Chapter 22

Science Panel for the Amazon (SPA)

Working Group 8

CLIMATE CHANGE IN THE AMAZON: TENDENCIES, IMPACTS AND ECOLOGICAL CONSEQUENCES

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TECHNICAL SUMMARY

The focus of the SPA WG8 is on the observed and projected changes in temperature, river discharge and precipitation patterns and extremes in the Amazon region, as well as their impacts and possible thresholds. The emphasis is on possible impacts of extremes of climate variability and climate change on biodiversity and ecological processes. An assessment of the impacts of climate change in the functioning of the Amazon forest, especially the risk of forest dieback caused by natural climate variability and human drivers of change is also provided at the end of this chapter. In the last 20 years, three extreme drought (2005, 2010, 2016) and flood episodes (2009, 2012, 2014) have occurred in the Amazon. While these events have been linked to natural climate variability (El Niño, warmer tropical North Atlantic), land use changes have amplified the effects of impacts of these extremes, by increasing the risk of fires and the vulnerability of human and natural systems. Over the long-term projected climate change in the Amazon may have strong impacts on the water cycle in the region, as well as on the structure of the forest, and this at the end may impact regional and global climate.

Variations and change in climate, hydrology, air temperature and moisture transport in the Amazon have been investigated extensively by many researchers using diverse data sets and time periods. The changes in the pulse of floods and droughts and how those changes reflect the observed intensification of the hydrological cycle in the region, and how these features may behave in the future are critical topics to be assessed. The impacts of observed climate extremes and future warmer climate on biodiversity, flora and fauna and vegetation stability and flora resilience are discussed in terms of vegetation and land use changes and climate feedbacks. Fire, biomass burning emissions and impact on rainfall in and outside the region are also discussed based on recent literature, especially field experiments and modeling studies. The impact of biomass burning emissions in forest carbon cycling will also be assessed. The intention is to investigate whether or not the extremes of warming/drying coupled with warming and land use change increase the risk of forest die back and so leads to a possible collapse of the Amazon forests.

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LONG-TERM VARIABILITY, EXTREMES AND CHANGES IN TEMPERATURE AND HYDRO METEOROLOGY

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ACRONYMS AND ABBREVIATIONS

AMO	Atlantic Multidecadal Oscillation
ANA	Agência Nacional das Águas
B.P.	Before the Present
CCST	Earth System Science Center
CDD	Consecutive Dry Days
CEMADEN	Centro Nacional de Monitoramento e Alerta de Desastres Naturais
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
CMIP5	Couple Model Intercomparison Programme Version 5
CNRS	Centre National de la Recherche Scientifique
CPM	Convection-Permitting Modeling
CRU	Climate Research Unit
DJF, MAM, JJA, SON	December-February, March-May, June-August. September-November
ECMWF	European Center for Medium Range Weather Forecast
EN, LN	El Niño, La Niña
ENSO	El Niño-Southern Oscillation
ERA	ECMWF Reanalyses
ET	Evapotranspiration
GCM	Global Climate Model
GISS	Goddard Institute for Space Studies

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GHG	Greenhouse Gases
GPCP	Global Precipitation Climatology Project
GPCC	Global Precipitation Climatology Centre
INPE	Instituto Nacional de Pesquisas Espacias
IAG	Instituto de Astronomia, Geofísica e Ciências Atmosféricas
INPA	Instituto Nacional de Pesquisas da Amazônia
ITCZ	Intertropical Convergence Zone
IPO	Interdecadal Pacific Oscillation
IRD	Research Institute Pour Le Développement
JAS	July-August-September
MODIS	Moderate-Resolution Imaging Spectroradiometer
PDO	Pacific Decadal Oscillation
RCP	Representative Concentration Pathway
SALLJ	South American Low-Level Jet
SAMS	South American Monsoon System
SST	Sea Surface Temperature
TNA	Tropical North Atlantic
TRMM	Tropical Rainfall Measurement Mission
UCLA	University of California Los Angeles
USP	Universidade de São Paulo

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UV	Universitat de València
VOC	Volatile Organic Component

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KEY MESSAGES

- Recent intensification of the Amazon hydrological extremes due to intensification of the interannual variability: the flood return period has increased from 20 years during the first half of the 20th century to 4 years since 2000: Regional discharge (Q) have increased in NW Amazon during the high-water season (1974-2009) and decreased in the SW Amazon during the low-water season (1974-2009).
- Recent severe droughts are linked to ENSO and/or TNA SST anomalies. The Indian Ocean also plays a role. SST indices based on EN3.4 region do not provide enough information about impacts due to different EN types.
- Lengthening of the dry season and changes in the frequency and intensity of extreme drought episodes are probably the most important threats for society and Amazonian ecosystem and wildlife. Current data show that the dry season has expanded by about 1 month in southern Amazon region since the middle 1970's up to present day.
- Warming over the Amazon is clear, but the magnitude of the warming trend varies with the dataset. The warming trend is more evident from 1980, and enhanced since 2000, with 2015-16 and 2020 among the warmest years in the last three decades.
- Identification of climate change is still difficult to determine due to short duration of the climate records, therefore, climate modeling studies simulating Amazonian deforestation show significant reductions in rainfall over the Amazon, affecting regional hydrology and thus increasing the vulnerability of ecosystem services for the local and regional population in and outside Amazonian region.

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ABSTRACT

This chapter discusses observed hydroclimatic trends and also projections of future climate in the Amazon. Warming over this region is a fact, but the magnitude of the warming trend varies among datasets and length of period used. The warming trend has been more evident from 1980, and 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 southern Amazon. Changes in floods and droughts largely due to natural climate variability and land use change are also assessed. For instance, in the first half of the 20th century we had extreme flood events every 20 years. Since 2000 this has changed to 1 severe flood every 4 years. During the last four decades, northern Amazon has experienced enhanced convective activity and rainfall, in contrast to the decreases of convection and rainfall in southern Amazon. Climate change in the Amazon will have impacts at regional and global scale. Significant reductions in rainfall are projected for eastern Amazon. This will have consequences in the regional hydrology, consequently, increasing vulnerability of ecosystem services for the local and regional population in and outside the Amazon.

Keywords: Amazon, Climate change, Land-use change, Warming, Moisture transport, Drought, Floods, Climate models, Climate variability, Climate trends

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GRAPHICAL ABSTRACT

Observed and projected changes in the Amazon shows that current climate and hydrology tendencies can be differentiated in both the spatial and temporal domains, with two seesaw kind of spatial patterns, north-south and west-east, and an intensification of the wet and dry seasons. In the present, northwestern Amazon shows an increase in rainfall and runoff, while in the southern part tendencies are the opposite. The region including central and eastern Amazon do not show a significant rainfall trend as a whole. However, observations suggest a trend towards an increase in rainfall extremes and the intensification of the pulse of drought and floods, with almost neutral trends for mean annual rivers' discharges. Temporal series of temperature evidence an overall warming over the Amazon in the last recent decades, especially from year 2000 to present over eastern Amazon. Evapotranspiration shows a reduction in southern Amazon, probably related to land use change, but uncertainties are still high due to lack of systematic observations across the basin. This analysis of changes and trends was conducted from literature review of trends based on different observational, reanalysis and satellite datasets of rainfall, temperature, and river discharge, and different trend methodology assessments (parametric and non-parametric techniques), leading to different levels of confidence, consistency and magnitude of trends.

Projections show a drier and warmer climate in eastern Amazon, leading to an increase in evapotranspiration. Western Amazon will also experience warmer conditions, but rainfall is expected to increase in the form of more intense rainfall events, leading to increasing runoff and decreasing evapotranspiration in northwestern Amazon. However, in the Amazon-Andes region, the spatial resolution of the CMIP5 models is insufficient to reproduce the main atmospheric features and projections show high uncertainties. The level of confidence is determined by the level of convergence among model signals of change from CMIP5 (Kirtman et al., 2013) and CMIP6 models (Cook et al., 2020) models.

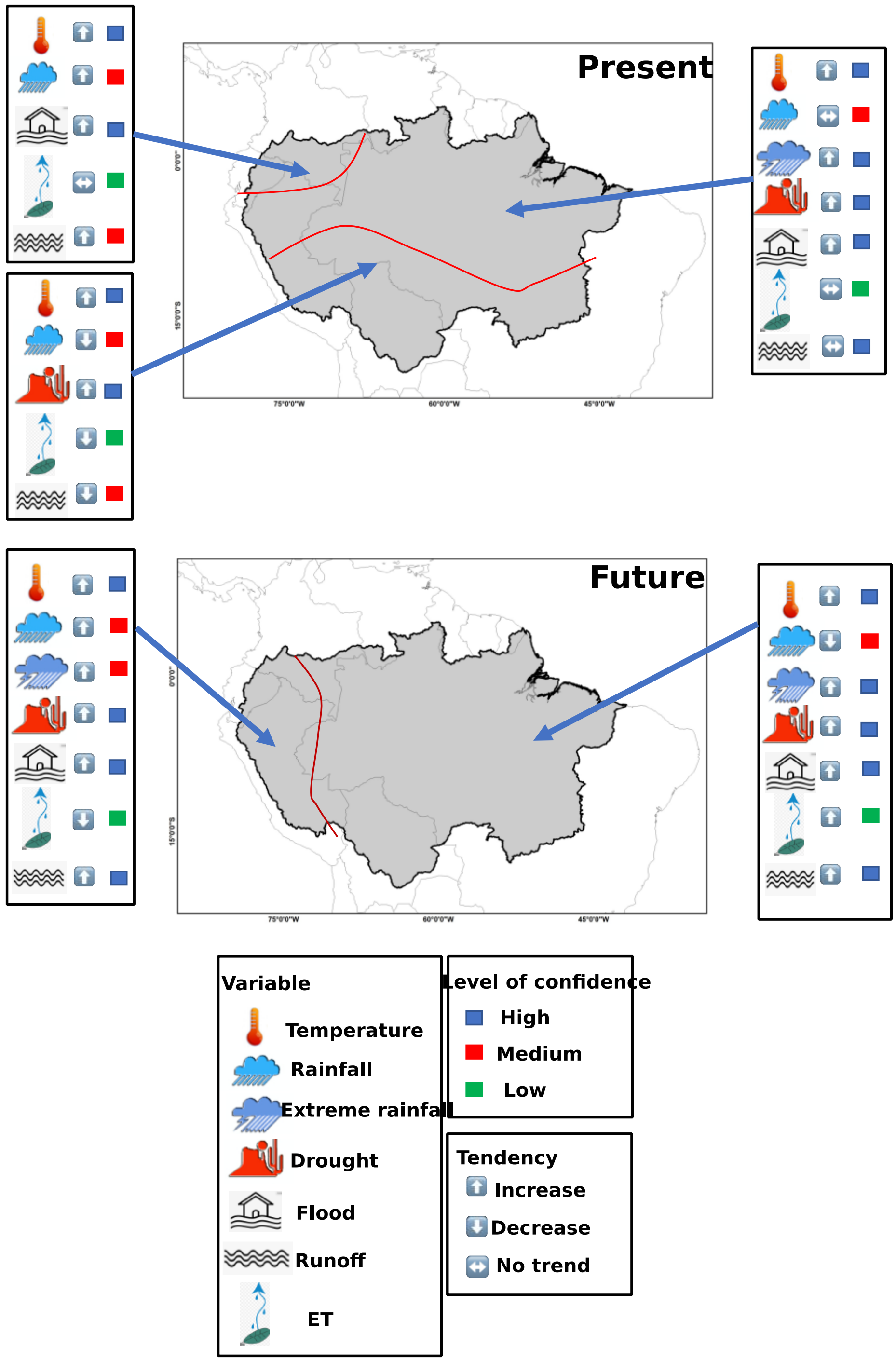

Figure Graphical Abstract. Summary of observed and projected changes of climate in the Amazon (based in several studies-see Magrin et al., 2014; Marengo et al., 2018; and references quoted therein). The level of confidence in future projections is determined by the level of convergence among model signals of change from CMIP5 (Kirtman et al., 2013) and CMIP6 (Cook et al., 2020) models.

