Amazon Assessment Report 2021

Chapter 22

Long-term Variability, Extremes, and Changes in Temperature and Hydro Meteorology

Cheia do rio Negro no centro de Manaus 2021 (Foto: Alberto César Araújo/Amazônia Real)

THE AMAZON WE WANT
Science Panel for the Amazon

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

About the Science Panel for the Amazon (SPA)

The Science Panel for the Amazon is an unprecedented initiative convened under the auspices of the United Nations Sustainable Development Solutions Network (SDSN). The SPA is composed of over 200 preeminent scientists and researchers from the eight Amazonian countries, French Guiana, and global partners. These experts came together to debate, analyze, and assemble the accumulated knowledge of the scientific community, Indigenous peoples, and other stakeholders that live and work in the Amazon.

The Panel is inspired by the Leticia Pact for the Amazon. This is a first-of-its-kind Report which provides a comprehensive, objective, open, transparent, systematic, and rigorous scientific assessment of the state of the Amazon's ecosystems, current trends, and their implications for the long-term well-being of the region, as well as opportunities and policy relevant options for conservation and sustainable development.

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Graphical Abstract

Observed and projected changes in the Amazon show that current climate and hydrology tendencies can be differentiated both spatially and temporally, exhibiting two seesaw spatial patterns, one north-south and the other west-east, and an intensification of the wet and dry seasons. In the present, the northwestern Amazon shows an increase in rainfall and runoff, while in the southern part it is the opposite. The region, including the central and eastern Amazon, does not show a significant rainfall trend as a whole. However, observations suggest an increase in rainfall extremes and intensification of droughts and floods, with little overall change in mean annual river discharges. Temperature records show an overall warming of the Amazon in recent decades, especially from the year 2000 to the present over the eastern Amazon. Evapotranspiration (ET) is reduced in the southern Amazon, probably as a result of land-use change, but uncertainties are still high due to the lack of systematic observations across the basin. This analysis is based on a literature review of findings based on different observational, reanalysis, and satellite datasets of rainfall, temperature, and river discharge records, and different methodologies (parametric and non-parametric techniques), leading to different levels of confidence, consistency, and magnitude of trends.

Projections show a drier and warmer climate in the eastern Amazon, leading to an increase in evapotranspiration. The western Amazon will also experience warmer conditions, but rainfall is expected to increase, due to more intense rainfall events, leading to increasing runoff and decreasing evapotranspiration in the 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.

