reduces the fraction of low cloud (Cao et al., 2010; Andrews et al., 2011). It is likely that physiological forcing may be more significant than radiative forcing in driving hydrological cycle changes in Amazonia (Cao et al., 2010; Chadwick et al., 2017; Skinner et al., 2017; Lemordant et al., 2018) and that beyond a doubling of CO_2 it may contribute to non-linear increases in temperature (Good et al., 2015) and non-linear decreases in evapotranspiration (Halladay and Good, 2016). Good et al. (2015) attribute these non-linear temperature increases to increases in the Bowen ratio, which are greatest over the Amazon region (**Figure 7**). Physiological forcing can also have a significant effect on precipitation distributions in forest regions where there is high transpiration (Skinner et al., 2017). Changes in forest structure at a variety of spatial scales are also expected to occur, such as increases in leaf area index (LAI) (Betts et al., 1997; Kergoat et al., 2002; Chapin et al., 2008) that may interact with the physiological effect and feed back on climate. However, there is evidence to suggest that LAI changes are dependent on initial values (Norby and Zak, 2011).

There is, however, a lot of variation in the modeled stomatal response (Rogers et al., 2017), which is particularly important to constrain as it has an impact on both the hydrological and carbon cycles. The stomatal response depends on both atmospheric CO_2 and temperature, indeed, the response of photosynthesis to temperature was found to be the most important source of carbon cycle uncertainty in a perturbed parameter experiment (Booth et al., 2012). These uncertainties highlight the importance of the proposed Amazon FACE experiment (Norby et al., 2016) in constraining vegetation responses to increasing atmospheric CO_2 concentrations, particularly as previous FACE experiments have been in temperate regions. In addition, it may provide data on phosphorus limitation, which is an additional source of model uncertainty that is not currently taken into account (Lapola, 2018).

In summary, large uncertainties still dominate the hypothesis of Amazonian forest dieback even though observational evidence

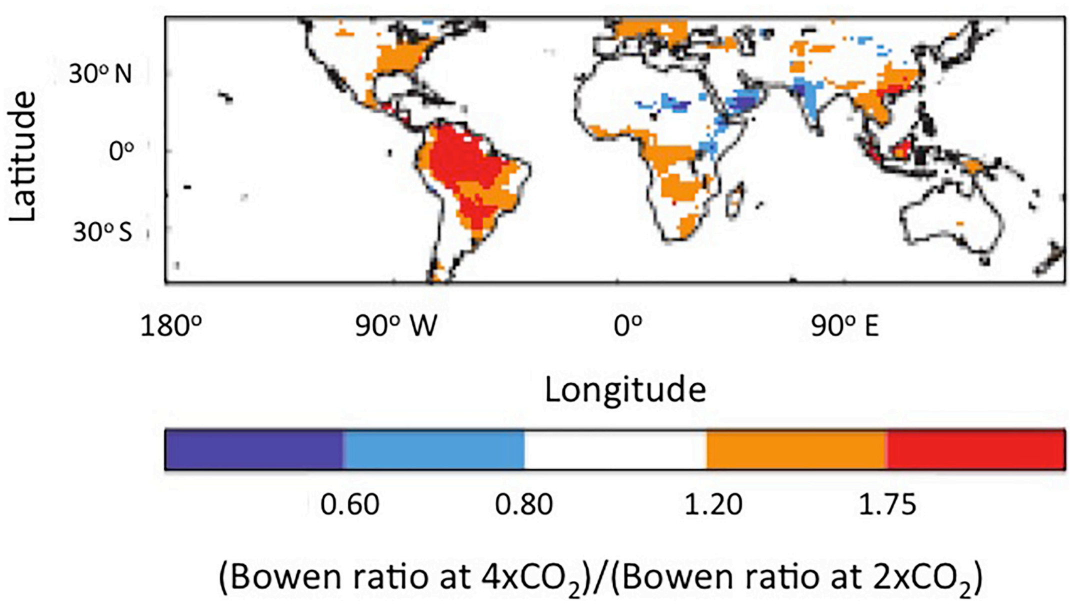

FIGURE 7 | Bowen ratio at 4 × CO_2 divided by Bowen ratio at 2 × CO_2, based on means over years 50–149 of abrupt 2 × CO_2 and abrupt 4 × CO_2 simulations using the HadGEM2-ES Earth System Model (reproduced from Good et al., 2015, British Crown Copyright, by permission of the Met Office).