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1. INTRODUCTION

This chapter provides an updated review of literature on climate and hydrology in the Amazon basin, including some of the classics and new studies developed in the recent decades, with the objective to answer these key questions relevant to the current and future functioning of the Amazon forest on regulation of local and regional climate: What are current trends in hydrometeorology, moisture transport and temperature in the Amazon? Are there signals of intensification or alteration of the hydrological cycle in the Amazon? Is this due to climate variability or human induced climate change? What about the length of the dry season? Is there an increasing variability of occurring droughts and floods in the Amazon? If so, are they due to El Niño (EN) or Tropical Atlantic or land use change, or a combination of them? How did EN and drought vary in the past as suggested by paleoclimate records? What are the expected changes in Amazonian climate due to the increases of greenhouse gases (GHG) and deforestation? What would be the impacts at regional and global scale?

2. LONG TERM VARIABILITY OF TEMPERATURE AND EXTREMES: WARMING TRENDS

Several studies have identified positive air temperature trends in the Amazon, and the magnitude of the trends depend on the data (stations or gridded based data, reanalyzes or satellite observations), methodologies (linear and non-linear), length of the climate records, region and season of the years. The early study by Victoria et al. (1998) used station data for the Brazilian Amazon and quantified an increasing trend of +0.56°C/century during 1913-1995. Malhi and Wright (2004) study trends in temperature over Amazonian tropical forests. They use the CRU dataset for 1960-1998, and for the subperiod 1976-1998. They identify positive temperature trends, that were steeper in 1976-1998 for the region. Jiménez-Muñoz et al. (2013) updated the analysis provided by Malhi and Wright (2004) by using the European Center for Medium Range Forecast Reanalysis ECMWF reanalysis (ERA-Interim) for 1979-2012, and also MODIS remote sensing data from the 2000s. They identify warming patterns that vary seasonally and spatially. Strong warming over southeastern Amazon was identified during the dry season July to September, with a warming rate of +0.49 ºC/decade during 1979-2012 according to the ERA-interim data (Gloor et al., 2015).

A summary of these studies and the tendencies for the entire Amazonian basin or at the regional level are summarized in Table 22.1. For the purposes of this work, northern and southern Amazon are defined as the basin north and south of 5ºS, respectively. This definition considers the difference in rainfall seasonal cycle and the fact that the dry season south of 5ºS may have months with precipitation lower that 100 mm, which does not occur north of 5ºS (See Chapter 5).

Table 22.1. 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.

Region	Period	Data used	Trend	Reference
Brazilian Amazon	1913-1995	Station	+0.56 º 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)
All Amazon	1980-2013	CRU	+0.7 ºC	Gloor et al. (2015)
Southeastern Amazon (July-September)	1973-2013	Station	+ 0.6◦C	Almeida et al. (2017)
All Amazon	1950-2019	CRU, GISS	+ 0.6◦C	Marengo et al. (2018)
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)
Manaus	1980-2015	Station	+0.5 ˚C	Schöngart and Junk (2020)

All data show that the recent two decades were the warmest, though there are some systematic differences among the trends estimated by different data. The EN year 2015/16 was the warmest year followed by EN year 1997/98 (Almeida et al., 2017; Marengo et al., 2018). Analyses of temperature data from CRU and ERA 20C/ERA-interim reanalysis showed that 2016 was the warmest since 1850, with warming up to +1ºC annually, and months surpassing +1.5 ºC (Jiménez-Muñoz et al., 2016). Later analyses will show that 2020 was the among the five warmest from the recent decades.

Historical records show an increasing trend for all seasons. A greater warming rate was detected for June-August (JJA) and September-November (SON) seasons (Figure 22.1). A contrasting West-East pattern is observed. Warming rates were almost twice over eastern Amazon that over to western Amazon. Warming for 1980-2020 is higher than that for the period of 1950-1979, especially over eastern Amazon. This recent increase on the warming rate is not observed over southwestern Amazon during December-February (DJF) and March-May (MAM), with even a slight reduction on the warming rate for the period 1980-2019. However, trends for the period 1950-1979 are not statistically significant.

Warm (cold) anomalies correspond to EN (LN) events, but this link is more clearly evidenced in the case of warming due to EN than cooling due to LN. Significant anomalously warm temperatures were recorded over the last two decades (2000-2019), especially over eastern Amazon. Higher warming rates over eastern Amazon are attributed to effects of land cover change, and subsequent alteration of the energy balance (Davidson et al., 2012). The land cover alone also plays a role over southeastern Amazon, where tropical forests are bordered by other land covers such as Cerrado and pastures. In contrast, western Amazon is influenced by the Andes barrier and a transition from montane tropical forests to lowland forest, where temperature trends decline with elevation (Malhi et al., 2017).

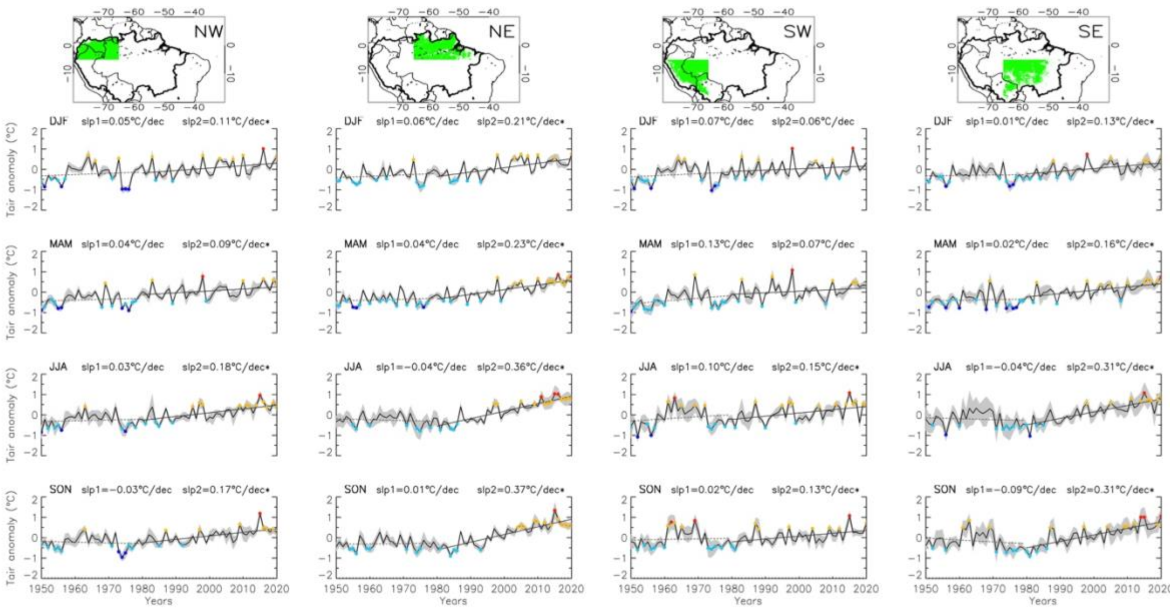


Figure 22.1. Temporal series of seasonal (DJF, MAM, JJA, SON) air temperature anomalies over different sectors of the Amazon (NW, NE, SW, SE) using CRUTS4 data for the reference period 1981-2010. Orange and red circles indicate temperature anomalies that surpass 1 standard deviation (σ) and 2σ, respectively, whereas light blue and dark blue circles indicate temperature anomalies below -1σ and -2σ, respectively. Linear trends for the period 1950-1979 and 1980-2020 are represented by a dashed line and a continuous line, respectively. Values of the slope for these two periods (slp1, slp2) are also included.

Local observations show that the average monthly temperatures in Manaus rose 0.5 ˚C during the period of 1980-2015 and the minimum and maximum monthly temperatures 0.3 ˚C and 0.6 ˚C, respectively in relation to the long-term average for the period 1910-1979. The highest temperatures recorded in Manaus since 1910 occurred during the dry season (September) of the year 2015. Strong EN events, as in 1997/98 and 2015/16, have a strong influence on air temperatures in the central region of the Amazon basin (Jiménez-Muñoz et al., 2016). In September 2015, the monthly average daily mean maximum and minimum temperature were 2.2-2.3 ˚C higher compared to the same month's averages for the previous five years (2010-2014). The average maximum temperature for October 1997 was 3.1 ˚C above this month's average for the previous five years 1992-1996 (Schöngart and Junk, 2020). Gatti et al (2021) found similar annual mean warming trends for the whole Amazon

(1.02±0.12˚C) as for the global average (0.98˚C) between 1979 and 2018. However, warming trends differ between months, and the largest increases were observed for three dry season months of August, September and October ASO (1.37±0.15˚C).

A recent study by Khanna et al. (2020) intercompares temperature trends from different datasets over the tropics. They show significant differences among datasets but a strong warming trend in wet climate regions such as the Amazon. Surface warming over these regions is amplified because of a positive radiative effect of high clouds and precipitable water in trapping the upwelling longwave radiation. This suggests a dominant role of atmospheric moisture in controlling the regional surface temperature response to GHG warming.

Other temperature indices also corroborate the warming trend over the Amazon (Dunn et al., 2020). A positive trend in the number of warm nights and reduction in the numbers of cool nights was detected, particularly in the last decade. The highest trend in warm days was observed during the JJA season. This behavior may be attributed to the combination of low seasonal/interannual temperature variability in this tropical region with land-use change effects. Seiler et al. (2013) reported a warming rate over Bolivia of 0.1 ºC/decade during the period of 1965-2004, with this warming rate was stronger over the Andes and during the dry season (JJA). Similarly, Lavado-Casimiro et al. (2013) found a significant warming trend in mean temperature of 0.09 ºC/decade during the 1965-2007 period in the Peruvian Amazon-Andes transition zone.