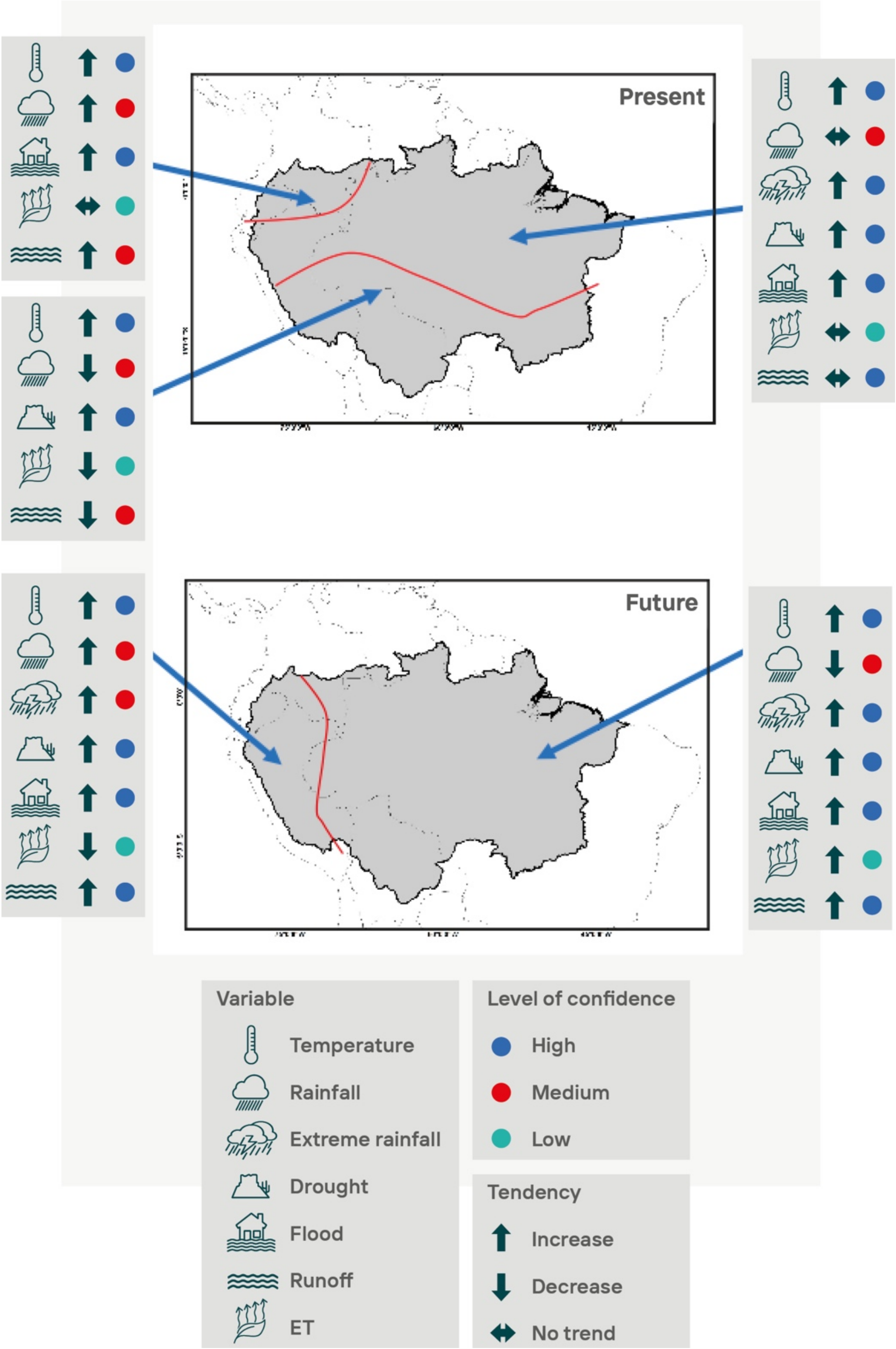

Figure 22.A Summary of observed and projected changes of climate in the Amazon, based on several studies (see Magrin *et al.* 2014; Marengo *et al.* 2018, and references quoted therein). The level of confidence in future projections is determined by the level of convergence among model signals of change from CMIP5 (Kirtman *et al.* 2013) and CMIP6 (Cook *et al.* 2020) models.

Long-term variability, extremes and changes in temperature and hydro meteorology in the Amazon region

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Key Messages

- Recent intensification of the Amazon's hydrological extremes are due to intensification of 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 discharges (Q) have increased in the northwestern Amazon during the high-water season (1974-2009) and decreased in the southwestern Amazon during the low-water season (1974-2009).
- Recent severe droughts are linked to the El Niño-Southern Oscillation (ENSO) and/or Tropical North Atlantic (TNA) sea surface temperature (SST) anomalies. The Indian Ocean also plays a role. SST indices based on the EN3.4 region along the central-equatorial Pacific Ocean do not provide enough information about impacts due to different El Niño (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, Amazonian ecosystems, and wildlife. Current data show that the dry season has expanded by about 1 month in the southern Amazon since the mid-1970's.
- 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.
- The climate change fingerprint is still difficult to determine due to the short duration of 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 the Amazonian region.

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 depending on the 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 the southern

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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 extreme flood events occurred every 20 years. Since 2000, there has been 1 severe flood every 4 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. This will have consequences for regional hydrology, and 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

22.1 Introduction

This chapter provides an updated review of literature on climate and hydrology in the Amazon basin, including classic and new studies developed in the recent decades, with the objective to answer key questions relevant to the current and future functioning of the Amazon forest as a regulator 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? 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 droughts and floods in the Amazon? If so, are they due to El Niño (EN), the Tropical Atlantic, land use change, or a combination of factors? How did EN and drought vary in the past as suggested by paleoclimate records? What are the expected changes to the Amazonian climate due to increasing greenhouse gases (GHG) and deforestation? What would be the impacts at the regional and global scales?

22.2 Long Term Variability of Temperature and Extremes: Warming Trends

Several studies have identified positive air temperature trends in the Amazon, with the magnitude dependent 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. An 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 Climate Research Unit (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 Moderate-Resolution Imaging Spectroradiometer (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°C/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 purpose of this work, the northern and southern Amazon are defined as the basin north and south of 5°S, respectively. This definition considers the difference in seasonal rainfall cycles and the fact that the dry season south of 5°S may have months with precipitation lower that 100 mm, which does not occur north of 5°S (See Chapter 5).

All data show that the recent two decades were the warmest, though there are some systematic differences among the trends estimated by different data.

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 °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)

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 El Niño (La Niña, or 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 the eastern Amazon. Higher warming rates over the eastern Amazon are attributed to the effects of land cover change, and subsequent alteration of the energy balance (Davidson *et al.* 2012). Land cover alone also plays a role over the southeastern Amazon, where tropical forests are bordered by other land covers such as Cerrado and pastures. In contrast, the western Amazon is influenced by the Andes barrier and a transition from montane tropical forests to lowland forests, where temperature trends decline with elevation (Malhi *et al.* 2017).