shows the forest and regional climate changing (Lapola et al., 2018). The uncertainties associated with projections of dieback are related to the vegetation response to climate change and its response to increases in atmospheric CO_2 concentration. These responses are both model and scenario dependent (particularly in terms of land use) and will interact with one another. For example, stomatal closure in response to elevated CO_2 leads to reduced transpiration and increased temperature (e.g., Good et al., 2015). Studies such as Doughty et al. (2015) gained insight into the vegetation response to climate by analyzing the forest response to drought. They found increases in mortality, which were thought to be caused by changes in carbon allocation, although there is still some uncertainty as to the mechanisms (Meir et al., 2015). It has been suggested that tropical forests may also be vulnerable to high temperatures (Doughty and Goulden, 2008; Doughty et al., 2012), but experiments have so far been limited in scope. Some studies (e.g., Slot et al., 2014) have suggested that acclimation will occur over climate timescales and alter the potential for dieback. Within the uncertainty related to the vegetation response to increased CO_2, is the increase in photosynthetic rate with increased water use efficiency and stomatal closure, which have been shown in the FACE experiments (Norby and Zak, 2011). These are well understood at the leaf scale but not when scaled up to ecosystems (De Kauwe et al., 2013). There is also uncertainty around how these responses are modulated by drought stress, temperature, nutrient availability, vegetation diversity and age (Norby et al., 2016). Furthermore, it is not known whether or not increased photosynthetic rates will increase biomass. Vegetation composition may also be affected as some species may be better adapted to future environments (e.g., Laurance et al., 2014), which may in turn affect forest resilience.

More recently, Lapola et al. (2018) discusss socioeconomic impacts of the dieback in the Amazon region. They estimated damage over a 30-year period after the dieback is estimated between US dollar (USD) $957 billion arising primarily from changes in the provision of ecosystem services, without mitigation options. In summary, acting now to save the Amazon would be up to 100 times cheaper than risking a mass forest die-off.

FINAL THOUGHTS

The present review outlines once more the importance of the Amazon forests for hydrology, climate and carbon cycling. It shows how intensely the different processes are intertwined to maintain ecosystem functioning of the Amazon forests. Having it preserved maintains regional hydrology, stabilizes local, regional and continental climate, dampens the impact of extreme climate events and maintains carbon storage and the biodiversity hotspot. Unsustainable human activities, i.e., large-scale deforestation, fires and predatory exploitation of natural resources are destabilizing this important, but sensitive equilibrium and it can influence agriculture intensification across the region.

The shortness of rainfall records is a major problem in the Amazon region. Most of these records start in the 1960s, which hampers the quantification of long-term trends. Only river data goes back to the beginning of the 20th century, and this allows identification of the range of flood and drought variability and risk. In this regard, recent work by Parsons et al. (2018) found that Amazonia has regularly experienced multi-year droughts over the last millennium, based on hydroclimatic variability within the western Amazon Basin shown in lake records. This suggests the need for a better climate and hydrological data bank for the wider Amazon region, with all Amazon countries contributing to it, mainly for rainfall and temperature. River data has allowed for detection of flood and drought variations starting in the 1900s and the availability of global reanalyses has enabled studies on water balance and moisture fluxes and transport in the region since the 1960s. Field data from experiments such as LBA have allowed for model validation and studies on carbon, energy and water cycles in some regions mainly in the Brazilian Amazon. Novel cloud computing capability enables the processing and analysis of planetary scale remote sensing data (Gorelick et al., 2017), which can help improve the understanding of water and land dynamics associated with land use and land cover activities, infrastructure construction and climate change (Hansen et al., 2013; Pekel et al., 2016).