The overall conclusion is that warming over the Amazon region is a fact. The warming trend is better evidenced from 1980, and it is enhanced from 2000, where three exceptional droughts occurred in 2005, 2010 and 2015/16. Warming in 2015-2016 reached 1.2 ^{o}C, while in 2019-2020 warming was 1.1 ^{o}C, becoming the second warmest since 1960 in the Amazon. The warming trend varies with the temperature dataset (station, gridded data sets, reanalysis or satellite derived), the time period for which the trend was computed and the spatial scale (all Amazon or at sub-regional level). Because of the different climate regimes over the Amazonian region, the warming trend is also seasonally and regionally dependent. The seasonal and spatial distribution of trends (with a strong warming in the SE Amazon) is consistent with the climatic gradient across the Amazon from continuously wet conditions in the northwest (with low warming rates) to long and pronounced dry seasons in the southeast Amazon with high warming rates (Section 22.3.2).

3. LONG TERM VARIABILITY OF HYDROMETEOROLOGY OF THE AMAZON AND ANDEAN-AMAZON REGION

3.1. Long-term variability and trends of rainfall and rivers

Paleoclimate records based on pollen, speleothems, charcoal, lake and flood sediments, archeological sites and tree rings were used to reconstruct Amazonian climate. There are indications that the region was affected by severe drought events. These were longer and probably with stronger magnitude than any observed in the instrumental period. Parsons et al. (2018) found that the region has regularly experienced multi-year droughts over the last millennium. Meggers (1994) suggests the occurrence of prehistoric mega-EN events around 1500, 1000, 700 and 500 B.P. influenced tributaries in the Amazon and flood-sediments from the north coast of Peru. Granato-Souza et al. (2020) used tree-ring chronologies of *Cedrela odorata* from the eastern Amazon (Paru River basin), to reconstruct wet season precipitation totals for 1759-2016. They show remarkable drought events in the past such as an 18-year drought period (1864–1881), that includes also the EN event 1877-1879.

Historical trends in Amazonian precipitation have been reported in literature. These vary considerably among studies, depending on the data set, time series period and length, season, and the region evaluated (Malhi and Wright, 2004; Espinoza et al., 2009; Fernandes et al, 2015; Marengo et al., 2018). For the recent periods, most of the rainfall records start in the 1960s. This shortness of records hampers the quantification of long-term trends in the Amazonian region. Various rainfall data sets (e.g., Climate Research Unit-CRU, Global Precipitation Climatology Center-GPCC, Global Precipitation Climatology Project--GPCP, Climate Hazards Group InfraRed Precipitation with Station data-CHIRPS-, TRMM-Tropical Rainfall Measurement Mission, satellite and reanalysis products) rely on few rain stations with short records and low spatial coverage. These data sets have been “gap-filled” by interpolation and satellite data estimates. The fact that these studies consider different periods in their tendency analysis complicates the identification of a consistent, long-term precipitation trend in the Amazon and its subregions.

Extremes of the interannual rainfall and river variability in the Amazon can be, in part attributed to sea surface temperatures (SST) variations in the tropical oceans. This is manifested as the extremes of the El Niño-Southern Oscillation (ENSO) in the tropical Pacific, and the meridional SST gradient in the Tropical North Atlantic (TNA). No unidirectional total rainfall trends have been identified in the region as a whole. However, at regional and seasonal level the situation may be different (Espinoza et al., 2009; Satyamurty et al., 2010; Almeida et al., 2017, Marengo et al., 2018). On the long-term, decadal variations linked to natural climate variability have significant influence on rainfall trends because most of the rainfall records over the Amazon are only available 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). Fernandes et al. (2015) show that rainfall decadal fluctuations over western Amazon vary closely with those of the north-south gradient of tropical and subtropical Atlantic SST. This is also evident in the 250-yr record of reconstructed precipitation totals from tree-ring data (Granato-Souza et al., 2020).

Studies analyzing rainfall trends in the Amazon for the past four decades show a north-south opposite trend, including rainfall increase in the northern Amazon and rainfall diminution in southern Amazon. These trends may be a consequence of the intensification of the hydrological cycle in the region (Gloor et al., 2013; Barichivich et al., 2018; Garcia et al., 2018). This intensification of the hydrological cycle means an increase of the climate variability reflected by the increase in recent extreme hydro-climatic events due to stronger northeast trade winds that transport moisture into the Amazon (such is observed in Figure 22.2 a). Alves (2016) detected a statistically significant negative rainfall trend in southern Amazon at the dry-to-wet season during 1979–2014. Recent work by Espinoza et al. (2019a) shows that while southern Amazon exhibits negative trends in total rainfall and extremes, the opposite is found in northern Amazon, particularly during the wet season.

Wang et al. (2018) combine both satellite and *in situ* observations and reveals changes tropical Amazonian precipitation over the northern Amazon. According to these authors rainfall has significantly increased by +180 to + 600 mm in the wet season during the satellite era (1979 to 2015). Due to increasing rainfall in the northern Amazon the overall precipitation trend on a basin scale showed a 2.8 mm/year increase for the 1981-2017 period (Paca et al., 2020).

Water level data of the Negro River at Manaus, close to its confluence with the Solimões (Amazonas) River started in September 1902 (Figure 22.2). The mean amplitude between annual maximum (floods) and minimum (droughts) water level is 10.22 m (1903-2015) (Schöngart and Junk, 2020). Barichivich et al. (2018) indicate a significant increasing of daily mean water level of about 1 m over this 113-yr period. Furthermore, the authors observed a fivefold increase in severe flood events resulting in the occurrence of severe flood hazards over the last two decades in the central Amazon (2009, 2012-2015, 2017, 2019) and droughts in 2005, 2010 and 2015-16. During the last three decades the mean amplitude of water level at Manaus was increased. The Negro River incremented by almost 1.50 m compared to the period before (Schöngart and Junk, 2020). This growth is mainly caused by a basin-wide increasing river runoff during the wet season and a slightly decreasing discharge during the dry season, defined as the intensification of the hydrological cycle (Gloor et al., 2013), although trends vary substantially among subbasins (Espinoza et al., 2009; Gloor et al., 2015).

As seen in previous sections, the intensification of the hydrological cycle in the Amazon has been reported in several studies. Substantial warming of the tropical Atlantic since the 1990s plays a central role in this trend (Gloor et al., 2013; Wang et al., 2018). The warming of the tropical Atlantic increased 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). The simultaneous cooling of the equatorial Pacific during this period increased differences in sea level pressure and SSTs between both tropical oceans resulting in a strengthening of the Walker circulation, trade winds and deep convection over the Amazon (McGregor et al., 2014; Gloor et al., 2015; Barichivich et al., 2018).

River discharge records at the Negro, Solimões, Madeira and Amazon rivers show significant negative trends (p<0.05) during the low-water periods 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). These studies show the floods in the four rivers as indicated by their maximum water levels reached in 2014. Additionally, it can be observed that the maximum water level of the Negro river (Manaus) in 2005 was 28.10 cm, above the long-term average (1903-2015) of annual maximum water levels. Finally, a weak positive trend can be noticed in the levels at Manaus and Óbidos since the late 1980's (Figure 22.2).

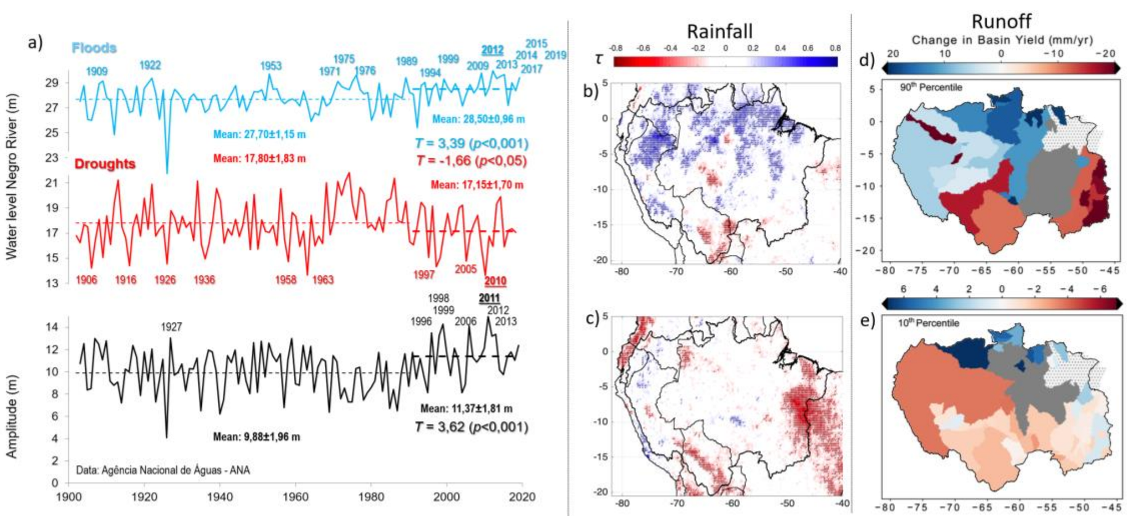


Figure 22.2. a) Maximum (floods, blue) and minimum (droughts, red) annual water level variability of Rio Negro at Manaus (1903-2020). Years corresponding to extreme hydrological years are indicated. The annual water level amplitude (droughts minus floods) is displayed in black line. Adapted from Schöngart and Junk (2020) based on data from the Brazilian National Agency of Waters (ANA). b) Spatial distribution of Kendall coefficient values (p<0.05 are indicated with a dark dot) showing the trend for 1981–2017 wet day frequency (>10 mm/day) during March-May season. c) As b, but for rainy days (>1 mm/day) during September-November season. b) and c) use CHIRPS data. Adapted from

Espinoza et al. (2019a). © Climate Dynamics. Reprinted by permission from Springer Nature. d) and e) slope of change in 90th and 10th percentile runoff (mm/yr), respectively, for the 1980-2014 period. Areas in grey represent no significant trend and areas with black dots represent no data. From Heerspink et al. (2020). © Journal of Hydrology: Regional Studies. CC license.

Hydroclimatic trends in the Andean-Amazon region are highly sensitive to the specific region and period considered. Long-term information is generally available from 1970 or 1980 onwards from a low density of meteorological network. Such low density and short records make it particularly 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). In various northern Andean-Amazon basins, precipitation trends have opposite signs (Carmona and Poveda, 2014; 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 a growth of around 17% of rainfall has been documented during the wet season (Espinoza et al., 2019a). Increasing rainfall over this region has been related to an intensification of the Walker and Hadley cells. This enhances convergence and convective activity towards the equator (e.g., Arias et al., 2015; Espinoza et al., 2019a). Consequently, since mid-1990s river discharge in the main northwestern tributaries of the Amazon river shows higher values during the high-water season (e.g., Caquetá-Japurá and Marañón rivers, Figures 22.2 and 22.3). In Santo Antonio do Iça station (Caquetá-Japurá river) a discharge increase of 16% was reported during the high-water season for the 1992-2004 period compared to the 1974-1991 period (Espinoza et al., 2009; Posada-Gil and Poveda, 2015). Increasing rainfall and discharge in the northwestern Andean-Amazon region are currently contributing to an intensification of extreme floods in the main channel of the Amazon river in Brazil during the last three decades (Barichivich et al., 2018).