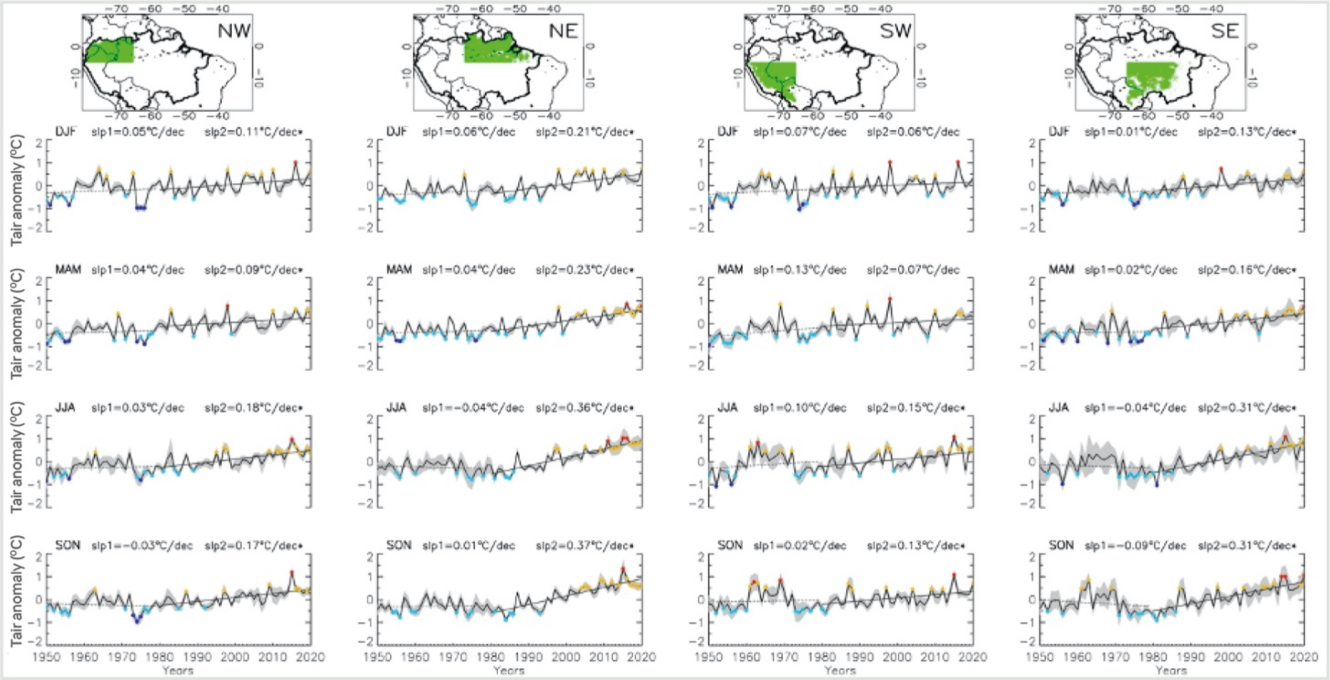

Figure 22.1 Temporal series of seasonal (DJF, MAM, JJA, SON) air temperature anomalies over different sectors of the Amazon (NW, NE, SW, SE) using data from the CRU Version 4 (CRUTS4) data for the reference period 1981-2010. Orange and red circles indicate temperature anomalies that surpass 1 standard 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 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 ±0.1°C) consistent with the global average (0.9°C) between 1979 and 2018. However, warming trends differ between months, and the largest increases were observed for the 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 the positive radiative effect of high clouds and precipitable water in trapping 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 number 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 a combination of low seasonal/interannual temperature variability with land-use change effects. Seiler *et al.* (2013) reported a warming rate over Bolivia of 0.1ºC/decade during the period of 1965-2004, with this warming rate more pronounced over the Andes and during the dry season (JJA). Similarly, Lavado-Casimiro *et al.* (2013) found a significant warming trend in mean temperature of 0.09ºC/decade during 1965-2007 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 1.2ºC, while in 2019-2020 warming was 1.1ºC, becoming the second warmest since 1960 in the Amazon. The warming trend varies depending on the dataset (station, gridded data sets, reanalysis or satellite derived), the time period for which the trend was computed, and the spatial scale (the whole Amazon or sub-regional). 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 (with a strong warming in the southeast 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).

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 Figure 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 Niño year 2015/16 as the warmest year followed by El Niño 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 the Amazon 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.

