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Long-term variability, extremes and changes in temperature and hydrometeorology in the Amazon region: A review

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ABSTRACT

This review discusses observed hydroclimatic trends and future climate projections for the Amazon. Warming over this region is a fact, but the magnitude of the warming trend varies depending on the datasets and length of the analyzed period. The warming trend has been more evident since 1980 and has further enhanced since 2000. Long-term trends in climate and hydrology are assessed. Various studies have reported an intensification of the hydrological cycle and a lengthening of the dry season in the southern Amazon. Changes in floods and droughts, mainly due to natural climate variability and land use change, are also assessed. For instance, in the first half of the 20th century, extreme flood events occurred every 20 years. Since 2000, there has been one severe flood every four years. During the last four decades, the northern Amazon has experienced enhanced convective activity and rainfall, in contrast to decreases in convection and rainfall in the southern Amazon. Climate change in the Amazon will have impacts at regional and global scales. Significant reductions in rainfall are projected for the eastern Amazon.

KEYWORDS: Climate change, land-use change, warming, moisture transport, drought, floods, climate models

Variabilidade de longo prazo, extremos e mudanças de temperatura e hidrometeorologia na Região Amazônica: Uma revisão

RESUMO

Essa revisão discute tendências hidroclimáticas observadas e projeções climáticas futuras para a Amazônia. O aquecimento sobre esta região é um fato, mas a magnitude da tendência de aquecimento varia dependendo dos conjuntos de dados e da duração do período analisado. A tendência de aquecimento tornou-se mais evidente a partir de 1980 e aumentou ainda mais desde 2000. São avaliadas as tendências de longo prazo no clima e na hidrologia. Vários estudos relataram uma intensificação do ciclo hidrológico e um prolongamento da estação seca no sul da Amazônia. Mudanças nas cheias e secas, em grande parte devido à variabilidade natural do clima e mudanças no uso da terra, também são avaliadas. Por exemplo, na primeira metade do século XX, eventos extremos de inundação ocorreram a cada 20 anos. Desde 2000, houve uma inundação severa a cada quatro anos. Durante as últimas quatro décadas, o norte da Amazônia experimentou aumento da atividade convectiva e precipitação, em contraste com a diminuição da convecção e precipitação no sul da Amazônia. As mudanças climáticas na Amazônia terão impactos em escalas regional e global.

PALAVRAS-CHAVE: Mudanças climáticas, mudanças no uso da terra, aquecimento, transporte de umidade, seca, enchentes, modelos climáticos

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INTRODUCTION

We provide an updated review of the literature on hydroclimate variability in the Amazon basin, including classic and new studies developed in recent decades, to answer critical questions relevant to the current and future role of the Amazon Forest as a regulator of local and regional climate. We analyze current trends in hydrometeorology, moisture transport, and temperature in the Amazon and Andean-Amazon regions, as well as signals of intensification or alteration of the hydrological cycle and whether these are due to climate variability or human-induced climate change. Specifically, regarding the hydrological cycle intensification, we analyze the increasing variability of droughts and floods in the Amazon and its relation to the El Niño Southern Oscillation (ENSO) phenomenon based on the past evolution of ENSO and hydroclimate in the paleoclimatic record. The temperature in the Tropical Atlantic, land-use change, and their combination with ENSO were also analyzed as contributing factors to the current drought and flood patterns. Finally, we evaluate future climate-change scenarios in the Amazon by projecting expected changes due to increasing greenhouse gases and deforestation and their impact on the regional and global scales. The content of this review paper is derived from an earlier report for the Science Panel for the Amazon SPA (Marengo *et al.* 2021). Among its objectives, the SPA looks to provide regular assessments of scientific knowledge based on all levels of information to understand the role of the Amazon on earth's system in the present and under scenarios of land use and climate change. So, in this article, we updated current knowledge on the climate system and variability and change in the Amazon region and are dedicated to a broad audience, from the scientific community to the public.

LONG-TERM TEMPERATURE VARIABILITY

Several studies have identified positive air temperature trends in the Amazon, with the magnitude dependent on the data (station- or grid-based data, reanalysis, or satellite data), methodology (linear and non-linear), length of the climate records, region, and season of the year. An early study by Victoria *et al*. (1998) used station data for the Brazilian Amazon and quantified an increasing trend of +0.56 oC per century during 1913-1995. Malhi and Wright (2004) studied trends in temperature over Amazonian tropical forests. They used a station-based gridded dataset from 1960-1998 from the Climate Research Unit CRU (Harris *et al.* 2020). The subperiod 1976-1998 shows positive temperature trends for the region that was steeper in 1976-1998 compared to previous decades. Jiménez-Muñoz *et al*. (2013) updated the analysis provided by Malhi and Wright (2004), identifying warming patterns that vary seasonally and spatially. Hence, strong warming over the southeastern Amazon was identified during the dry season (July to September), with a warming rate of +0.49 ºC per decade during 1979-2012, according to the ERA-Interim (Jimenez-Muñoz *et al.* 2013). Table 1 summarizes the studies that analyzed temperature trends in different periods and datasets. All these studies show that, despite the differences among trends estimated from different datasets, the recent two decades were the warmest. The warming trend is better evidence from 1980 and is enhanced

Table 1. Summary of studies dealing with temperature trends in the Amazon. It includes region of the Amazon, period of data, type of data, magnitude of the trend and reference. (Source: Marengo *et al.* 2021).

Region	Period	Data used	Trend	Reference
Brazilian Amazon	1913-1995	Station	+0.56 ° C/century	Victoria et al. (1998)
Western and Central Amazon	1960-1998	CRU	-0.15 ºC/decade	Malhi and Wright (2004)
Northeastern Amazon	1960-1998	CRU	+0.1 ºC/decade	Malhi and Wright (2004)
All Amazon	1976-1998	CRU	+0.26 ºC/decade	Malhi and Wright (2004)
Southern Amazon	1976-1998	CRU	+0.4 ºC/decade	Malhi and Wright (2004)
Northeastern Amazon	1976-1998	CRU	+0.2 ºC/decade	Malhi and Wright (2004)
Brazilian Amazon	1961-2000	Station	+0.3º ºC /decade	Obregon e Marengo (2007)
Tocantins River basin	1961-2000	Station	+1.4 ºC /decade	Obregon e Marengo (2007)
All Amazon	1979-2012	ERA-Interim	+0.13 ºC/decade	Jiménez-Muñoz et al. (2013)
All Amazon	2000-2012	ERA-Interim	+0.22 ºC/decade	Jiménez-Muñoz et al. (2013)
Southeastern Amazon (July-September)	2000-2012	ERA-Interim	+1.22 ºC/decade	Jiménez-Muñoz et al. (2013)
Southeastern Amazon (July-September)	2000-2102	MODIS	+1.15 ºC/decade	Jiménez-Muñoz et al. (2013)
Bolivian Amazon	1965-2004	Station	+0.1 ºC/decade	Seiler et al. (2013)
Peruvian Amazon	1965-2007	Station	+0.09 ºC/decade	Lavado-Casimiro et al. (2013)
All Amazon	1980-2013	CRU	+0.7 ºC	Gloor et al. (2015)
Southeastern Amazon (July-September)	1973-2013	Station	+ 0.6 ºC	Almeida et al. (2017)
All Amazon	1950-2019	CRU, GISS	+ 0.6 ºC	Marengo et al. (2018)
Manaus	1980-2015	Station	+0.5 ºC	Schöngart and Junk (2020)

from 2000 onwards, when three exceptional droughts occurred in 2005, 2010, and 2015/2016 (Figure 1).

Analyses of temperature data from CRU and ERA 20C/ERA-Interim reanalysis showed that 2016 (an El Niño year) was the warmest since 1850, warming up to +1 ºC above the mean annual temperature for the reference period 1961-1990, and some monthly temperature anomalies surpassing +1.5 ºC during this same year (Jiménez-Muñoz *et al.* 2016). Historical records show an increasing trend for all seasons, with a greater warming rate from June to November (Figure 1). A contrasting west-east pattern is also observed, as warming rates were almost twice over the eastern Amazon than over the western Amazon (Figure 1). Higher warming rates over the eastern Amazon are attributed to land cover change and subsequent alteration of the energy balance (Davidson *et al*. 2012). The land cover alone also plays a role over the southeastern and eastern Amazon, where tropical forests transition to other land cover types such as pastures and Cerrado savannas (Marengo *et al* 2022). In contrast, the Andes barrier influences the western Amazon and a transition from montane tropical forests to lowland forests, where temperature trends decline with increasing elevation (Malhi *et al*. 2017).

From 1979 to 2018, a mean warming trend for the whole Amazon (1.02 ± 0.12 ˚C) was consistent with the global average (0.98 ˚C) (Gatti *et al.* 2021). However, warming trends differ between months, and the most significant increases were observed for the dry-season months of August to October (1.37 ± 0.15 ˚C). A recent study comparing temperature trends from different datasets over the tropics showed a strong warming trend in wet climate regions such as the Amazon, where surface warming is amplified due to the positive radiative effect of high clouds and precipitable water in trapping upwelling longwave radiation, suggesting a dominant role of atmospheric moisture in controlling the regional surface temperature response to greenhouse gas (GHG) warming (Khanna *et al*. 2020).