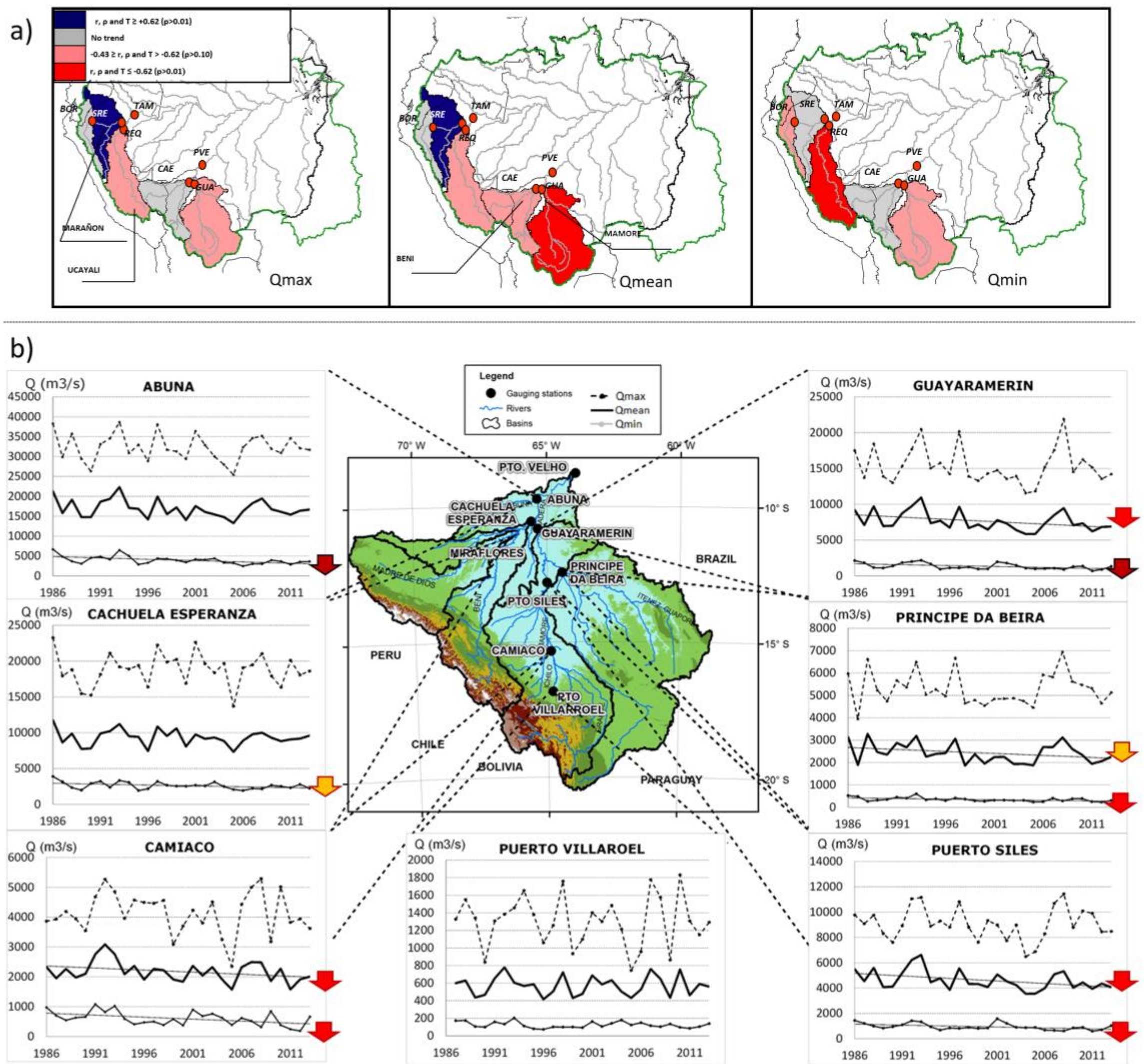


Figure 22.3. Discharge trends in the Ecuadorian, Peruvian and Bolivian Amazon-Andean rivers: a) Discharge trends for the annual maximum (Q_{max}, left panel), the mean annual (Q_{mean}, middle) and the annual minimum discharge (Q_{min}, right) computed in Borja (BOR) and San Regis (SRE) stations in Marañón river, Requena (REQ, Ucayali), Cachuela Esperanza (CAE, Beni) and Guayaramerin (GUA, Mamoré) for the 1990-2005 period. 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 SNO-HYBAM observatory. © Journal of Hydrology. Reprinted by permission from Elsevier. b) 1985-2013 evolution of Q_{max}, Q_{mean} and Q_{min} in the main rivers of the

Bolivian Amazon. Arrows indicate negative trends at $p<0.1$ (yellow), $p< 0.05$ (red) and $p<0.01$ (black red) of significant levels. Adapted from Molina-Carpio et al. (2017) based on data from SNO-HYBAM observatory.

In the southern part of the Peruvian Andean-Amazon basins decreasing rainfall was documented in general since the mid-1960s (e.g., Silva et al., 2008; Lavado-Casimiro et al., 2013; Heidinger et al., 2018), and consequently, discharge diminution was reported during the low-water season in the rivers that drain from the south, such as the Ucayali River in Peru. Annual discharge diminution was also detected downstream at Tamshiyacu (Amazonas River in Peru) and Tabatinga (upper Solimões River in Brazil) stations (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 instance, as a result of rainfall diminution, discharge during the low water season in the Tabatinga station, that drain rainfall over Andean-Amazon basins, diminished by 14% in the 1969-2006 period (Lavado-Casimiro et al., 2013).

In the Bolivian Amazon, a positive rainfall trend was identified in the 1965–1984 period, and a diminution of rainfall for the 1984-2009 period (Seiler et al., 2013). Rainfall diminution since the 1980s is mainly observed in the southern part of the Bolivian Madeira basin, involving the Mamoré and Guaporé basins (Figure 20.3). Related to rainfall changes, river discharge during the low-water season at Porto Velho station in the upper Madeira river shows a significant diminution of around 20% since the 1970s (Espinoza et al., 2009; Lopes et al., 2016; Molina-Carpio et al., 2017). Discharge diminution at Porto Velho station was detected for the 1974-2004 period (before the start of operation of the Santo Antonio and Jirau hydropower plants) and confirmed for the 1967-2013 period. Discharge diminution is also observed in the Mamoré and Guaporé rivers (southern tributaries of the Madeira river) at Principe da Beira (Guaporé), Puerto Siles (Mamoré), Guayaramerín (Mamoré) and Abuña (upper Madeira) stations for the 1985-2013 period (Molina-Carpio et al., 2017). The period analyzed here was before the building of the Santo Antonio and Jirau hydropower dams along the Madeira river main channel. Discharge diminution over this region is related to rainfall diminution and a lengthening of the dry season in southern Amazon (see Section 22.3.2).

For the Tocantins and Itacaiúnas basin, no significant trend was observed in the rainfall patterns. However, in Tocantins River, significant decrease in observed in discharge during the high-water season for the period 1980-2014 (Heerspink et al., 2020; Figure 22.2). In the Itacaiúnas River there was a significant upward trend observed in the minimum (baseflow) of this River. The increasing river flow and baseflow may be attributed to increasing deforestation and land use (Oti and Ewusi, 2016). This conclusion is based on the non-existence of trends in both the maximum and the mean flow patterns of the Itacaiúnas River, and no trend was observed in the rainfall patterns of this basin, together with a significant upward trend observed in the minimum (baseflow) of the Itacaiúnas River but not that of the Tocantins River. Studies by Timple and Kaplan (2017) show the impact of the Tucurui hydropower dam resulting in an increase of minimum water levels and decline of maximum water levels during the operational period in contrast to pre-dam conditions. Previously, Costa et al. (2003) compared the discharge of the Tocantins River (upstream of Tucurui dam) during periods with small and large deforestation in the catchment area of the Tocantins river basin, showed that due to deforestation increase the maximum water discharge increased and occurred earlier compared to the period of reduced deforestation.

Other factors leading to changes in the hydrological cycles are related to 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) and the implementation of hydroelectric power plants in the Amazon (Anderson et al., 2018). Costa et al. (2003) compared monthly discharge of the Tocantins River between periods with small (1949-1968) and substantial (1979-1998) land-use changes in the catchment area. Between both periods the authors observed a growth of 24% in annual mean discharge and of 28% of discharge during high-water period, although no significant difference in rainfall was observed between both periods. Massive and abrupt changes of the streamflow regimes are expected from hydroelectric power plants which change the hydrological cycle downstream of the dams as a consequence of power generation, resulting in complex spatiotemporal disturbances on floodplains downstream the dams (Resende et al., 2019). In particular, multiple dams in rivers which being built or are planned for the Tapajós, Xingú, Tocantíns-Araguaia, Marañón and many other river basins in the Amazon will have cumulative and cascading effects on the downstream hydrological cycle (Timpe and Kaplan, 2017). These disturbances affect the integral functioning of floodplains leading to massive losses of biodiversity and environmental services which at the end affect the welfare of Indigenous peoples and local communities as well as the society. Synergies of land-use and climate changes can be expected especially for the southern tributaries, such as the Madeira, Tapajós, Xingú and Tocantins-Araguaia basins, which experienced in the last decades high deforestation rates of their catchments, the implementation of several hydroelectric dams and an increasing dry season length (Timpe and Kaplan, 2017). In summary, the above-mentioned studies have documented the key role of the hydroclimatic variability of the Andean-Amazon and low-land Amazon rivers, such as the upper Madeira, upper Solimões, Caquetá-Japurá, Tocantins and Negro rivers for a broad understanding of hydrological system of the entire Amazon basin. This includes seasonal and interannual time scales, as well as long-term hydrological trends, extreme events, atmospheric and surface water balances (e.g., Builes-Jaramillo and Poveda, 2018).

3.2. Variability of the rainy and dry season

The rain falling in wet seasons helps the forest survive dry seasons as water is readily available in soils and roots. Dry seasons in the Amazon have become more intense in recent years leading to greater forest loss and increase in fire risk. Various studies have shown evidence of lengthening of the region's dry season, primarily over the southern Amazon region since the 1970s (Marengo et al., 2011, 2018; Fu et al., 2013 and references therein). This tendency can be related to large-scale influence of meridional SST gradients across the North and South Atlantic, or a strong influence of dry season 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 ITCZ (Arias et al., 2015). Arias et al. (2015), Espinoza et al. (2019b) and Leite-

Filho et al. (2019) identified rainfall diminution in the southern part of Peruvian, Brazilian and Bolivian Amazon basin during the dry season, that is associated with a delay in the onset of the SAMS and an enhanced atmospheric subsidence over this region (Espinoza et al., 2019b, Leite-Filho et al., 2019). Indeed, these atmospheric changes are also related to the increase in dry season length documented over the southern Amazon basin since the 1970s.

Various studies have also investigated rainfall seasonality showing changes in recent decades. The rainy season in the southern Amazon now starts almost a month later than it did in the 1970s as shown by Marengo et al. (2011) (Figure 22.4). 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 increment of about 6.5 ±2.5 days per decade over the southern Amazon region since 1979. During the 2015/16 drought, the onset of the rainy season in 2015 occurred 2–3 pentads (10-15 days) later than the normal onset date. Gatti et al. (2021) show that nnual mean precipitation has not significantly changed, but similar to temperature trends, August-October precipitation has decreased by 17%, enhancing the dry-season/wet-season contrast.