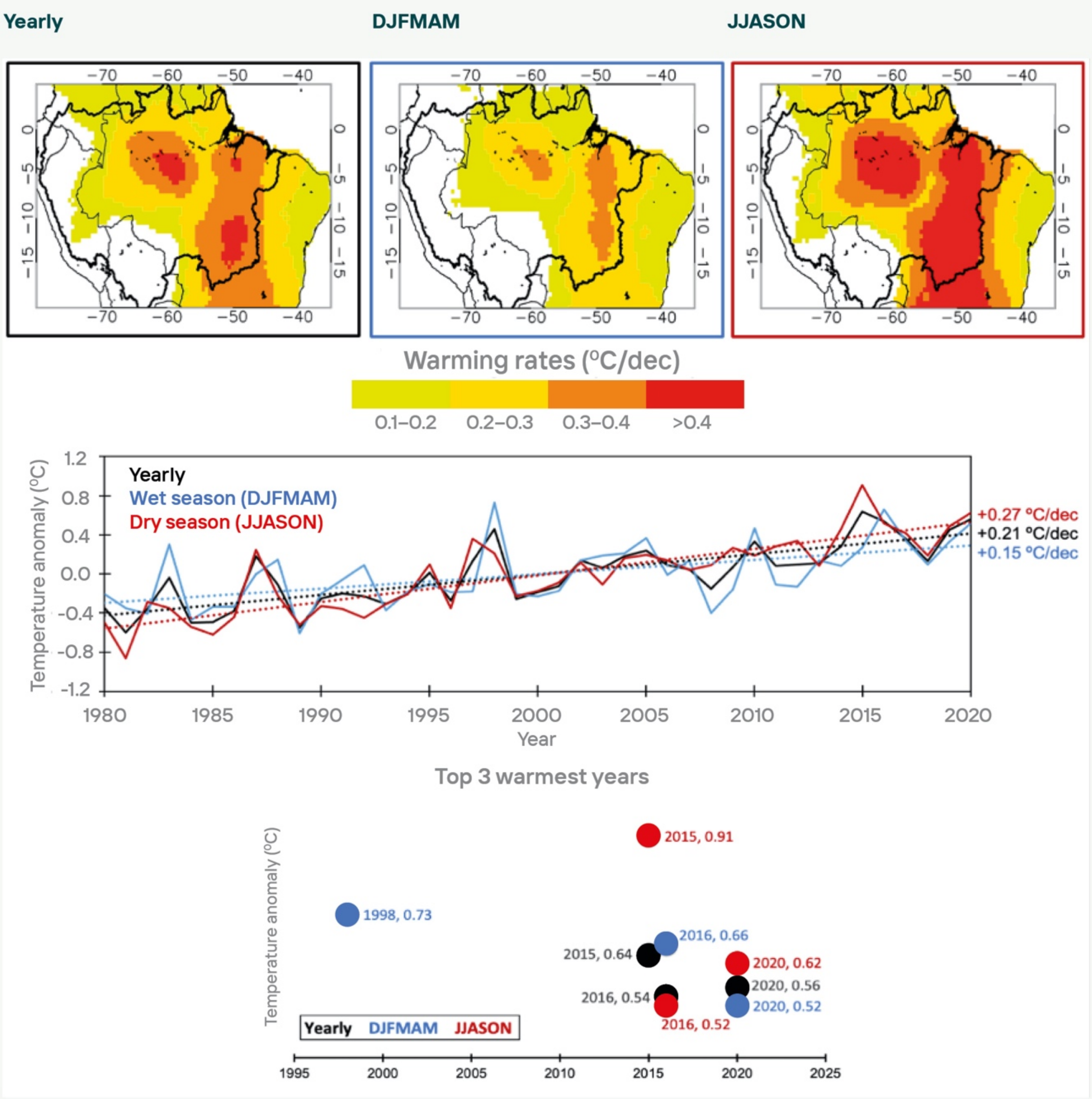

Figure Box 22.1 Temporal series of air temperature anomalies over the Amazon forests (broadleaf evergreen forest land cover class) from 1980 to 2018 using the last version of the CRUTS dataset (v4.04). Temporal series have been extracted at yearly level (black) and half-yearly levels (first half of the 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 °C per decade.