The overall conclusion is that warming over the Amazon region is a fact. Because of the different climate regimes over the Amazon, the warming trend is also seasonally and regionally dependent. The seasonal and spatial distribution of trends is consistent with the climatic gradient across the Amazon, from continuously wet conditions in the northwest (with lower warming rates) to long and pronounced dry seasons in the southeastern Amazon (with higher warming rates).

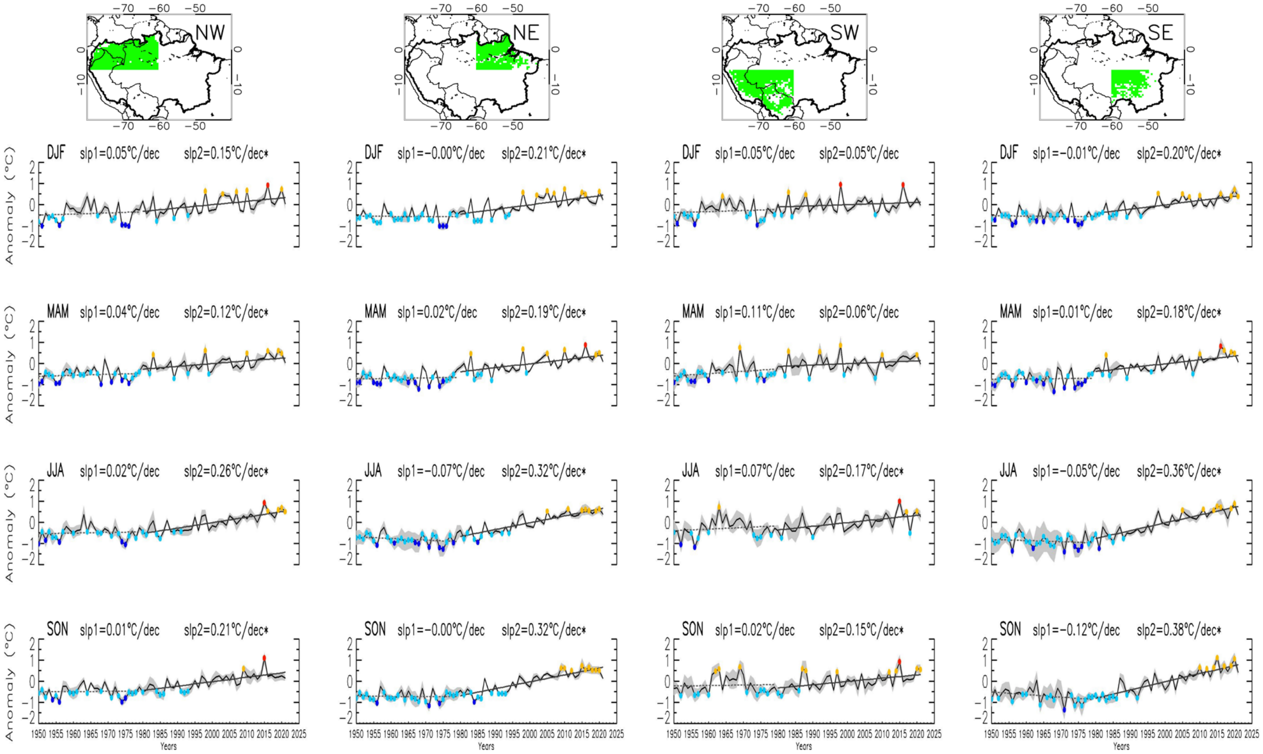

Figure 1. Temporal series of seasonal (DJF, MAM, JJA, SON) air temperature anomalies over different sectors of the Amazon evergreen forests (NW, NE, SW, SE) using data provided by the Climate Research Unit CRU Version 4 (CRUTS4) data (Harris *et al* 2020) for the reference period 1981-2010. Orange and red circles indicate temperature anomalies that surpass one standard deviation (σ) and 2σ, respectively, whereas light blue and dark blue circles indicate temperature anomalies below -1σ and -2σ, respectively. Linear trends for the period 1950-1979 and 1980-2021 are represented by a dashed line and a continuous line, respectively. Values of the slope for these two periods (slp1, slp2) are also included. DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November. NW = northwest; NE = northeast; SW = southwest; SE = southeast.

LONG-TERM VARIABILITY IN HYDROMETEOROLOGY

Long-term trends in rainfall and river levels

Historical trends in Amazonian precipitation vary considerably among studies, depending on the dataset, time series period and length, season, and region evaluated (Malhi and Wright 2004; Espinoza *et al*. 2009; Fernandes *et al.* 2015; Marengo *et al.* 2018). A review by Marengo and Espinoza (2016) show that extremes of interannual rainfall and river levels in the Amazon can be, in part, attributed to sea surface temperature (SST) variations in the tropical oceans, manifesting as the extremes of the ENSO events in the tropical Pacific and the meridional sea surface temperature gradient in the Tropical North Atlantic (TNA).

While no unidirectional trend in annual rainfall has been identified in the region, the situation may be different at regional and seasonal levels (Espinoza *et al*. 2009; Satyamurty *et al*. 2010; Almeida *et al*. 2017; Marengo *et al*. 2018). Long-term, decadal variations linked to natural climate variability significantly influence rainfall trends because most of the rainfall records over the Amazon are only available for up to four decades. Decadal changes in Amazonian precipitation have been attributed to phase shifts of the Pacific Decadal Oscillation (PDO), Interdecadal Pacific Oscillation (IPO), and Atlantic Multidecadal Oscillation (AMO) (Andreoli and Kayano 2005; Espinoza *et al*. 2009; Aragão *et al.* 2018). Decadal rainfall fluctuations over the western Amazon vary closely with the north-south gradient of tropical and subtropical Atlantic SST (Fernandes *et al*. 2015).

Studies analyzing rainfall in the Amazon over the past four decades show contrasting north-south trends of increasing rainfall in the northern Amazon and decreasing rainfall in the southern Amazon (Gloor *et al*. 2013; Barichivich *et al*. 2018; Garcia *et al*. 2018; Espinoza *et al.* 2022). Recent analyses reinforce the trend towards negative rainfall extremes in the southern Amazon, and of positive rainfall extremes in the northern Amazon, particularly during the wet season (Figure 2b,c) (Wang *et al*. 2018; Espinoza *et al*. 2019a; Rao *et al.*, 2022). Due to the higher rainfall in the northern Amazon, the overall basin-wide precipitation increased by 2.8 mm per year during the 1981–2017 period (Paca *et al*. 2020).

Water level data for the Negro River at the city of Manaus (Amazonas, Brazil), close to its confluence with the Solimões (Amazonas) River have been recorded daily since September 1902 (Figure 2a). The mean amplitude between the annual maximum and minimum water levels is 10.22 m (period 1903-2015; Schöngart and Junk 2020). Over the last two