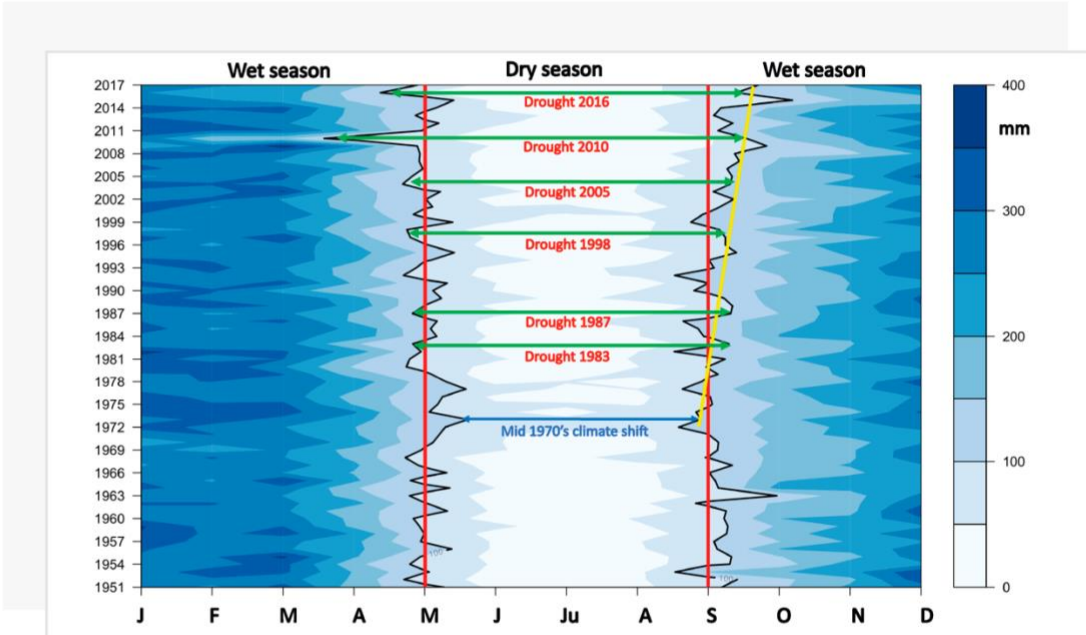


Figure 22.4. Hovmoller diagram showing monthly rainfall from 1951 to 2017 for southern Amazon (mm/month). The isoline of 100 mm/month is an indicator of dry months in the region (Sombroek, 2001). Drought years are indicated with green lines. Red lines show the average onset and end of the rainy season (Marengo et al., 2018, © Frontiers in Earth Science). Yellow line shows the tendency for a longer dry season after the mid 1970's climate shift. This climate shift detected in 1976–1977 shows a cold-to-warm sea surface temperature (SST) shift in the tropical Pacific Ocean, which has been associated with a phase change of the Pacific Decadal Oscillation (PDO) index (Jacques-Coper and Garreaud 2015).

The length of the dry season also exhibits interannual and decadal-scale variations linked to natural climate variability, apparently related to the 1970's climate's shift (Figure 22.5). Wang et al. (2011), Alves et al. (2017), Leite-Filho et al. (2019) suggest that land-use change influence dry season length in the Amazon, with a longer dry season and a late onset of the rainy season. 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 (Zhang et al., 2009). 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 (Costa and Pires, 2010; Lejeune et al., 2016). Recent work by Agudelo et al. (2018) and Arias et al. (2020) show that longer dry seasons in southern Amazon are also related to enhanced atmospheric moisture content over the Caribbean and northern South America regions, changes in moisture transport and moisture recycling in southern Amazon. This may be due to an enhanced contribution of water vapor from oceanic regions, and the growth of surface moisture convergence over the equatorial region linked to the warm surface temperature anomalies over the tropical Atlantic.

The analysis of 40 years of temperature and precipitation data over the Amazon by Gatti et al. (2021) shows the relationship between deforestation extent and decreases in precipitation and increases in temperature, mainly during the dry season, with different trends observed for the eastern, western and whole Amazon.

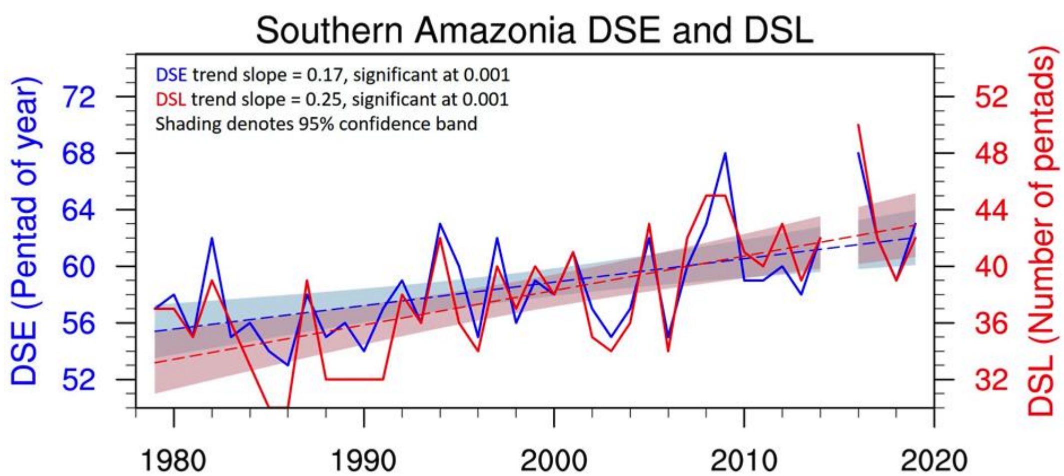


Figure 22.5. Annual time series of the dry season length (DSL, red line) and dry season ending (DSE, blue line) dates (in unit of pentad or 5-day) over southern Amazon how an increase of dry season length at the rate of 12.5±2.5 days per decade of due to a delay of dry season ending at the rate of 8.8±2.5 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

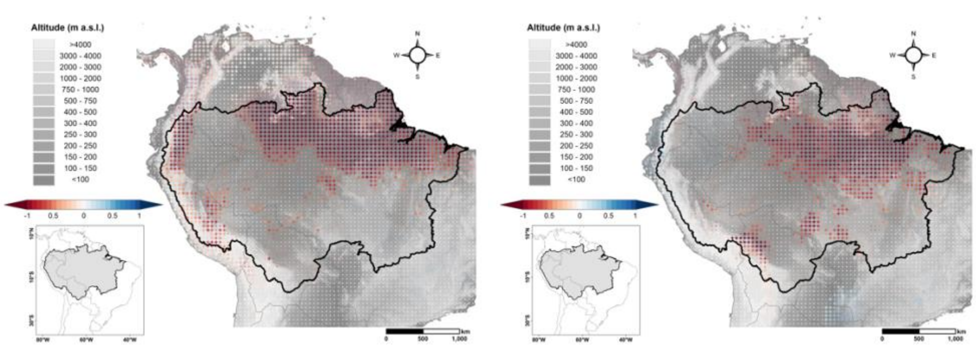
National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) daily rainfall data. The linear trend is determined by a least-square fitting. Trends are significant ($p<0.01$) and the shades show the 95% confident intervals for the trends.

The reasons for the delayed onset of the wet season are not completely understood, and the authors adds evidence to the idea that deforestation is probably playing a role (Wright et al., 2017). Leite-Filho et al. (2019) shows a delay of the wet season onset by about 4 days per decade for each 10% of the deforestation area relative to existing forested area. Such an interaction between ET and rainfall could further reduce ET and enhance the dryness over the Amazon. Staal et al. (2020) relate observed fluctuations in deforestation rates to dry-season intensity and find that deforestation over the Amazon has contributed to the increasing severity of dry seasons in Bolivia and southern Brazil and Peru, and how this leads to greater forest loss.

3.3 Historical droughts and floods and ENSO or Tropical Atlantic influences

It is well known that the strong interannual variability of rainfall over the Amazon basin has direct impacts on the water balance of the Amazon River (e.g., Tomasella et al., 2011). As a consequence of this variability, the Amazon basin is affected by recurrent droughts and floods of variable intensity. Drought not only implies a shortage of precipitation, but it is also almost always associated with an increase in surface air temperature. Most of the severe droughts in the Amazon region are EN-related (Cai et al., 2020). However, in 1963, 2005 and 2010, the Amazon was affected by a severe drought that was not El Niño-related, as most of the rainfall anomalies that have happened in southwestern Amazon are driven by sea surface temperature anomalies in the TNA (Table 22.2). In fact, during the last 20 years the three “megadroughts" in 2005, 2010 and 2015/16 (Jiménez-Muñoz et al., 2016; Marengo and Espinoza, 2016) were events classified at the time of their occurrence as “one-in-a-100-year event”. Past mega-droughts were registered in 1925–1926, 1982–1983, and 1997–1998 mainly driven by El Niño (Marengo et al., 2018 ad references quoted in). In contrast, “mega-floods” were detected in 2009, 2012, and 2014 (Marengo and Espinoza 2016 and references quoted in), and currently in 2021. Most of those events have been related to EN, LN or to warm TNA (Table 22.2). However, the very unusual wet 2014 austral summer period located in 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 (Espinoza et al., 2014).

Recent studies have documented different "types" of ENSO events, for instance with warm SST anomalies in the eastern Pacific (EP or E) or in the central equatorial Pacific (CP or C) (Cai et al., 2020). The role of the different ENSO types (E vs C) and TNA over the observed spatial patterns of drought in the Amazon are evidenced in Figure 22.6 through linear regression of precipitation anomalies versus the E, C and TNA indices. During austral summer (DJF) EN events inhibits precipitation over wide areas of northeastern Amazon, with similar pattern for E and C indices. However, the signal of the C index is stronger than the E index, particularly over the Andean-Amazon region. In contrast, the role of TNA is evidenced during the austral autumn (MAM), with a characteristic north-south dipole (wetness over northern Amazon and dryness over southern Amazon). Dryness induced by warm TNA temperatures is also observed during the austral spring (SON), but the signal observed in this season is weaker than then signal observed during the austral autumn. Although ENSO and TNA are main drivers of droughts over the Amazon, some recent events were not fully explained by the contribution of these two oceanic regions (Jimenez-Muñoz et al., 2019). In the case of EN 2015/16, dry conditions were observed over some Amazonian regions even after the if E, C and TNA contributions were removed, which may be attribute to an anthropogenic factor among other causes (Erfanian et al., 2017). Other studies revealed that Amazonian droughts are most related to one dominant pattern across the entire regions, followed by north-south and east-west seesaw patterns (Builes-Jaramillo et al., 2018).