22.3 Long-Term Variability of Hydrometeorology of the Amazon and Andean-Amazon Region

22.3.1 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 of 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. (before present) 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 the literature. These 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). For recent periods, most rainfall records start in the 1960s. The short period of record keeping hampers the quantification of long-term trends in the Amazonian region. Various rainfall datasets (e.g., Climate Research Unit, Global Precipitation Climatology Center [GPCC], Global Precipitation Climatology Project [GPCP], Climate Hazards Group InfraRed Precipitation with Station data [CHIRPS], Tropical Rainfall Measuring Mission [TRMM], satellite and reanalysis products) rely on few rain stations with short records and low spatial coverage. These datasets 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 interannual rainfall and river variability in the Amazon can be, in part, attributed to sea surface temperature variations in the tropical oceans. This manifests as the extremes of the El Niño-Southern Oscillation in the tropical Pacific, and the meridional SST gradient in the Tropical North Atlantic. 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). 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 the 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 increasing rainfall in the northern Amazon and diminution in the 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 means increased 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 as is observed in Figure 22.2 a). Alves (2016) detected a statistically significant negative rainfall trend in the southern Amazon at the dry-to-wet season transition during 1979–2014. Recent work by Espinoza *et al.* (2019a) shows that while the southern Amazon exhibits negative trends in total rainfall and extremes, the opposite is found in the northern Amazon, particularly during the wet season. Wang *et al.* (2018) combine both satellite and *in situ* observations and reveal changes in 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 for the Rio Negro at Manaus, close to its confluence with the Solimões (Amazonas) River, started being recorded in September 1902 (Figure 22.2). The mean amplitude between annual maximum (floods) and minimum (droughts) water levels 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 levels at Manaus increased. The Rio Negro rose by almost 1.5 m compared to the period before (Schöngart and Junk 2020). This growth 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, 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 atmospheric circulation that induces rainfall, with the trade winds and deep convection over the Amazon, referred as the Walker circulation. This circulation represents a direct cell zonally oriented along the equator induced by the contrast between the warm waters of the western Pacific and the cooler waters of the eastern Pacific (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 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 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 Rio Negro (Manaus) in 2005 was 28.10 cm above the long-term average (1903-2015). Finally, a weak positive trend can be noticed in the levels at Manaus and Óbidos since the late 1980’s (Figure 22.2).

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 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

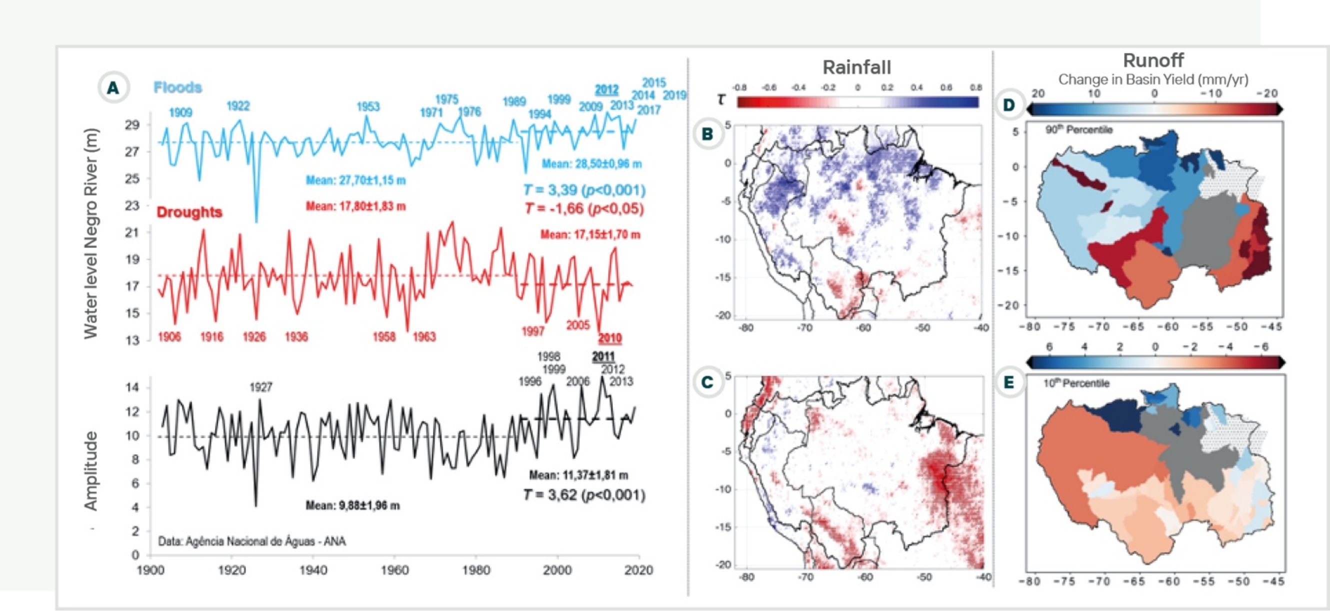

Figure 22.2 a) Maximum (floods, blue) and minimum (droughts, red) annual water level variability of the Rio Negro at Manaus (1903-2020). Years corresponding to extreme hydrological events are indicated. The annual water level amplitude (droughts minus floods) is displayed in black. Adapted from Schöngart 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.