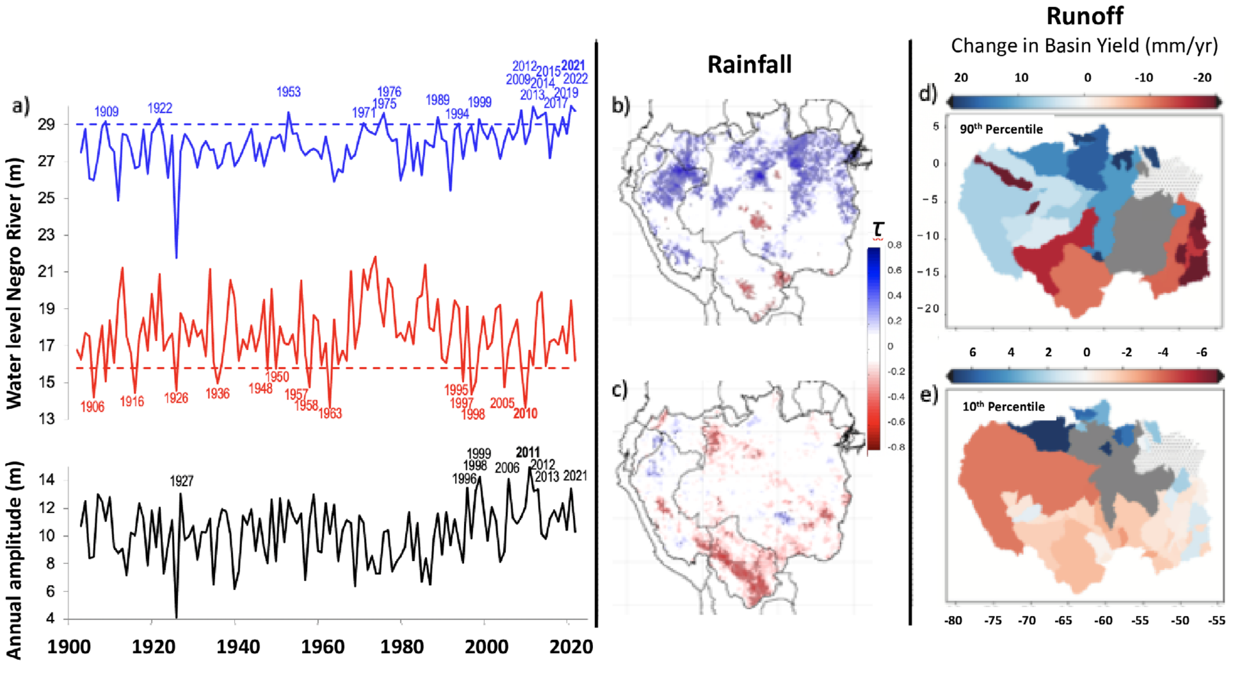

Figure 2. A – Variation of the Negro River at Manaus (Amazonas, Brazil) from 1903 to 2021. The graphs indicate the annual maximum (blue) and minimum (red) levels, and the amplitude between maximum and minimum levels (black). The blue dotted line indicates the 29-m threshold for extreme floods that trigger the emergency state in Manaus. The red dotted line indicates the 15.8-m threshold for extreme droughts. Years corresponding to extreme hydrological events for annual minimum and maximum water levels as well as for annual amplitudes are indicated. Adapted from Schöngart and Junk (2020) based on data from the Brazilian National Agency of Waters (ANA). **B**,**C** – Spatial distribution of significant ($p < 0.05$) Kendall coefficient values for rainfall in the Amazon region for the period 1981–2017. Maps show rainy days (>10 mm per day) during March-May (blue), and rainy days (>1 mm per day) during September-November (red) using CHIRPS data. Adapted from Espinoza *et al.* (2019a). Runoff maps indicate the slope of change in the 90th (**D**) and the 10th (**E**) percentile runoff (mm yr^{-1}) per river sub-basin in the Amazon region for the period 1980-2014. Areas in grey represent no significant trend. Adapted from Heerspink *et al.* (2020).

decades, a fivefold increase in severe flood events has been observed in the central Amazon, resulting in severe flood hazards (Barichivich *et al.* 2018). Nine extreme flood events reaching or passing the 29-m threshold for emergency in Manaus (Figure 2a) were observed during the last 15 years, among them to four highest floods on record (2021, 2012, 2009 and 2022). The total duration of the flood emergency in the first two decades of this century (2001-2021) in Manaus is already 20% longer than the flood emergency duration during the entire 20th century (Espinoza *et al.* 2022). This increase in flood and duration is mainly caused by a basin-wide increase in river runoff during the wet season and a slight decrease in discharge during the dry season (Gloor *et al*. 2013), although trends vary substantially among subbasins (Figure 2d,e) (Espinoza *et al*. 2009; Gloor *et al*. 2015).

Substantial warming of the tropical Atlantic since the 1990s has played a central role in the intensification of the hydrological cycle in the Amazon (Gloor *et al*. 2013; Wang *et al*. 2018). The warming of the tropical Atlantic increases atmospheric water vapor, which is imported by trade winds into the northern Amazon basin. This raises precipitation and discharge, especially during the wet season (Gloor *et al*. 2013; 2015; Heerspink *et al*. 2020). During this period, the simultaneous cooling of the equatorial Pacific increases differences in sea level pressure and SSTs between both tropical oceans, resulting in a strengthening of the Walker circulation, which contributes to rainfall in the region (Barichivich *et al*. 2018). This circulation represents a direct cell zonally oriented along the Equator, induced by the contrast between the western Pacific's warm waters and the eastern Pacific cooler waters (McGregor *et al*. 2014; Gloor *et al*. 2015; Barichivich *et al*. 2018).

A weak positive trend can be noticed in the maximum river levels recorded at Manaus since the late 1980s (Figure 2a). On the other hand, discharge records during the low-water period at the Negro, Solimões, Madeira, and Amazon rivers show significant negative trends since the mid-1970s (Espinoza *et al.* 2009; Lavado-Casimiro *et al.* 2013; Marengo *et al.* 2013; Gloor *et al.* 2015; Molina-Carpio *et al.* 2017).

Hydroclimatic trends in the Andean-Amazon rivers are region and period specific. Long-term information is generally available from 1970 or 1980 onwards from a low-density meteorological network, which makes it difficult to identify clear trends in rainfall in most of the inter-Andean valleys of the upper Amazon basin (Lavado-Casimiro *et al*. 2013; Carmona and Poveda 2014; Posada-Gil and Poveda 2015; Heidinger *et al*. 2018; Pabón-Caicedo *et al*. 2020). However, in the Amazon lowlands of Colombia, Ecuador, and northern Peru, precipitation has been increasing since the 1990s, as observed in most of the Amazon basin north of 5˚S (Espinoza *et al*. 2009; Wang *et al*. 2018; Jimenez *et al*. 2019; Paca *et al*. 2020), where rainfall increased approximately 17% during the wet season (Espinoza *et al*. 2021a). Consequently, since the mid-1990s, discharge of the main northwestern tributaries of the Amazon River (e.g., Caquetá-Japurá and Marañón rivers) increased during the high-water season (Figures 2d and 3). For example, at Santo Antonio do Iça station, on the lower Caquetá-Japurá River, during the high-water season, the discharge increased 16% from 1974-1991 to 1992-2004 (Espinoza *et al*. 2009; Posada-Gil and Poveda 2015). Increasing rainfall and discharge in the northwestern Andean-Amazon region contributed to an intensification of extreme floods in the main channel of the Amazon River in Brazil over the last three decades (Barichivich *et al*. 2018).

In the southern part of the Peruvian Andean-Amazon basins, decreasing rainfall has been documented since the mid-1960s (e.g., Silva *et al*. 2008; Lavado-Casimiro *et al*. 2013; Heidinger *et al*. 2018), and, consequently, discharge reduction was reported during the low-water season in the rivers that drain from the south, such as the Ucayali River in Peru. Annual discharge decrease was also recorded in stations downstream at Tamshiyacu (Amazonas River in Peru) and Tabatinga (upper Solimões River in Brazil) (e.g., Lavado-Casimiro *et al*. 2013; Posada-Gil and Poveda 2015; Marengo and Espinoza 2016; Ronchail *et al*. 2018; Heerspink *et al*. 2020). For example, during the low-water season at the Tabatinga station, where the river drains rainfall from over the Andean-Amazon basins, recorded a decrease in discharge of 14% in the 1969-2006 period compared to discharge during the 1970s (Lavado-Casimiro *et al*. 2013).

In the Bolivian Amazon, a negative rainfall trend was identified in 1984-2009 relative to 1965–1984 (Seiler *et al*. 2013). A decrease in rainfall since the 1980s is mainly observed in the southern part of the Bolivian sub-basin of the Madeira River basin, involving the Mamoré and Guaporé rivers (Figure 3). Related to these changes in rainfall, the discharge of the upper Madeira River during the low-water season at the Porto Velho station showed a significant decrease of around 20% for 1970-2013 (Espinoza *et al*. 2009; Lopes *et al*. 2016; Molina-Carpio *et al*. 2017). A decrease in discharge has also been observed upriver from Porto Velho, in the Madeira River (Abunã station), Mamoré River (Guayaramerín and Puerto Siles stations), and Guaporé River (Principe da Beira station), over the period 1985-2013 (Molina-Carpio *et al*. 2017). The period analyzed here was prior to the operation as designed of the Santo Antonio and Jirau hydropower dams along the upper Madeira River's main channel. Analyses of the annual maximum water levels (data: Hydroweb/ANA) from 1968 to 2014 of hydrological stations upstream (Guajara-mírim and Abunã) and downstream (Porto Velho and Humaita) of the Madeira Hydropower Complex (MHC) indicate the same trends during the period of construction in the upstream and downstream section (not shown). This also holds for the record flood in 2014, which occurred before the operation of the MHC. The decrease in discharge in this region observed by