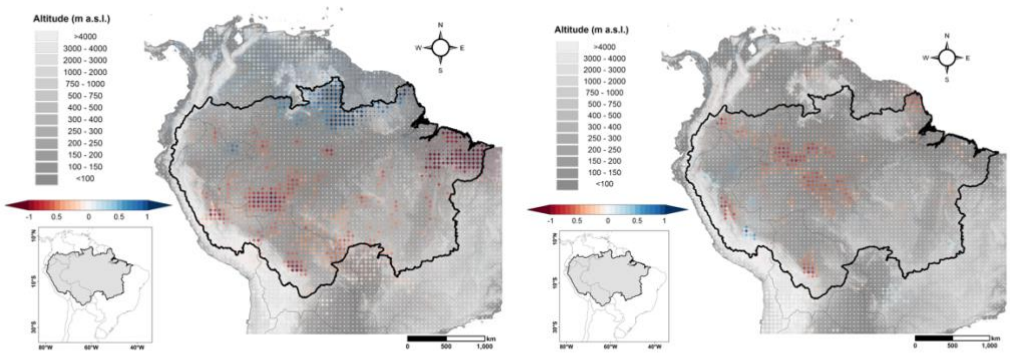


Figure 22.6. Slope of the linear regression coefficient between standardized SST indices (E, C, TNA) and precipitation anomalies for different seasons. Values are in mmday^{-1} per standard deviation. Pixels at the 95% confidence level are marked. Regions colored in red (blue) indicate a reduction (increase) in precipitation with increasing (decreasing) warm (cold) SST anomalies over the Eastern Pacific (E), Central Pacific (C) or Tropical North Atlantic (TNA) regions.

Table 22.2. History of droughts and floods in the Amazon, indicating whether they are related to El Niño, La Niña or SST conditions in the tropical Atlantic. 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. Updated from Marengo and Espinoza (2016), Marengo et al. (2018) and Espinoza et al. (2019 a, b).

Year	Extreme seasonal event	Causes
1906	Drought	EN (E and -C índices suggest a strong CP event in 1905, and weak EP and CP 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	EN
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 CP region)
1995	Drought	EN-C + warm TNA
1997-98	Drought	EN-E + warm TNA
1999	Flood	LN (Cold anomalies over CP 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

Observed extreme climatic events in the region, such as droughts and floods, changes in the rainy and dry seasons, augmented fire risk with associated their impacts on climate, health, and biodiversity suggest an increase in climate variability in the region (Aragão et al., 2018, and references quoted in). This could be an indicator of the intensification of the hydrological cycle in the Amazon observed in the last decades by Gloor et al. (2013) and Barichivich et al. (2018), that 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, while in the beginning of the 21-century there has been an unprecedented number of extreme drought events, while the Amazonian region has undergone a large-scale conversion of forests into pasture and cropland over the last decades thus 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).

3.4 Changes in evapotranspiration (ET) and possible land use change

Precipitation and ET recycling are strongly correlated in the Amazon. Regional ET provides about 28% of the precipitation falling in the basin, whereas 48% of ET returns as water for the precipitation (van der Ent et al., 2010). A review by Kunert et al. (2017) shows altogether an estimated 25–56% of the precipitation falling on Amazon forests results from local to regional recycling within the ecosystem (for more information of recycling, see Chapter 7).

Deep roots of the rainforests pump soil moisture recharged during wet season to maintain ET in dry season as the same level of the wet season (da Rocha et al., 2004; Juarez et al., 2007; Costa et al., 2010), especially an increase of ET during late dry season (Rocha et al., 2009b; Sun et al., 2019). This constant or even higher ET during dry season than during wet season is central for maintaining relatively humid atmospheric moisture and so to initiate the increase of rainfall during the dry to wet transition season (Li and Fu, 2004;

Wright et al., 2017). In addition, ET, especially over the southern Amazon, provides moisture for the downwind region, including the Andean mountains, and help buffer again droughts across the Amazon (Staal et al., 2018).

ET changes are influenced by climate variability, forest type and forest conversion to crop/pasture (da Rocha et al., 2009a; Costa et al., 2010). Indeed, surface net radiation is the main control of ET year-round especially over the wet equatorial Amazon, but also affecting other regions where surface conductance is greatly affected in general at east, south and southeast transitional tropical forests in Amazon towards the boundary of the Cerrado biome. The degree of these influences can vary regionally. For example, Costa et al. (2010) and Rodell et al. (2011) have shown that surface radiation is the main controller of evapotranspiration in the wet equatorial Amazon, whereas stomatal control is an important controller in regions with strong dry seasons (such as southern Amazon).

The influences of climate variability such as ENSO on ET have been observed directly by flux measurements and indirectly by satellites. For example, flux tower measurements have shown that the 2002 EN reduced ET by 8% in the southern Amazon (Vourlitis et al., 2015). Satellite based estimate of ET using moisture budget approach has also shown reductions of ET and rainforest photosynthesis during the 2015/2016 EN over the Solimões and Negro basins (e.g., Sun et al., 2019). Land use has strong impact on ET, especially during the dry season. Flux tower measurements showed an ET reduction over pastures compared to two forest sites in eastern Amazon (Santarem) from about 24% to 39% in the wet season and between 42% to 51% in the dry season, whereas in southern Amazon (Rondônia) the reduction was less than 15% in the dry season and not significant in the wet season, as summarized in da Rocha et al. (2009b). Alternatively, satellite-based ET models estimated a reduction of ET in the dry season between 28% (Silva et al., 2019) up to 40% (Khandy et al., 2017) in southern Amazon, whereas in the wet season the difference was not significant (Silva et al., 2019). Mechanisms of ET reduction because of changes in the land cover, as occurs when forest is replaced by other land cover (e.g., crops or bare deforested areas) or even in fragmented forests, are to some extent well-known, which supports a decrease of ET in southern Amazon, particularly in regions affected by deforestation (including the so-called Arc of Deforestation). However, ET models over the Amazon Basin do not always show consistent results, which leads to low confidence level on temporal trends of ET. Therefore, it is difficult to extract a clear conclusion on ET trends over Amazon Basin based on literature review (Wu et al., 2020).

Changes of ET, especially during the dry season has significant impact on rainfall and wet season onset. For example, the surface Bowen ratio during the dry season has strong impact on interannual variation of the wet season onsets (Fu and Li, 2004). The augmented surface dryness and resultant convective inhibition energy during the dry season is a leading contributor to the delaying of wet season onset over the southern Amazon in the past several decades (Fu et al., 2013). Shi et al. (2019) further shows that the 2005 drought has reduced dry season ET and contributed to the delay of wet season onset in 2006. Thus, ET response to drought could have legacy impact on rainfall of the following wet season.

3.5.Long-term variability of atmospheric moisture transport, moisture recycling from the Amazon and influences in southeastern South America and Andean region hydrology

On average the Amazon rainforest receives about 2000-2500 mm of rain each year. Much of this water comes sweeping in on winds from the Atlantic Ocean but the forest itself provides a substantial part of rainfall (Salati and Vose, 1984) as water evaporates or transpires from leaves and blows downwind to fall as rain elsewhere in the forest. Furthermore, the forest itself influences cloud formation and precipitation by producing secondary organic aerosols. These are formed by photooxidation of volatile organic compounds (VOCs) or condensation of semi- and low VOCs on primary biological aerosols (e.g., bacteria, pollen spores) or biogenic salt particles (Andreae et al., 2018).

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 the 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 than come from the tropical Atlantic and that gain more moisture due to recycling of the forest when crossing the Amazon. For more information, please refer to Box 7.1 from Chapter 7. The aerial river to the east of the Andes contributes to precipitation over southern Brazil and the La Plata River Basin by the South American Low Level Jet East of the Andes (SALLJ). During the major drought in southern Amazon in the summer of 2005, the number of SALLJ events during January 2005, at the height of the peak of the rainy season, was zero, suggesting a disruption of the moisture transport from the tropical North Atlantic into southern Amazon during that summer. The SALLJ transports large amounts of moisture from the Amazon basin towards the subtropics of South America and intense mesoscale convective systems and heavy precipitation frequently develop near its exit region (Zipser et al., 2006; Rassmussen and Houze 2016).

Evapotranspiration from the Amazon basin contributes substantially to precipitation regionally as well as over other remote regions such as the La Plata basin and the tropical Andes (Zemp et al., 2014; Staal et al., 2018; Gimeno et al., 2019). Montini et al. (2019) developed a new climatology of the SALLJ with a focus in the central branch. They showed that the SALLJ reveals significant increases in recent decades in the northwesterly moisture flux especially in austral spring, summer, and fall, which have possibly enhanced precipitation and extremes over southeastern South America. Additionally, the SALLJ in the central Andes shows decreasing frequency during MAM. Jones (2019) shows substantial growth in the activity of the SALLJ northern branch in the last 39 years and explains the dynamical reasons for that. This expansion in activity is observed in frequency and intensity of the SALLJ in the northern Andes.

At the interannual time scale, the transport during a weak and a strong monsoon in the Amazon Basin are distinctly different. For the South American monsoon, the DJF transport was 28.5×10^{7} kg s^{-1} in the dry year 2004–2005 and 45.1×10^{7} kg s^{-1} in the wet year 2011–2012, in contrast to the climatological value of 31.4×10^{7} kg s^{-1} (Costa, 2015). Reducing atmospheric moisture transport and respective recycling of precipitation due to deforestation and land use change 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 reduce moisture export to the Southeastern Brazil, the La Plata basin and the Andean mountains (Zemp et al., 2017a; Staal et al., 2018). 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 as previously thought. These authors further identify a growth of the fraction of total precipitation over the La Plata basin from 18–23% to 24–29% during the wet season as well as 21–25% during the dry season, driven by moisture from the Amazon basin. They also show that the south-western part of the Amazon basin is not only a direct source of rainfall over the subtropical La Plata basin, but also a key intermediary region that distributes moisture originating from the entire Amazon basin towards the La Plata basin during the wet season.

In addition, Staal et al. (2018) shows that around 25–50% of annual rainfall in the tropical Andes is originated by Amazon tree transpiration. 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 as previously thought (Zemp et al., 2014). Removal of forests causes increases in temperature and reduces evapotranspiration, and has been shown to reduce precipitation downwind of deforested area (Nobre et al 2016, Staal et al 2018).

4. CHANGE SCENARIOS IN THE AMAZON: LOCAL AND REMOTE CAUSES AND INFLUENCES

This section summarizes future changes in the temperature and precipitation across the Amazon, considering the temporal means and extreme. It assesses future projections derived from the global climate models (GCMs) participating in phase 5 of the Coupled Model Intercomparison project (CMIP5) for two representative concentration pathways (RCPs), RCP4.5 representing moderate and RCP8.5 large emissions of GHG by the end of the twenty-first century (2081-2100) relative to present day (1986-2005). CMIP5 GCMs 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 of the individual models. For precipitation, all the models, in particular those from CMIP5, have been found to be able to simulate Amazon recent past climate reasonably well, although the GCMs show large errors in representations of regional rainfall patterns and their controlling processes.

Annual mean temperature is projected to augment everywhere. Averaged over the Amazon, warming projected in a RCP4.5 scenario is about 2ºC higher than the present day, whereas in RCP8.5 scenario, temperature increases will continue, reaching more than 6ºC by the late 21st century (Figure 22.7). This could have a negative effect on forest health and on its functioning in 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).