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 in rainfall of around 17% 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 the 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 contribute 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 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

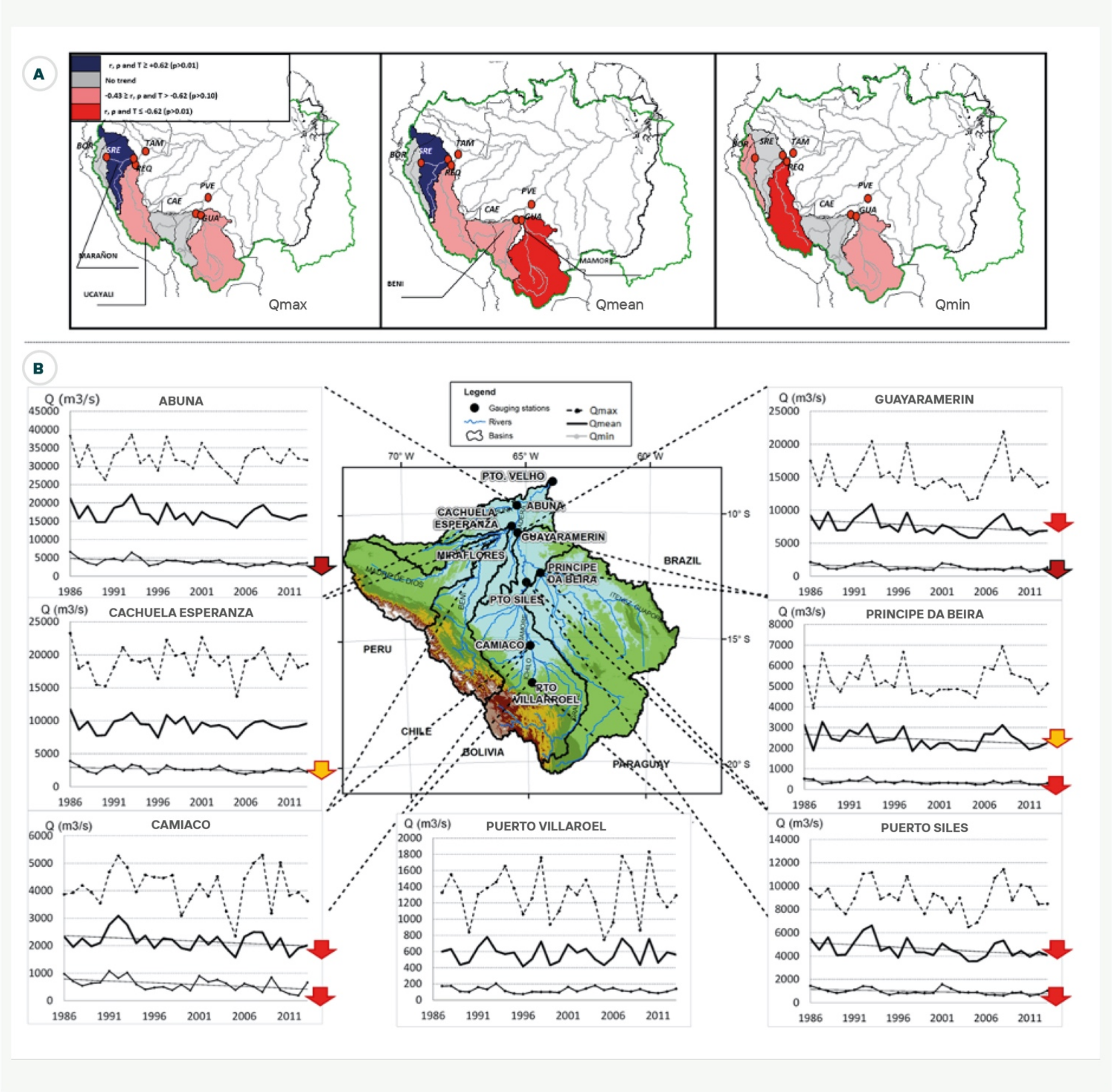

Figure 22.3 Discharge trends in Ecuadorian, Peruvian, and Bolivian Amazon-Andean rivers: a) Discharge trends for the annual maximum (Q_{max}, left panel), the mean annual (Q_{mean}, middle) and the annual minimum discharge (Q_{min}, right) computed in Borja (BOR) and San Regis (SRE) stations in Marañón 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.

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 at the Tabatinga station, which drains rainfall over the 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 22.3). Related to rainfall changes, river discharge during the low-water season at the 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 operations at 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 the 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 construction of the Santo Antonio and Jirau hydropower dams along the Madeira river's main channel. Discharge diminution over this region is related to rainfall diminution and a lengthening of the dry season in the southern Amazon (see Section 22.3.2).