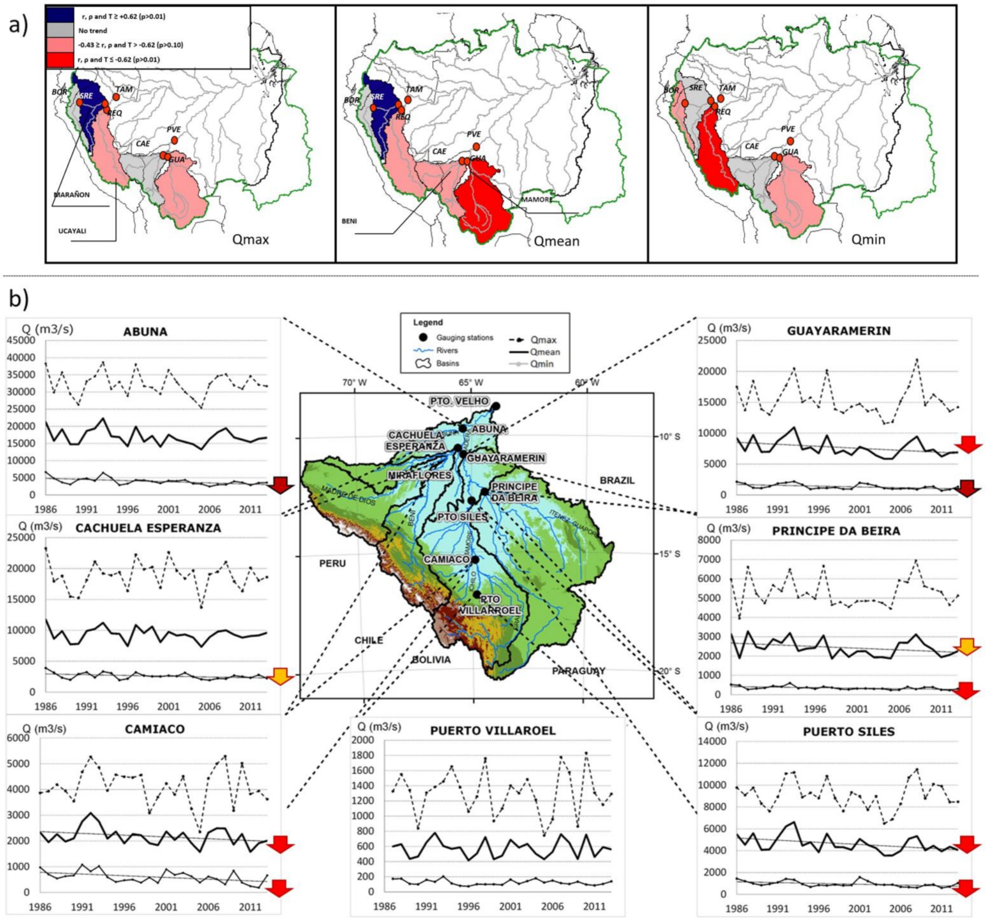

Figure 3. Discharge trends in Amazon-Andean rivers in Ecuador, Peru and Bolivia. **A** – Annual maximum (Qmax), mean (Qmean) and minimum (Qmin) discharge computed for the period 1990-2005 from the stations in Borja (BOR, Peru) and San Regis (SRE, Peru) on the Marañon River, Requena (REQ, Peru) on the Ucayali River, Cachuela Esperanza (CAE, Bolivia) on the Beni River and Guayaramerin (GUA, Bolivia) on the Mamoré River. The colors indicate the sign and the strength of the trends estimated using Pearson (r), Spearman rho (ρ) and Kendall Tau (T) coefficients. Adapted from Espinoza *et al*. (2009) based on data from the SNO-HYBAM international observatory. Reprinted by permission from Elsevier. **B** – Evolution of Qmax, Qmean, and Qmin in the main rivers of the Bolivian Amazon in the period 1985-2013. Arrows indicate increasingly significant negative trends (yellow < red < black). Adapted from Molina-Carpio *et al.* (2017) based on data from the SNO-HYBAM observatory.

Molina-Carpio *et al*. (2017) was thus related to the decrease in rainfall and the concomitant lengthening of the dry season in the southern Amazon (Marengo *et al.* 2011; 2018). Other factors that likely contributed to the observed changes in the hydrological cycles are land-use changes, such as large-scale deforestation in the catchment areas for agriculture and cattle ranching (Costa *et al*. 2003; Davidson *et al*. 2012; Heerspink *et al*. 2020).

Seasonal and interannual variability in the rainy and dry season

The decrease in rainfall in the southern part of the Peruvian, Brazilian, and Bolivian Amazon basin during the dry season has been associated with a delay in the onset of the South American Monsoon System (SAMS) and enhanced atmospheric subsidence over this region (Leite-Filho *et al.* 2019; Espinoza *et al.* 2021). These atmospheric changes are also related to the increased dry season length documented over the southern Amazon basin since the 1970s (Marengo *et al.*, 2011; Fu *et al.*, 2013). The rainy season in the southern Amazon now starts almost a month later than it did in the 1970s (Figure 4) (Marengo *et al.* 2011). In the extreme drought years of 2005, 2010, and 2016, as well as in previous droughts, the rainy season started late, and/or the dry season lasted longer (Marengo *et al.* 2011; Alves 2016). Since 1979, there has been an average increment of 6.5 ± 2.5 days per decade in the length of the dry season in the southern Amazon region (Fu *et al.*, 2013). Overall annual mean precipitation has not significantly changed, but, like temperature trends, August-October precipitation has decreased by 17%, enhancing the dry-season/wet-season contrast (Gatti *et al.* 2021).

Dry seasons in the Amazon have become more intense in recent years, leading to greater forest loss and increasing fire

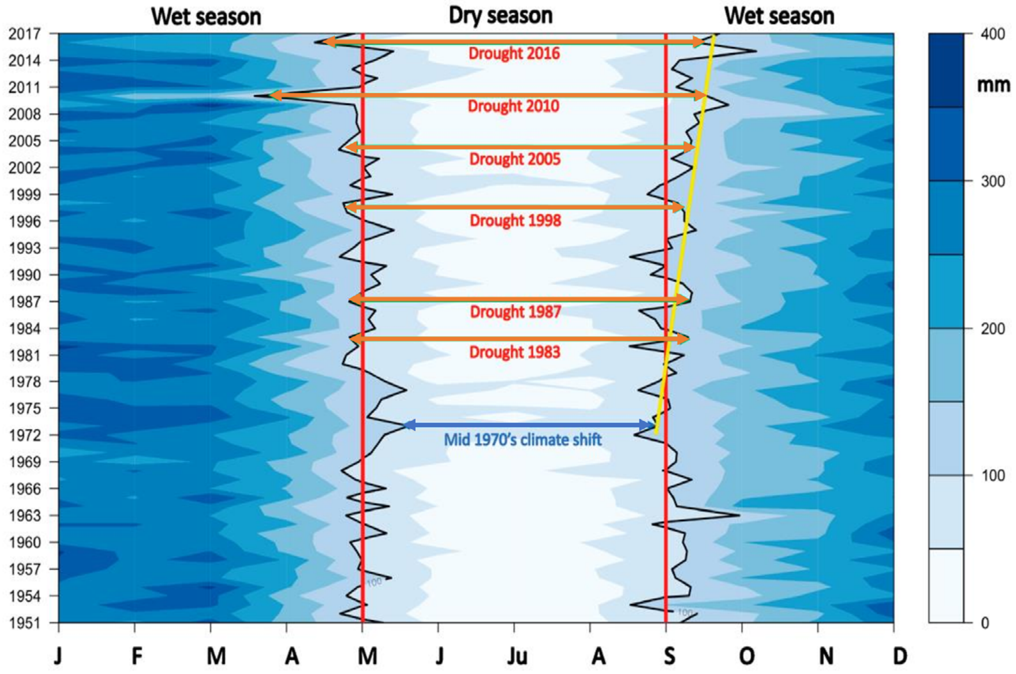

Figure 4. Hovmoller diagram showing monthly rainfall from 1951 to 2017 for the southern Amazon (mm month^{-1} according to the color scale on the right). The isoline of 100 mm month^{-1} (solid black line) is an indicator of dry months in the region (Sombroek 2001). Drought years are indicated with green lines. The red lines mark the average onset and end of the rainy season (Marengo *et al.* 2018). The yellow line shows the tendency for a longer dry season after the mid 1970's climate shift. Adapted from Marengo *et al.* (2018).

risk. Various studies have shown evidence of the lengthening of the dry season in the region, primarily over the southern Amazon, since the 1970s (Marengo *et al*. 2011, 2018; Fu *et al*. 2013 and references therein). This tendency can be related to the large-scale influence of meridional SST gradients across the North and South Atlantic or the strong influence of dry season evapotranspiration (ET) in response to a seasonal increment of solar radiation (Fu and Li 2004; Butt *et al*. 2011; Lewis *et al*. 2011; Dubreuil *et al*. 2012; Fu *et al*. 2013; Alves 2016; Marengo *et al*. 2018), a poleward shift of the southern hemispheric subtropical jets (Fu *et al*. 2013), and an equatorward contraction of the Atlantic Intertropical Convergence Zone (ITCZ) (Arias *et al*. 2015).

The length of the dry season in the Amazon also exhibits interannual and decadal-scale variations linked to natural climate variability, apparently related to the 1970s climate's shift. Wang *et al*. (2011), Alves *et al*. (2017), and Leite-Filho *et al*. (2019) suggest that forest loss influences dry season length in the Amazon, with a longer dry season and a late onset of the rainy season (Figure 5). Wright *et al*. (2017) and Zhang *et al*. (2009) highlight the mechanisms by which interactions among land surface processes, atmospheric convection, and biomass burning may alter the timing of the onset of the wet season. 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 feedback that enhances drought conditions (Costa and Pires 2010; Lejeune *et al*. 2016). Longer dry seasons in the southern Amazon are also related to enhanced atmospheric moisture content over the Caribbean and northern South America, changes in moisture transport, enhanced atmospheric subsidence, and moisture recycling in the southern Amazon (Agudelo *et al*. 2018; Arias *et al*. 2020; Espinoza *et al*. 2021; Rao et al., 2022). There is a delay of about four days per decade in the onset of the wet season for each 10% of deforested area relative to an existing forested area (Leite-Filho *et al*. 2019).

This interaction between ET from the forests and rainfall creates negative feedback that enhances season intensity and can explain the contribution of deforestation to the increasing severity of dry seasons in the Bolivian, Brazilian, and Peruvian Amazon and how this leads to greater forest loss. As shown in Table 2, major droughts have been detected during El Nino years, as in 1983, 1998, and 2015-16, and the dry conditions increased the risk of fire. Longo et al (2020) show that when severe drought hit the Amazon, intact forests start to behave like degraded forests because all forests run out of water and become hot. This suggests that forest degradation caused by people can have large impact on dry-season climate and favor more fire, especially during typical, non-drought years (Lapola *et al.* 2023).