The region has warmed, the dry-season length increased and more climate extremes affect the region with impacts on carbon sequestration and storage, river streamflow and biodiversity, even in the large forested areas designated to conservation and protection. Recent "once-in-a-century" droughts and floods have shown the impacts of extreme climate variability and change on this region's vegetation, carbon storage, water cycling, biodiversity, land use, and economy, as explained by Parsons et al. (2018). The perception of the population of the impacts of such extremes has been matter of on-going research (Pinho et al., 2015). Considering ecological impacts, there may be a natural range to which the ecosystem is adapted; however, it is still uncertain whether or not those extreme events lie outside this natural variability. Work by Domingues et al. (2018) provides evidence of robust acclimation potential to drought intensification in the diverse flora of an Amazonian forest community.

Furthermore, it is this increasing vulnerability and risk that underpins the ambition of the COP21 Paris Agreement to pursue efforts to limit global warming to no more than 2.0°C above pre-industrial levels. The challenges involved in keeping the mean global warming below 1.5–2.0°C have, if anything increased since the Paris COP21 agreement. So, there is a need for decisive action from governments worldwide so that a 4°C warmer world can be avoided (Reyer et al., 2015). It is fundamental that we find innovative mechanisms that promote financial compensations for crops that seek to reduce deforestation or to promote forest conservation, protection of abandoned secondary forests, as well as to discuss new areas for a region that reconcile environmental, social and economic dimensions. Impacts of future deforestation on the hydrological cycle are still uncertain but could be of similar magnitude to those caused by climate change. Thus, climate and sustainable development policies need to account for the impacts of deforestation on regional rainfall. Mechanisms such as Reducing Emissions from Deforestation and Degradation (REDD+) have been proposed, but so far we do not know if they will be successful or not.

Grand questions on Amazon climate variability and change that need to be explored in more detail include the following: (1) What are the current drought and flood trends in Amazonia? (2) Are those trends linked to natural climate variability and/or to land-use changes? (3) What are the relative roles of local and remote forcings in atmospheric moisture transport and hydro-climatic extremes in the region? (4) What will be the impacts of aerosols from biomass burning, and changes in atmospheric circulation and rainfall in the Amazon, including changes in the length of the dry season and onset of the rainy season? (5) While highly biodiverse forests are more resilient, although not resistant to severe climate change impacts, what would be the physiological processes controlling carbon and water balances in Amazon forests in future climates? (6) Can we improve our knowledge of interactions between biodiversity, rooting schemes and evapotranspiration to buffer drought conditions (increasing dry-season length, extreme drought years)? (7) What are the uncertainties of the occurrence of a dieback of the Amazon forest in future climate change projections given all possible interactions and feedbacks? (8) How do we understand and reduce future deforestation and human activities and their uncertainties and how do the latter impact on regional climate, water and the carbon cycles? (9) What are the trade-offs between different economic, social and environmental development strategies in the region to cope with impacts of climate change? (10) How can we integrate knowledge on Amazon dieback with socioeconomic assessments in order to anticipate impacts and to assess the feasibility and efficacy of mitigation/adaptation options?

The answers to these questions will be revealed by combining intensive observational monitoring data with an environmental modeling strategy, directed toward a more realistic simulation of the characteristics and variability of Amazon functioning at various time scales. This will also lead to better projections of future climate and environmental change scenarios with uncertainty quantifications. We need integrated and responsive research, and an engagement program that tackles economic, social and environmental development strategies by learning from governance failures at multiple levels, barriers to scaling up innovative locally based sustainable development programs in the Amazon, and poor communication between different knowledge systems, Amazon societies and policy making.

As suggested by Parsons et al. (2018), the future sustainability of the Amazonian forest and the ecosystem services it offers may require management strategies that consider the likelihood of multi-year droughts superimposed on a continued warming trend. While science can still advance further in this area, we have also assembled enough knowledge to underline the global and regional importance of an intact Amazon region, in order to support policymaking and to keep this sensitive ecosystem functioning. This major challenge requires substantial resources and strategic cross-national planning, and a unique blend of expertise and capacities established in Amazon countries and from international collaboration.

AUTHOR CONTRIBUTIONS

JM, CS, and RB conceptualized the study. CB, KT, and KH helped the model output analyzes. LA and WS helped with the data analysis and figures. JM, CS, KT, CB, KH, RB, LA, and WS wrote the manuscript.

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