For the Tocantins and Itacaiúnas basin, no significant trend was observed in rainfall patterns. However, in the Tocantins River, a significant decrease in discharge was observed 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). This may be attributed to increasing deforestation and land use change (Oti and Ewusi 2016). This conclusion is based on the non-existence of trends in both the maximum and mean flow patterns of the Itacaiúnas River, the lack of change in rainfall patterns, and the significant upward trend in the minimum (baseflow) of the Itacaiúnas River but not 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 discharge of the Tocantins River (upstream of Tucurui dam) during periods with small and large deforestation in the catchment area. They found that deforestation increased the maximum water discharge and that it occurred earlier in the season, as compared to the period of reduced deforestation. The authors 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. 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; see also Chapters 19, 23 and 24).

Massive and abrupt changes of streamflow regimes are expected from hydroelectric power plants which change the hydrological cycle downstream of the dams, resulting in complex spatiotemporal disturbances of floodplains downstream of dams (Anderson *et al.* 2018; Resende *et al.* 2019). Multiple dams are under construction or planned for the Tapajós, Xingú, Tocantíns-Araguaia, Marañón, and many other river basins in the Amazon. These 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, to the detriment of the welfare of Indigenous peoples, local communities, and society at large (see Chapter 20). 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 high deforestation rates of their catchments in recent decades, construction of several hydroelectric dams, and increasing dry season length (Timpe and Kaplan 2017).

In summary, the above-mentioned studies have documented the key role of hydroclimatic variability in the Andean-Amazon and lowland Amazonian rivers, such as the upper Madeira, upper Solimões, Caquetá-Japurá, Tocantins, and Negro rivers for a broad understanding of the hydrological system of the entire Amazon basin. This includes seasonal and interannual time scales, as well as long-term hydrological trends, extreme events, and atmospheric and surface water balances (e.g., Builes-Jaramillo and Poveda 2018).

22.3.2 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 (see Chapter 7). Dry seasons in the Amazon have become more intense in recent years leading to greater forest loss and increasing fire risk. Various studies have shown evidence of lengthening of the region's dry season, 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 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). Arias *et al.* (2015), Espinoza *et al.* (2019b) and Leite-Filho *et al.* (2019) identified rainfall diminution in the southern part of the Peruvian, Brazilian, and Bolivian Amazon basin during the dry season, that is associated with a delay in the onset of the South American Monsoon System (SAMS) and enhanced atmospheric subsidence over this region (Espinoza *et al.* 2019b; Leite-Filho *et al.* 2019). Indeed, these atmospheric changes are also related to increased 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 season 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 10-15 days later than the normal onset date. Gatti *et al.* (2021) show that annual 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.

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), and 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 late onset of the rainy season may have direct impacts on the risk of fire and hydrology of the region, enhancing regional vulnerability to drought. Wright *et al.* (2017) highlight the mechanisms by