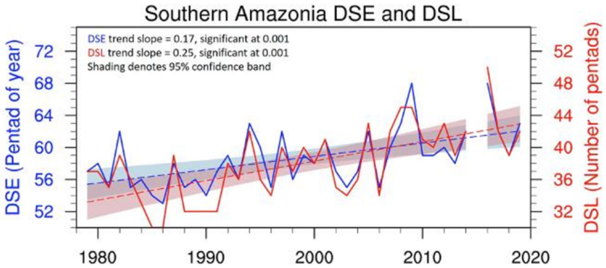

Figure 5. Annual time series of the dry season length (DSL, red line) and dry season ending (DSE, blue line) dates (in unit of pentad or 5-day) over the southern Amazon show an increase of dry season length at the rate of 12.5 ± 2.5 days per decade due to a delay of dry season ending at the rate of 8.8 ± 2.5 days per decade for the period of 1979-2019. On the left axis, the 55th pentad corresponds to September 2–7 of the calendar date, and the 70th pentad corresponds to December 10–15. The DSL and DSE are derived from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) daily rainfall data. The linear trend is determined by a least-square fitting. Trends are significant ($p<0.01$) and the shades show the 95% confident intervals for the trends. Adapted from Fu *et al.* (2013) with the updated analysis period to 1979-2019.

Recent studies have documented different "types" of ENSO events, with warm SST anomalies in the eastern Pacific (E) or in the central equatorial Pacific (C) (e.g., Cai *et al*. 2020 and references therein). To evaluate the role of the different ENSO types (E vs C) and SST in the TNA in the observed spatial and temporal patterns of drought in the Amazon, precipitation anomalies for the 1981-2020 period were regressed with ENSO-E, ENSO-C, and TNA indices and the correlations are shown in Figure 6. During the austral summer (December to February), El Niño (EN) events inhibit precipitation over broad areas of the northeastern Amazon, with a similar spatial distribution pattern for the E and C indices (Figure 6). However, the signal of the C index is stronger than that of the E index, particularly over the Andean-Amazon region. In contrast, the signal of the TNA index is stronger during the austral autumn (March to May MAM), with a characteristic north-south dipole (increased precipitation over the northern Amazon and decreased precipitation over the southern Amazon) (Figure 6). Dryness induced by warm TNA temperatures is also observed in the austral spring (September to November SON), but the signal in the austral autumn is stronger (Figure 6). Although ENSO and TNA are the main drivers of droughts in the Amazon, some recent events were not fully explained by the contribution of these two oceanic phenomena (Marengo and Espinoza., 2016; Jimenez-Muñoz *et al*., 2021). For example, in the drought of 2015/2016, dry conditions were observed over some Amazonian regions even after E, C, and TNA contributions were removed, which may be attributed to anthropogenic factors, among other causes (Erfanian *et al.* 2017).

Historical droughts and floods

It is well known that the strong interannual rainfall variability over the Amazon basin directly impacts the Amazon River's water balance (e.g., Tomasella *et al.* 2011; Marengo *et a.l* 2018). Because of this variability, the Amazon basin is

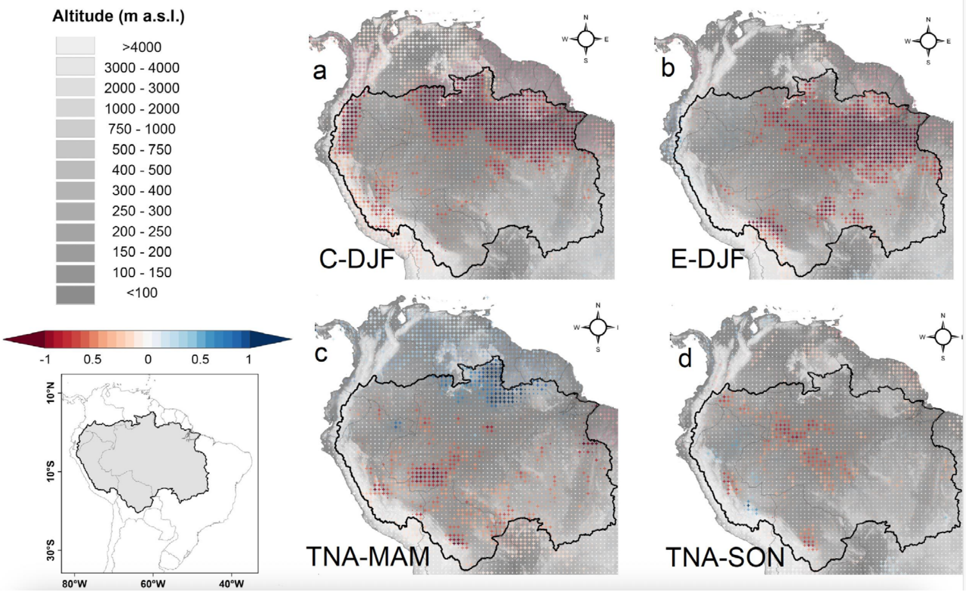

Figure 6. Slope of the linear regression coefficient between standardized SST indices for the Eastern Pacific (E), Central Pacific (C), and Tropical North Atlantic (TNA) and precipitation anomalies for different seasons. Values are in mm day^{-1} per standard deviation. Pixels at the 95% confidence level are marked. Regions colored in red (blue) indicate a reduction (increase) in precipitation with increasing (decreasing) warm (cold) SST anomalies over the Eastern Pacific (E), Central Pacific (C) or Tropical North Atlantic (TNA) regions. We did a linear regression in a pixel-by-pixel basis between SST indices and precipitation, so yes, there is a linear regression behind the data. What we show in the maps is the slope value of the linear regression for each pixel. The confidence inteval refers to the statistical significance of the linear regression ($p<0.05$). We did the analysis and the figure for this review, but anyway we have included a reference to a previous paper in which we used a similar figure. Adapted and updated from Jimenez *et al.* (2021).

affected by recurrent droughts and floods of variable intensity. Drought not only implies a shortage of precipitation, but it is also generally associated with an increase in surface air temperature (Jimenez-Muñoz *et al.*, 2016). Most of the severe droughts in the Amazon region are EN-related (Cai *et al.*, 2020). However, in 1963 and 2005, the Amazon was affected by a severe drought that was not EN-related, as SST anomalies drive most of the rainfall anomalies that have happened in the southwestern Amazon in the TNA (Table 2). In fact, during the last 20 years, the three "megadroughts" (2005, 2010, and 2015/2016) (Jiménez-Muñoz *et al.* 2016; Marengo and Espinoza 2016) were events classified at the time as "one-in-a-100-year events". Past mega-droughts were registered in 1925/1926, 1982/1983, and 1997/1998, mainly driven by EN (Marengo *et al.* 2018 and references therein). In contrast, "mega-floods" occurred in 2009, 2012, 2014, and 2021 (Marengo and Espinoza 2016; Espinoza *et al.* 2022 and references therein). Most of these events have been related to EN, La Niña (LN), or warm TNA (Table 2). However, the very unusual wet 2014 austral summer period on the eastern slope of the Peruvian and Bolivian Andes has been associated with warm anomalies in the western Pacific-Indian Ocean and over the subtropical South Atlantic Ocean [leading to the historic flood event in the Madeira River basin (Espinoza *et al.* 2014)].

Historical droughts and floods have been reported as the result of the addition of various climatic factors. For instance, the drought in 2010 was associated with an EN during the austral summer and a warmer-than-usual tropical Atlantic SST during the austral winter and spring (Marengo and Espinoza 2016). On the other hand, the 2021 flood was mainly related to an intensification of the atmospheric upward motion in northern Amazonia, which is associated with an intensification of the Walker and Hadley circulations, which contributes to rainfall in the region (Espinoza *et al.* 2022; Rao *et al.*, 2022). In addition, as documented in the previous major floods of the 21st century (2009 and 2012), the 2021 flood also occurred under LN conditions in the central equatorial Pacific. During the 2021 flood, an intensification of the continental Hadley circulation was also reported, producing in June 2021 the highest-ever level of the Negro River at the port in Manaus in 120 years of record (Figure 2). This flood surpassed the "once-in-a-century" Amazon flood of 2012 (Espinoza *et al.*, 2022).

The intensification of the hydrological cycle in the Amazon over the last decades (Gloor *et al.* 2013; Barichivich *et al.* 2018) is partly explained by changes in moisture transport coming from the tropical Atlantic, presumably caused by SST-induced northward displacement of the ITCZ (Marengo *et al.* 2013, 2018; Gimeno *et al.* 2020). Furthermore, at the beginning of the 21st century, there has been an unprecedented number of extreme drought events, which is related to the large-scale conversion of forests to pasture and cropland over the last decades across the region, altering the land–atmosphere interface and contributing to changes in the regional and local hydrological cycle (Zemp *et al.* 2017a,b; Garcia *et al.* 2018). Observed extreme climatic events that lead to a drier climate and drought can increase the risk of fires (Aragão *et al.* 2018 and references therein).