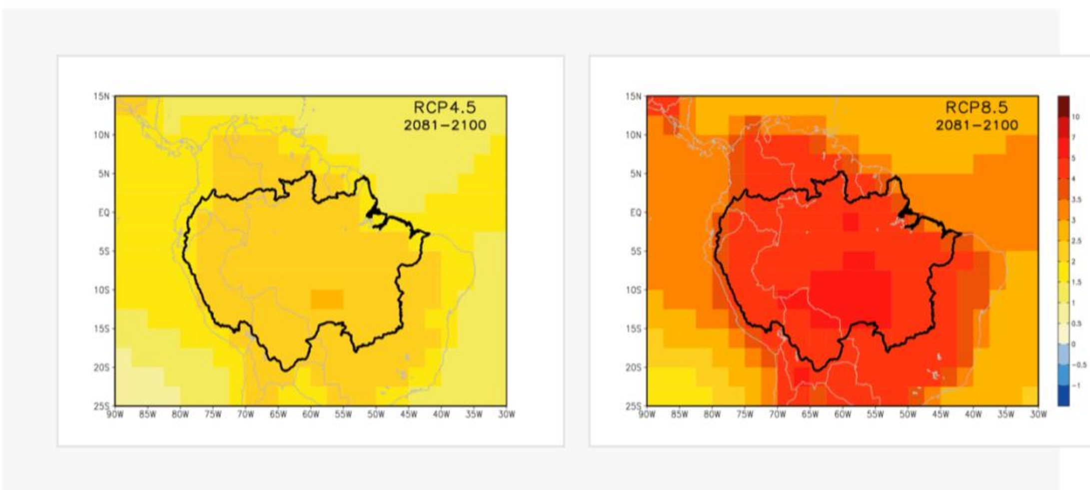


Figure 22.7. Multi-model CMIP5 average percentage change in annual mean near-surface air temperature relative to the reference period 1986–2005 averaged over the period 2081–2100 under the RCP4.5 and 8.5 forcing scenarios.

Over the basin as a whole, the changes in rainfall projected by the ensemble mean are mixed over the Amazon, varying by season, and showing that rainfall change impacts in the form of floods or droughts tend to increase under higher concentration scenarios. Despite rather low confidence in the CMIP5 ensemble mean projections of precipitation, some consensus can be found in the literature. There is high confidence that annual mean precipitation will decline in the Amazon, which is more pronounced in the eastern and south of the Amazon over the 21st century (Figure 22.8), small changes in rainfall are projected under a moderate emission scenario. In line with observed historical precipitation trends, dry season length is also expected to expand over southern Amazon (Boisier et al., 2015).

Spracklen and Garcia-Carreras (2015) assessed relevant peer-reviewed literature published over the last 40 years based on analysis of model simulations of 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 influences regional rainfall as simulated by the model and in general; it leads to a reduction in rainfall. However, there are some differences between them mainly in term of amplitude, magnitude and predictability that is strongly dependent on the spatial and temporal scales being considered.

There is also generally model agreement for an increase in precipitation for the end of the 21st century over northwestern Amazon (Colombia, Ecuador and north of Peru) (Schoolmeester et al., 2016). In the Peruvian-Ecuadorian Andean-Amazon basins (Marañón basin), Zulkafli et al. (2016) show an increasing seasonality of precipitation under RCP 4.5 and 8.5 scenarios. This study also suggests an augmented severity of the wet season flood pulse. On the other hand, in southern Peruvian and Bolivian Amazon, a reduction of precipitation is expected during the dry season, where a longer dry season is also projected (e.g., Fu et al., 2013; Boisier et al., 2015). Consequently, Siqueira-Junior et al. (2015 and references therein) projected diminution in runoff in Bolivian Amazon and Southern Peruvian Amazon during the low-water season for the middle and end of the 21st Century. In summary, while large range of uncertainty exist regarding future rainfall projection over the Andean-Amazon region, most studies show that an intensification of the hydrological cycle is likely to occur in this region, with intensification of wet conditions in the north and dry conditions in the south, as observed during the last decades (Section 22.3).

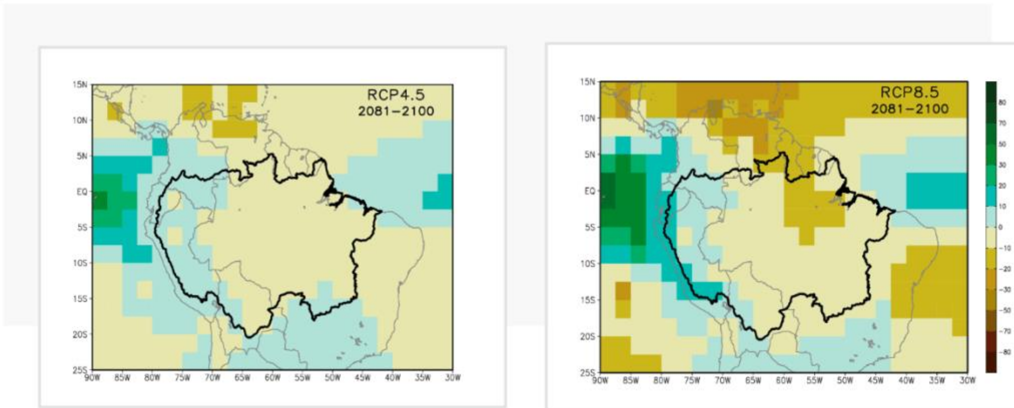


Figure 22.8. Multi-model CMIP5 ensemble percentage change in annual mean precipitation relative to the reference period 1986–2005 averaged over the period 2045–2081–2100 under the RCP4.5 and 8.5 forcing scenarios.

Analyzing projected changes, Minvielle and Garreaud (2011) documented a future reduction in easterly winds at 200hPa during the austral summer, which could translate into reduced rainfall in the Andes-Altiplano (-10% to -30%) and probably over the highest region of the upper Amazon by the end of the 21st century. In addition, glaciers are an important water source for cities in the upper Andes (Buytaert et al., 2017) and unprecedented glacial retreat is currently observed, with an acceleration since the late 1970s (Rabatel et al., 2013). Air temperatures is expected to increase by the end of the 21st century (Vuille et al., 2015) and many glaciers could disappear, which will increase the risk of water scarcity in the upper Andean valleys.

Recent studies have revealed the strong dependence of Andean hydroclimatology to the Amazonian rainforest (e.g., Espinoza et al., 2020 and cited articles). Indeed, loss of Amazonian rainforests probably will affect the entire hydrological cycle over both the Amazon basin and the Andes by changing moisture advection and regional atmospheric circulation (Segura et al., 2020).

The most serious impacts of climate change are often related to changes in climate extremes. There is a general model agreement for an increment in precipitation for the end of the 21st century over northwestern Amazon, while annual mean precipitation is projected to decline in the future in eastern Amazon under a high emission scenario (Figure 22.9). 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 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 22.9a). The projected changes indicate not only more frequent CDD, but also increase in intense precipitation as shown by the maximum five-day precipitation accumulation (RX5day) index, a strong contributor to floods (Figure 22.9a).

It is also important to note that the impacts of deforestation are frequently reflected in changes of the amount, intensity and frequency of precipitation. Alves et al. (2017) conducted a modeling study to examine possible connections between changes in Amazon land cover and the spatiotemporal variability of precipitation in South America. They also found more extreme precipitation events and, as compensation, an expanded duration of the dry season. Lan et al. (2016) found no signals of a higher frequency of intense precipitation events over the Amazon rainforests but found a widespread decline in precipitation over the Amazon (especially over eastern Amazon) from 1981 to 2100, although trends were mostly not statistically significant at the 95% confidence level (Student's t-test). Declines in trends for evapotranspiration, total runoff and available water were also observed. Decreases in precipitation are countered by decline in evapotranspiration and total runoff, leading to an almost neutral trend in the terrestrial water flux over Amazon (Figure 22.9b). Results also indicated that soil moisture will become lower over Amazon in the future (1981-2000 vs 2181-2100), and the seasonal range of total soil moisture will become larger (Kirtman et al., 2013).

The ratio runoff/precipitation indicated dramatic changes from June to September over the Amazon for the period 2081-2100, which is attributable to the low amounts of precipitation and runoff, and with more reduced precipitation than reduced runoff.

These results are also supported by Zaninelli et al. (2019), with less humid conditions with decreasing surface runoff over southern and southeastern Amazon for the period 2071-2100.

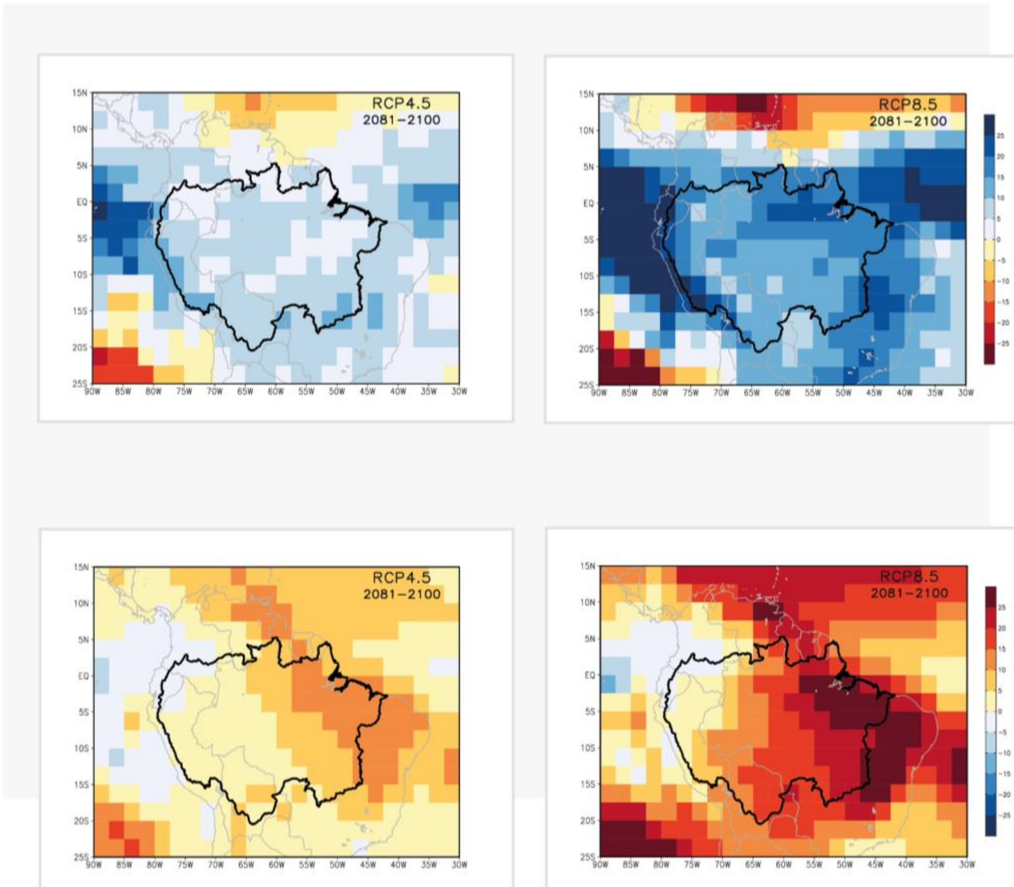


Figure 22.9. (a) Projected percent changes in annual RX5day, the annual maximum five-day precipitation accumulation and (b) projected change in annual CDD, the maximum number of consecutive dry days when precipitation is less than 1 mm, over the 2081–2100 period in the RCP4.5 and 8.5 scenarios (relative to the 1986–2005 reference period) from the CMIP5 models.