Evapotranspiration and land-use change

Precipitation and ET recycling are strongly correlated in the Amazon. About 48% of ET returns to the ground as precipitation, and about 28% of the precipitation that falls in the basin originated as ET (van der Ent *et al.* 2010). An estimated 25–56% of the precipitation falling on Amazon forests results from local to regional recycling within the ecosystem (Kunert *et al.* 2017). Deep-rooted vegetation pulls up soil moisture recharged during the wet season to maintain

Table 2. History of droughts and floods in the Amazon, indicating whether they are related to El Niño, La Niña or Sea Surface Temperatures SST anomalies in the tropical Atlantic Ocean. References listed in the table are from studies that assess causes and impacts of droughts or floods in the region. EN = El Niño; LN = La Niña; TNA = Tropical North Atlantic; TSA = Tropical South Atlantic; SSA = Subtropical South Atlantic; IP = Indo-Pacific Ocean. E/C index suggests a strong warming in the Eastern Pecific/Central Pacific region during EN event. Updated from Marengo and Espinoza (2016), Marengo et al. (2018) and Espinoza *et al*. (2019).

Year	Extreme seasonal event	Causes
1906	Drought	EN (E and C indices suggest a strong C event in 1905, and weak E and C events in 1906)
1909	Flood	?
1912	Drought	EN-E
1916	Drought	EN
1922	Flood	?
1925-26	Drought	EN
1936	Drought	?
1948	Drought	EN
1953	Flood	weak LN
1958	Drought	EM
1963-64	Drought	warm TNA
1971	Flood	LN?
1975	Flood	LN?
1976	Flood	LN
1979-81	Drought	warm TNA
1982-83	Drought	EN-E + warm TNA
1989	Flood	LN (Cold anomalies were higher in the C region)
1995	Drought	EN-C + warm TNA
1997-98	Drought	EN-E + warm TNA
1999	Flood	LN (Cold anomalies over C region)
2005	Drought	warm TNA (+moderate EN-C)
2009	Flood	warm TSA
2010	Drought	EN-C + warm TNA
2012	Flood	LN + warm TSA
2014	Flood	warm IP + warm SSA
2015-16	Drought	EN-C (also strong EN-E in 2016), warm TNA
2021-22	Flood	LN (Cold anomalies over C region), warm TSA

ET at the same level in the dry season (da Rocha *et al.* 2004; Juárez *et al.* 2007; Costa *et al.* 2010), with an increase of ET during the late dry season (da Rocha *et al.* 2009; Sun *et al.* 2019). Constant or even increasing ET during the dry season is central for maintaining relatively humid atmospheric moisture and promoting increased rainfall during the transition from the dry to the wet season (Li and Fu 2004; Wright *et al.*, 2017). In addition, especially over the southern Amazon, ET provides moisture for the downwind region, including the Andean mountains, and helps buffer against droughts across the Amazon (Staal *et al.* 2018; Sierra *et al.* 2021).

Changes in ET are influenced by climate variability, forest type, and forest conversion to crop/pasture (da Rocha *et al.* 2009; Costa *et al.* 2010; Wongchuig *et al.* 2021). Surface net radiation is the main control of ET year-round, especially over the wet equatorial Amazon, but also greatly affects surface conductance in other regions, generally the eastern, southern, and southeastern transitional tropical forests towards the boundary to the Cerrado biome (Marengo et al. 2021 and references therein). The degree of these influences can vary regionally, e.g., surface radiation is the main controller of ET in the wet equatorial Amazon, whereas stomatal control is an important controller in regions with strong dry seasons, as in the southern Amazon (Costa *et al.* 2010; Rodell *et al.* 2011).

The influences of climate variability, such as ENSO on ET, are through changes in cloudiness and radiation and have been observed directly by flux measurements and indirectly by satellites. Flux tower measurements have shown that the 2002 EN reduced ET by 8% in the southern Amazon (Vourlitis *et al.* 2015). Satellite-based estimates of ET using the moisture budget approach also showed reductions in ET and rainforest photosynthesis during the 2015/2016 EN over the Solimões and Negro basins (e.g., Sun *et al.* 2019). An analysis by Baker et al. (2021) revealed a gradient in ET from east to west/southwest across the Amazon Basin, a strong seasonal cycle in basin-mean ET primarily controlled by net incoming radiation, and no trend in ET over the past 2 decades. However, this approach has a degree of uncertainty due to errors in each of the terms of the water budget.

Land use strongly impacts on ET, especially during the dry season. Flux tower measurements showed an ET reduction over pastures as compared to two forest sites in the eastern Amazon (Santarém, Pará state, Brazil), from about -24% to -39% in the wet season and between -42% to -51% in the dry season. In the southern Amazon (Rondônia state, Brazil) the reduction from forest to pasture was less than 15% in the dry season, and the difference did not reach statistical significance in the wet season (da Rocha *et al.* 2009). Forests degraded by fire and timber extraction can have a 2 to 34% reduction in dry-season evapotranspiration (Lapola et al. 2023).

Changes in ET, especially during the dry season, significantly impact rainfall and wet season onset. In terms of the surface energy balance, the relationship between sensible and latent heat, known as the Bowen ratio, during the dry season strongly impacts on interannual variation at the onset of the wet season (Fu and Li 2004). The augmented surface dryness and resultant convective inhibition energy during the dry season have been a leading contributor to the delay of wet season onset over the southern Amazon in the past several decades (Fu *et al.* 2013). The 2005 drought reduced dry season ET and contributed to the delay of the wet season onset in 2006 (Shi *et al.* 2019). Thus, the response of ET to drought could have a legacy impact on rainfall of the subsequent wet season.

Long-term variability of moisture cycling

On average, the Amazon rainforest receives about 2000-2500 mm of rain each year, and much of this water comes sweeping in on winds from the Atlantic Ocean, while the forest itself also provides a substantial part of the rainfall, as water evaporates or transpires from leaves and blows downwind to fall as rain elsewhere in the forest (Salati and Vose 1984). Furthermore, the forest itself influences cloud formation and precipitation by producing secondary organic aerosols of mainly biogenic origin (Marengo *et al.* 2021 and references therein). Moisture transport into and out of the Amazon basin has been studied since the 1990s using a variety of upper air and global reanalysis datasets, as well as data from climate model simulations. During the wet season in particular, moisture is exported from the Amazon basin and transported via so-called "aerial rivers" to regions outside the basin (Arraut *et al.* 2012; Poveda *et al.* 2014; Gimeno *et al.* 2016, 2020; Marengo *et al.* 2004, 2018; Molina *et al.* 2019).

These aerial rivers represent the humid air masses that come from the tropical Atlantic and gain more moisture due to water recycling of the forest when crossing the Amazon. The aerial river to the east of the Andes contributes to the precipitation over southern Brazil and the La Plata River basin via the South American Low-Level Jet East of the Andes (SALLJ). This moisture feeds intense mesoscale convective systems, and heavy precipitation frequently develops near its exit (Zipser *et al.* 2006; Rassmussen and Houze 2016). During the major drought in the southern Amazon in the summer of 2005, the number of SALLJ events during January 2005, at the peak of the rainy season, was zero, suggesting a disruption of moisture transport from the tropical North Atlantic into the southern Amazon during that summer (Nobre *et al.* 2016a). The SALLJ transports large amounts of moisture from the Amazon basin towards the subtropics of South America, and evapotranspiration from the Amazon basin contributes substantially to regional precipitation patterns (Zemp *et al.* 2014; Staal *et al.* 2018; Gimeno *et al.* 2019). In recent decades, a significant increase in the northwesterly moisture flux occurred, especially in austral spring, summer, and fall, possibly enhancing precipitation and climatic extremes over southeastern South America (Montini *et al.* 2019). This is mainly due to an expansion in the frequency and intensity of the SALLJ in the northern Andes (Jones 2019).

Land-use change in the Amazon basin may weaken moisture recycling processes and have stronger consequences for rainfed agriculture and natural ecosystems regionally and downwind than previously thought. The intensity of the South American monsoon is quite variable. For example, the atmospheric moisture transport during the austral summer (December to February) was 28.5 x 10^7 kg s^{-1} in the dry year 2004–2005 and 45.1 x 10^7 kg s^{-1} in the wet year 2011–2012, as compared to the average moisture transport of value of 31.4 x10^7 kg s^{-1} (Costa 2015). Reducing atmospheric moisture transport and the respective recycling of precipitation due to deforestation and land-use change in climate-critical regions may induce a self-amplified drying process which would not only further destabilize Amazon forests in downwind regions, i.e., the southwestern and southern Amazon but also reduce moisture export to southeastern Brazil (Zemp *et al.* 2017a; Staal *et al.* 2018).

In sum, around 25–50% of annual rainfall in the tropical Andes originates as transpiration from Amazonian trees, land-use change in these regions may weaken moisture recycling processes and may have stronger consequences for rainfed agriculture and natural ecosystems regionally and downwind than previously thought (Zemp *et al.* 2014). Removal of forests increases temperature, reduces evapotranspiration, and has been shown to reduce precipitation downwind of deforested areas (Nobre *et al.* 2016b; Staal *et al.* 2018; Sierra *et al.* 2021).

CLIMATE CHANGE SCENARIOS IN THE AMAZON

Spracklen and Garcia-Carreras (2015) assessed relevant peer-reviewed literature published over the previous decades on analyses of models simulating the impacts of Amazon deforestation (deforested areas varied from 10% to 100%) on rainfall. Results show that more than 90% of simulations agree on the sign of change and deforestation's influences on regional rainfall as simulated by the model; in general, deforestation reduces in rainfall. However, there are some differences among models, mainly in amplitude, magnitude, and predictability, that strongly depend on the spatial and temporal scales considered. For example, a model that examined the connection between changes in land cover in the Amazon and the spatiotemporal variability of precipitation in South America found that it resulted in more extreme precipitation events and a longer dry season (Alves *et al.* 2017).

Future changes in temperature and precipitation across the Amazon, considering the temporal means and extremes from the Coupled Model Intercomparison Program CMIP5 models used in the IPCC Fifth Assessment Report IPCC AR5 have been used widely for studying future climate over the Amazon (e.g., Gulizia and Camilloni 2015; Joetzjer *et al.* 2013). These studies show that temperature is generally better simulated than precipitation in terms of the amplitude and phase of the seasonal cycle, and the multi-model mean is closer to observations than most individual models. Averaged over the Amazon, warming projected in a RCP4.5 scenario from IPCC AR5 is about 2 ºC higher than the present-day temperature, whereas, in a RCP8.5 scenario, temperature increases will reach more than 6 ºC by the late 21st century (Figure 7). This could have a negative effect on forest health and functioning and its effect on the regional and global climate. However, large uncertainties still dominate the hypothesis of an abrupt, large-scale shift of the Amazon Forest caused by climate change (Lapola *et al.* 2018).

There is some confidence that annual mean precipitation will decline in the Amazon over the 21st century, more pronouncedly in the east and south of the region as shown

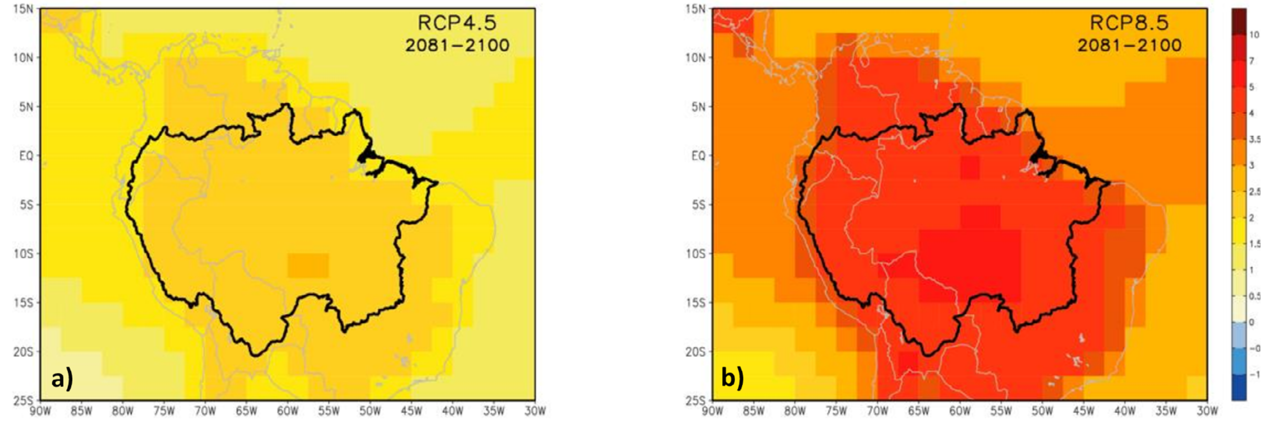

Figure 7. Multi-model CMIP5 average percentage change in annual mean near-surface air temperature over the Amazon region projected for the period 2081-2100 relative to the reference period 1986–2005 under the RCP4.5 (2 ºC warming) and RCP8.5 (>6.5 ºC warming) forcing scenarios. Plot created based on the CMIP5 dataset (Taylor *et al.* 2012) used in the IPCC AR6.

in the IPCC Sixth Assessment Report IPCC AR6 (IPCC 2021) and in (Figure 8). However, there is a considerable variation between models and a nearly even split between models that get wetter and drier (Baker *et al.*, 2021). GCMs and RCMs projections suggested a decrease in precipitation over the southern Amazonia, and an increase in precipitation over southeastern South America over the 21st century (Almazroui *et al.* 2021; Ortega *et al.* 2021). Small changes in rainfall are projected under a moderate emission scenario (IPCC 2021). In line with observed historical precipitation trends, dry season length is also expected to expand over the southern Amazon (Boisier *et al.* 2015). While a great deal of uncertainty exists regarding future rainfall projections over the Andean-Amazon region, most studies show that an intensification of the hydrological cycle is likely to occur in this region, with the intensification of wet conditions in the north and dry conditions in the south, as observed during the recent decades (Marengo *et al.* 2021 and references therein).

The most severe impacts of climate change are often related to changes in climate extremes. There is general model agreement on an increment in precipitation by the end of the 21st century over the northwestern Amazon, while annual mean precipitation is projected to decline in the future in the eastern Amazon under a high emission scenario (Figure 9). The differences in magnitude between the moderate emission scenario (RCP4.5) and the high emission scenario (RCP8.5) are even greater (on the order of 10%) in the eastern and southern Amazon and can be expected to lead to a change in the likelihood of events such as wildfires, droughts, and floods. The maximum number of consecutive dry days (CDD) is projected to increase substantially (Figure 9a). The projected changes indicate not only more frequent CDD but also increases in intense precipitation, as shown by the maximum five-day precipitation accumulation (RX5day) index, a strong contributor to floods (Figure 9a) (Seneviratne *et al.* 2021; Ranasinghe *et al.* 2021; Gutiérrez *et al.* 2021).

Lan *et al.* (2016) found no signals of a higher frequency of extreme precipitation events over the Amazon rainforests but found a widespread decline in precipitation over the Amazon (especially over the eastern Amazon) from 2081-2100 versus 1981 to 2000. However, although trends mainly were statistically non-significant at the 95% confidence level (Student's t-test), suggesting no change.

On other water cycle components, declining trends in evapotranspiration ET, total runoff, and available water were also observed. Decreased precipitation declines are countered by evapotranspiration and total runoff, resulting in an almost neutral trend in the terrestrial water flux over the Amazon (Figure 9b). Results also indicated that soil moisture will decrease in the Amazon in the future (1981-2000 vs. 2081-2100), and the seasonal range of total soil moisture will widen (Kirtman *et al.* 2013). The results are also supported by Zaninelli *et al.* (2019), who projected a decrease in humidity and surface runoff over the southern and southeastern Amazon for 2071-2100.

Mohor *et al.* (2015) suggest climate change will likely reduce discharges in the Madeira, Tapajós, and Xingú river basins. Their results suggest that, for temperature increases over 4 °C, discharges are more sensitive to precipitation changes than for lower temperature increases. However, climate sensitivity largely varies between basins, affected by surface characteristics and the basin's scale. Hydrologic projections considering the conversion of tropical forests to pasture and farming were carried out by Siqueira-Junior *et al.* (2015) and Guimberteau *et al.* (2017), applying potential scenarios for land-use and land-cover change in Amazonian basins, showing that augmented deforestation in the basins results in lower rates of evapotranspiration and higher runoff generation, which counterbalances the climate change effects on streamflow.

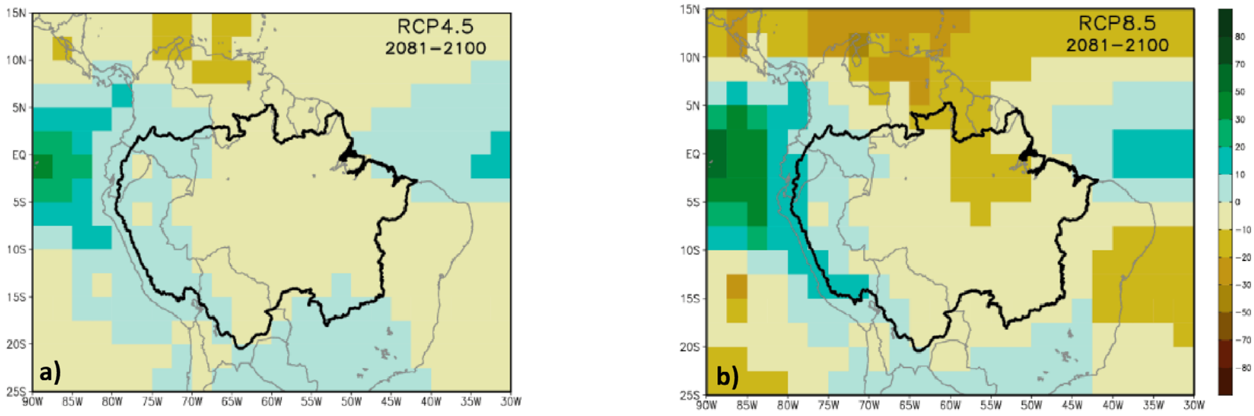

Figure 8. Multi-model CMIP5 ensemble percentage change in annual mean precipitation in the Amazon region for the period 2081-2100 relative to the reference period 1986–2005 under the RCP4.5 (2 ºC warming) and RCP8.5 (>6.5 ºC warming) forcing scenarios. Plot created based on the CMIP5 dataset (Taylor *et al.* 2012) used in the IPCC AR6.