Mohor et al. (2015) suggest climate change is likely to reduce discharges in the Madeira, Tapajós and Xingú river basins Such reduction is largely related to decreasing precipitation and increasing temperature, which working together to exacerbate increase ET and discharge reduction. In general, for the scenarios considered in these hydrological simulations, a larger decreasing precipitation scenario also has a stronger increase in temperature, which explains the rates of change in discharge. Results suggest that for strong temperature warming, i.e., larger than 4 °C, discharges are more sensitive to precipitation changes than that for weak temperature increase. However, climate sensitivity largely varies between basins, affected by surface characteristics and basin's scale. Hydrologic projections considering conversion of the tropical forest 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.

The Amazonian forest's ability to provide environmental services is threatened by anthropogenic forcing at various scales, such as deforestation, fire, global and regional climate change, and extreme events. Such services include services maintenance of biodiversity, water cycling, evaporative cooling and carbon stocks. These services have a much greater value to human society than do the timber, beef and other products that are obtained by destroying the forest (Nobre et al., 2016). Perhaps one of the most valuable service provided by the Amazon forest is water. Evapotranspiration from the forest across the basin provides moisture for the downwind region, including the Andean mountains, and help buffer again droughts across the Amazon and also contribute for rainfall in southern Amazon, Pantanal and the La Plata Basin. In these downwind regions a suppression of moisture transport from the Amazon may favor rainfall reductions and warmer temperatures and increase the risk of drought, fire, water, food and energy insecurity in regions to the south of the Amazon.

For instance, during the water crises in Sao Paulo in 2014-2015 atmospheric moisture coming from the Amazon did not reach southeastern Brazil in the summer of 2014 reducing rainfall in almost 50%. The higher temperatures and increase water use by population, together with reduced rainfall triggered a water crisis situation that lasted until 2015 (Nobre et al., 2006). In the summer of 2019 and 2020, the summer rainy season in Pantanal was very weak, with moisture transport from the Amazon. The reduced rainfall induced drought in the region, increased the risk of fire and lower river levels in the basin (Marengo et al., 2021). Reducing atmospheric moisture transport and respective recycling of precipitation due to deforestation may induce a self-amplified drying process which would further destabilize the Amazon forests. However, the droughts in Sao Paulo and Pantanal were related to atmospheric circulation anomalies and cannot be attributed to deforestation in the Amazon or to climate change.

Future climate scenarios project progressively higher warming that may exceed 4°C in the Amazon in the second half of the century, particularly during the dry season in the region (Sampaio et al., 2019). Model projections show that this moisture flux from the Amazon to the La Plata basin may be also reduced, and there is a possibility that these environmental services provided by the Amazon now may also be affected in a warmer and drier future.

The new 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 with global warming (Ukkola et al., 2020). Specially, CMIP6 models show drying across eastern and southern Amazon in the 21st century (Parsons et al., 2020), and most CMIP6 models agree on future decreases in soil moisture and runoff across most of the Amazon in all emissions scenarios (Cook et al., 2020).

Among the different global warming levels, particularly the central Amazon, is projected to increase more than 75% in the number of hot days and a decrease in Rx5day. This region is also projected to have increased droughts' probability (Santos et al., 2020).

5. CONCLUSIONS

Long-term instrumental records for climate and streamflow (>80 years) have a low spatial coverage across the continental-sized Amazon basin which limits our ability to assess the spatial and temporal variability and changes of precipitation and temperature.

Our trend studies demonstrate that there is no unidirectional signal towards either wetter or drier conditions over the entire Amazon during the period of the observational records. However, for specific regions there are consistent trends. In general, the size and direction of the trends depend on length of the rainfall data sets how long they are, if there are breaks in the record, and if and how they are aggregated. For surface temperature, while warming appears in all data sets, the magnitude of it depends on the length of the observational period. However, all the datasets show that the last 20 years have been the warmest in the Amazon, with some datasets suggesting that 2020 may be the warmest year over particular regions. In a region where measurements are very scarce, the uncertainty in the size and direction of any temperature trend must be high.

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 by the increase in recent extreme hydro-climatic events (Marengo and Espinoza, 2016 and references quoted in). During the last four decades, various studies show that an enhancement of convective activity and increases in rainfall and river discharge over northern Amazon and decreases of these hydroclimate variables over southern Amazon (Paca et al., 2020 and references therein).

Our current interpretation of water cycle and trends in the Amazon is still limited by the lack of complete long-term and homogeneous historical climate and river data in different sub-basins. At interannual time scales ENSO and TNA have played an important role in temperature and rainfall variability. At large 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. These oceanic influences have been confirmed by dendroclimatic or stable isotopes studies that have provided a reconstruction of climatic and hydrological features in the basin. The role of vegetation and land use in the region on the hydrological and temperature variability has been demonstrated by modeling as well as 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 will occur predominantly in dry and transition seasons. 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.

A summary of observed and projected changes in the Amazon are shown in graphical abstract, in that the observed tendencies can be different in western and eastern Amazon, and the projected changes suggest a drier and warmer climate in eastern Amazon, while in western Amazon together with warm conditions rainfall is expected to increase in the form or more intense rainfall events in that section of the Amazon. The level of confidence is determined by the level of convergence among model signals of change from CMIP5 models (Kirtman et al., 2013).

6. RECOMMENDATIONS

Our knowledge on temperature and rainfall trends is limited by the lack of complete, homogeneous and long-term climate records to identify changes in extremes, such as droughts and floods due to increase of the interannual climate variability. Furthermore, the most important changes in the hydroclimate system are happening in the transition between the dry and the rainy seasons, with a warmer, longer and dryer dry season, which has important ecological and hydrological consequences. Future studies should focus on these particular transition season. This limitation leads to considerable uncertainty in determining the recent intensification of the hydrological cycle in the Amazon, how it compare to other intensifications of hydrological cycle may have occurred in the past. There is an urgent need to rescue data and integrate among Amazon countries, with free access for the scientific community. High-resolution climatic and hydrological gridded data set for the Amazon should be generated by means of a cooperation between state and national meteorological services, international climate agencies and universities, as well as private data sets.

When consider policy and practical implications of our assessment, it is important to note that despite of the fact that CMIP5 and CMIP6 models reasonably well simulated some aspects of the observed present-day climate over the Amazon, 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 between climate and land-use change, the model projections would likely have considerable uncertainty, particularly for rainfall projections. With increased field experiments and high-resolution models, we will be able to enhance the understanding and modeling of complex interactions, and where improvements should be made. The increase in extreme droughts may cause extremely low water levels and an elevated tree mortality due to fires, which are more pronounced at the edges between vegetated and non-vegetated areas, due to relation between land-use change and fire.

Last but not least, there is a strong need for better education of local people as well as policy and decision makers about climate, hydrology and atmospheric sciences, especially the impacts of land use and climate change on their livelihood. Traditional and cultural knowledge are also considered as invaluable sources of climate-proxy information. In sum, we have to improve ground monitoring, data accessibility and quality, better research infrastructure, and climate model development. Furthermore, model development and calibration at key research centers and universities working with climate modeling region can promote collaboration among scientist working in the region. These efforts may need support from national and international funding agencies.

All these pressures from climate changes and land use push Amazonian forest closer to its projected "bio-climatic tipping point" than any other tropical forests, especially for the eastern and southern Amazon basin, despite of large uncertainty in precisely predicting thresholds for the tipping points (see Chapter 24).

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8. CORE GLOSSARY

Aerial Rivers: In the context of this chapter aerial rivers or flying rivers are air currents to the east of the Andes that bring water vapor from the tropical Atlantic and the Amazon down as far south as southern Brazil and northern Argentina.

Climate change: Long-lasting changes to the climate of a region.

Deforestation: Forest loss, conversion of forest to non-forest.

Meteorological Drought: An absence of rain for long periods.

Global warming: A gradual increase in the overall temperature of the earth's atmosphere, generally attributed to the greenhouse effect caused by increased levels of greenhouse gases, mainly carbon dioxide.

Moisture recycling: A process in which water evaporates from land surface, especially from a forest, lake, river and wetland, and falls again as rain over the same area.

9. BOXES

BOX 22.1. Warming in the Amazon region

Warming over the Amazon Basin is a fact, but the magnitude of the warming trend varies with the dataset used and the length of the temperature records. Intercomparisons among temperature trends from different datasets shows significant differences among datasets, but overall, all datasets show widespread warming in recent decades over Amazon Basin, with higher warming rates during the dry seasons (roughly, from June to September) (see Fig Box 20. 1).

FIG. BOX 22.1

Warming rates also vary with the time period considered. Hence, early studies in 1998 quantified a warming of +0.56ºC/century during 1913-1995 in the Brazilian Amazon using station data, whereas more recent studies using other data sets (station data, gridded data, reanalysis and remote sensing estimates) evidenced an increasing warming in southern Amazon during the dry season, at a rate of +0.49 ºC/decade during 1979-2012. A contrasted spatial pattern between eastern Amazon and western Amazon is also observed, with eastern Amazon (and especially southeastern Amazon) providing a warming rate almost twice as higher than western Amazon. This may be attributed to effects of land cover change and interactions with fire and drought.

Warming trends for the recent period 1980-2019 are higher than trends over the period 1950-2019. The warming trend is better evidenced from 1980, and it is enhanced from 2000, where three exceptional droughts occurred in 2005, 2010 and 2015/16. All temperature datasets show that the recent two decades were the warmest, with El Nino year 2015/16 as the warmest year followed by El Nino year 1997/98. The year 2016 may have reached the highest value of the anomaly in the last century, up to +1ºC annually, with particular months surpassing +1.5 ºC. Other temperature indices also corroborate the warming trend over the Amazon, with increases in the number of warm nights and decreases in the numbers of cool nights, especially over the last decade. One of the strongest trends in warm days was observed over the Amazon in all seasons, but especially during the winter dry season.

In the light of the above discussion, future warming of the Amazon in 4°C or higher may induce changes in the hydrological cycle and in the functioning of the forest. Evaluating the consequences of such substantial climatic change, several negative effects in Amazonia can be anticipated, including short-term hydrological changes similar to the events associated to the extreme 2005, 2010 and 2016 droughts, and longer time-scale modifications of broad scale characteristics such as different biome distribution.

Figure Box 22.1 Temporal series of air temperature anomalies over the Amazon forests (broadleaf evergreen forest land cover class) from 1980 to 2018 using the last version of the CRUTS dataset (v4.04). Temporal series have been extracted at yearly level (black) and half-yearly levels (first half of the year, DJFMAM, in blue, and second half of the year, JJASON, in red). Dashed lines indicate the linear trend, including also the value of the trend in ºC per decade.