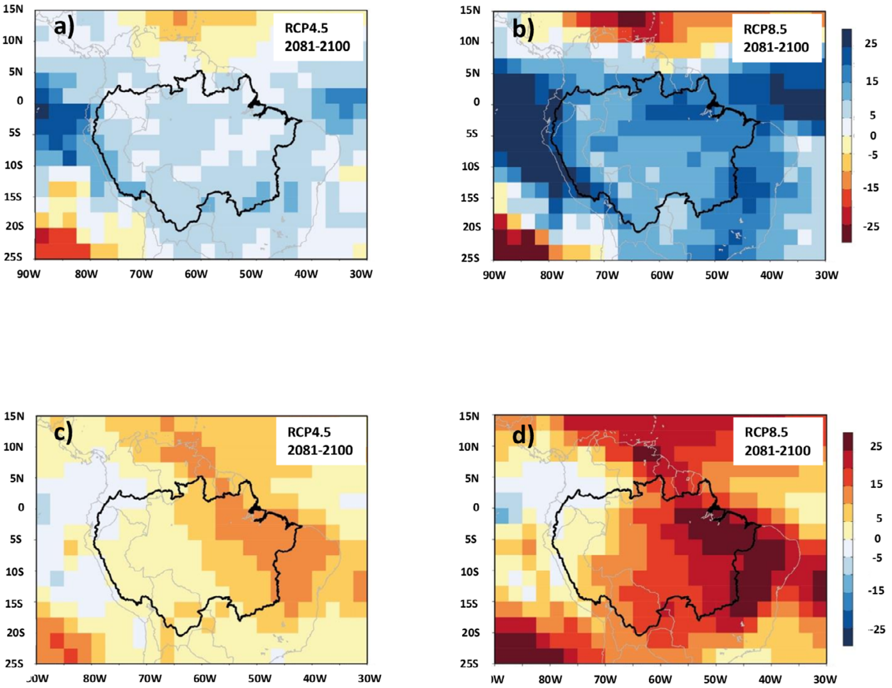

Figure 9. Projected percent changes in the annual maximum five-day precipitation accumulation (RX5day) (**A, B**) and projected change in the annual maximum number of consecutive dry days (CDD) (**C,D**) in the Amazon region when precipitation is less than 1 mm, for the period 2081–2100 relative to the reference period 1986-2005 in the RCP4.5 (2 ºC warming) and RCP8.5 (>6.5 ºC warming) scenarios forced with CMIP5 models. CDD index is the maximum number of consecutive dry days per time period with daily precipitation amount of less than 1 mm. It was calculated for the entire historical (1986-2005) and future (2081-2100) period. Similar to the RX5day index. Plot created based on the CMIP5 dataset (Taylor *et al.* 2012)) used in the IPCC AR6.

The CMIP phase 6 (CMIP6) simulations agree on the sign of decreasing future rainfall trends in the Amazon, with droughts projected to increase in duration and intensity under global warming (Ukkola *et al.* 2020). These models show drying across the eastern and southern Amazon in the 21st century (Parsons *et al.* 2020), and most agree on future decreases in soil moisture and runoff across most of the Amazon in all emission scenarios (Cook *et al.* 2020). Under different global warming scenarios, the Amazon, notably the central Amazon, is projected to experience a 75% increase in hot days and a decrease in maximum five-day precipitation accumulation (Rx5day). This region is also projected to have increased meteorological droughts (Santos *et al.*, 2020). The combined effects of large-scale deforestation in the Amazon and global warming can subject millions of people in the region to a heat stress index beyond the level of survivability by the end of the 21st century (Oliveira *et al.* 2021). The results of the latter authors indicate that the effects of deforestation alone are comparable to those of the worst-case scenarios of global warming under the RCP8.5 scenario.

Climate and land use changes are pushing the Amazon closer to its projected "bio-climatic tipping point" (Lovejoy and Nobre 2018) faster than any other tropical forest, especially in the eastern and southern part of the Amazon basin. This is despite large uncertainties in precisely defining thresholds for tipping points. There is feedback between drought and deforestation in the Amazon (Staal *et al.* 2020). Deforestation and climate change, through the increase of the dry season and drought frequency, may already have pushed the Amazon close to a critical threshold of rainforest dieback (Boulton *et al.* 2022; Marengo *et al.*, 2022). Recent work by Canoa et al (2022) shows that the response of tropical forests to more frequent weather extremes and long-recovery disturbances like fires remains uncertain.

CONCLUSIONS AND RECOMMENDATIONS

Our trend studies demonstrate that there is no unidirectional signal towards either wetter or drier conditions over the entire Amazon during the observational records. However, for specific regions, there are consistent trends. In general, the size and direction of the trends depend on the details of the dataset used, such as the length of rainfall datasets, if there are breaks in the record, and if and how they are aggregated. For surface temperature, while warming appears in all datasets, the magnitude of the warming depends on the length of the observational period. However, all datasets show that the last 20 years have been the warmest in the Amazon, with some suggesting that the 2020's decade may be the warmest year over particular sections of the basin.

An intensification of the hydrological cycle in the region has been observed in various studies (Gloor *et al*. 2013; Barichivich *et al*. 2018; Wang *et al*. 2018), and this is reflected in the recent increase in extreme hydro-climatic events (Marengo and Espinoza 2016; Marengo *et al*. 2018; Espinoza *et al*. 2022). Furthermore, during the last four decades, various studies show an enhancement of convective activity and increases in rainfall and river discharge over the northern Amazon and decreases of these hydroclimate variables over the southern Amazon (Paca *et al*. 2020, and references therein) creating a "dipole" of rainfall in the Amazon region.

The lack of complete long-term and homogeneous historical climate and river data in different sub-basins still limits our current interpretation of water cycle and trends in the Amazon. At interannual time scales ENSO, and TNA have played an important role in temperature and rainfall variability. At the decade scale, teleconnections with anomalies of Pacific and Tropical and Subtropical Atlantic SSTs, as represented by the AMO, PDO, and others, have shown impacts on rainfall anomalies. The role of vegetation and land use in the region on hydrological and temperature variability has been demonstrated by modeling and observational studies.

As shown by model projections, large-scale deforestation and the prospects of global climate changes can intensify the risk of a drier and warmer Amazon. Changes in seasonal distribution, magnitude, and duration of precipitation may have significant impacts on Amazon hydrology and other sectors, since rainfall reductions may occur predominantly in the dry-to-wet transition season. While land-use change is the most visible threat to the Amazon ecosystem, climate change is emerging as the most insidious threat to the region's future creating feedback loops and synergies with land-use changes.

The observed tendencies can be different in the western and eastern Amazon, and the projected changes suggest a drier and warmer climate in the east, while in the west, rainfall is expected to increase in the form of more intense rainfall events. The level of confidence is determined by the level of convergence among model signals of change from CMIP5 and CMIP6 models (Kirtman *et al*. 2013; IPCC 2021).

We must accept that our knowledge of temperature and rainfall trends is limited because of the lack of complete, homogeneous, and long-term climate records needed to identify climate trends and the occurrence of extreme events. Threfore, the most important changes in the hydroclimate system occur in the transition between the dry and the rainy season, with a warmer, longer, dryer dry season, which has significant ecological and hydrological consequences. Future studies should focus on this transition season. This limitation leads to considerable uncertainty in determining the recent intensification of the hydrological cycle in the Amazon and how it compares to other intensifications of the hydrological cycle that may have occurred in the past. There is an urgent need to rescue data and integrate it among Amazon countries, with free access for the scientific community and other private and public stakeholders. High-resolution climatic and hydrological gridded datasets for the Amazon should be generated through cooperation between state and national meteorological services, international climate agencies, universities, and private datasets.

When considering the political and practical implications of our assessment, it is important to note that even though the CMIP5 and CMIP6 models simulated some aspects of the observed present-day climate reasonably well, key processes such as evapotranspiration, clouds and precipitation, vegetation, and climate feedbacks are highly uncertain and poorly represented in the current generation of GCMs. Because the climate projection does not represent well the complex synergetic and antagonistic effects linking climate to land-use change, model projections likely have considerable uncertainty, particularly for rainfall projections. With increased field experiments and high-resolution models, we can enhance understanding and modeling of complex interactions and discern where improvements should be made. For example, a possible increase in dry conditions and higher temperatures may induce low water levels and elevated tree mortality due to fires. This is more pronounced at the southeastern edges of the Amazon between forest and cerrado due to the relation between land-use change and fire.

Analyses of field data and ecological theory raise concerns about the possibility of the Amazon crossing a tipping point leading to catastrophic tropical forest loss. Therefore, there is a need for a better observational network of the water cycle in the region at the regional level. This should include flux towers to measure ET and more rainfall stations to have a better of space-time rainfall variations. In addition, more numerical experiments on transient deforestation in Amazonia would be needed to see the impacts of land use changes in the water cycle inside the Amazon and the moisture transport outside the region. This will show the importance of the Amazon region on nearby regions that are strategically important for regional economic activities such as hydroelectric generation and agribusiness, so water, food, and energy security will be guaranteed.

Finally, there is a strong need for better education of local people and policy and decision-makers on climate, hydrology, and the atmospheric sciences, especially the impacts of land use and climate change on their livelihoods. Traditional and cultural knowledge are also invaluable sources of climate-proxy information. We must improve ground monitoring, data accessibility and quality, research infrastructure, and climate model development. Furthermore, model development and calibration at key research centers and universities working with climate modelers in the region can promote collaboration among scientists, ideally with support from national and/or international funding agencies.

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