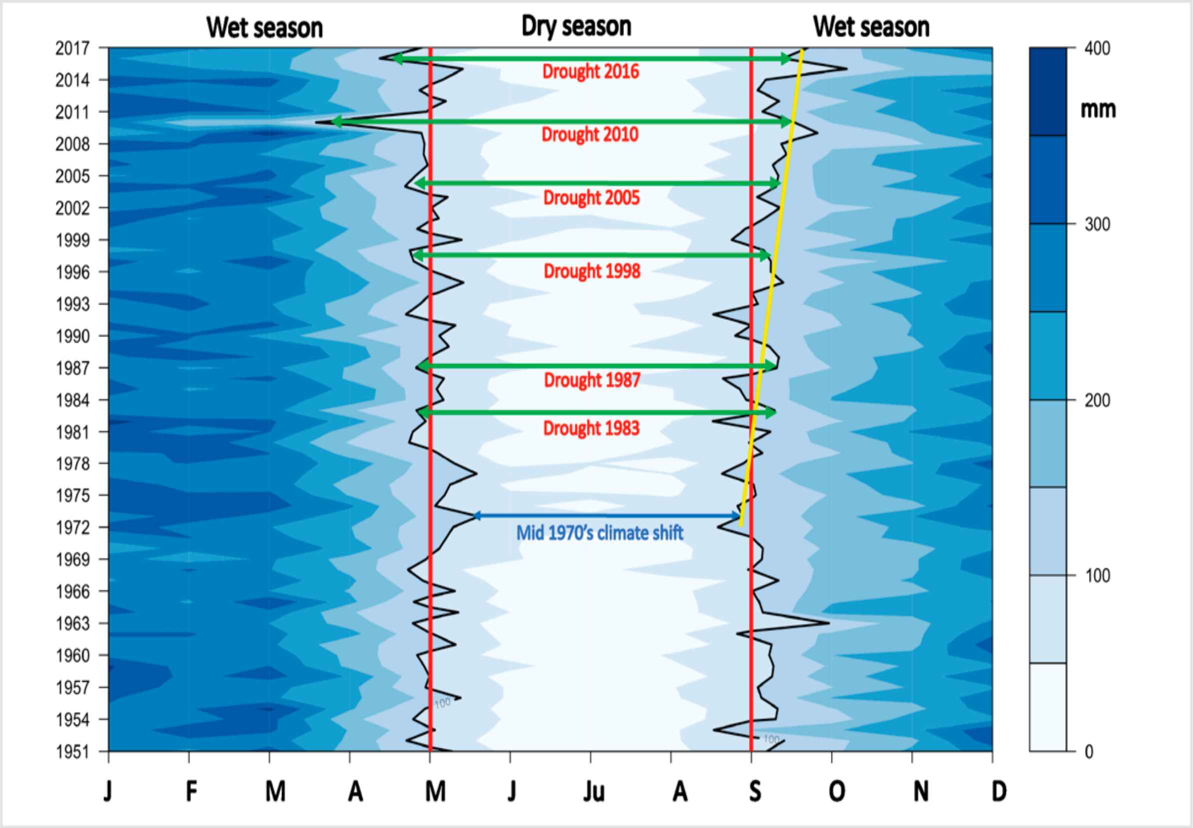

Figure 22.4 Hovmoller diagram showing monthly rainfall from 1951 to 2017 for the southern Amazon (mm/month). The isoline of 100 mm/month is an indicator of dry months in the region (Sombroek 2001). Drought years are indicated with green lines. Red lines show the average onset and end of the rainy season (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 shift in the tropical Pacific Ocean, which has been associated with a phase change of the Pacific Decadal Oscillation index (Jacques-Coper and Garreaud 2015).

which interactions among land surface processes, atmospheric convection, and biomass burning may alter the timing of the onset of the wet season (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 the southern Amazon are also related to enhanced atmospheric moisture content over the Caribbean and northern South America, changes in moisture transport, and moisture recycling in the 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 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, decreases in precipitation, and increases in temperature, mainly during the dry season, with different trends observed for the east-

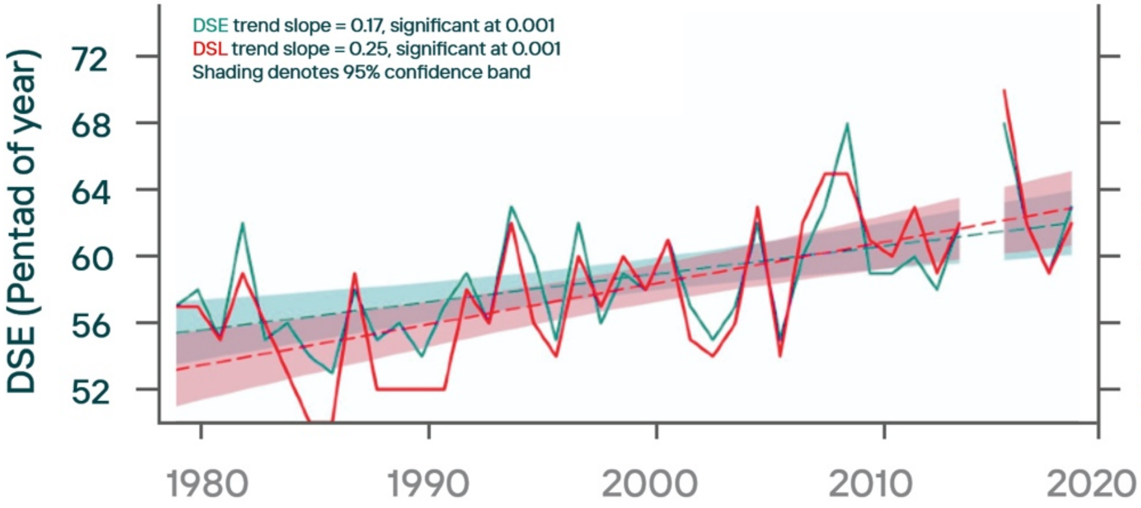

Figure 22.5. Annual time series of the dry season length (DSL, red line) and dry season ending (DSE, blue line) dates (in unit of pentad or 5-day) over southern Amazon how an increase of dry season length at the rate of 12.5±2.5 days per decade of due to a delay of dry season ending at the rate of 8.8±2.5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

ern, western, and whole Amazon.

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

22.3.3 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" (2005, 2010, and 2015/16) (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 El Niño (Marengo *et al.* 2018 and 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 these events have been related to EN, LN, or to warm TNA (Table 22.2). However, the very unusual wet 2014 austral summer period located 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 (Espinoza *et al.* 2014).

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 indices 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

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 inhibit precipitation over wide areas of the 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 the northern Amazon and dryness over the 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 the signal observed during the austral autumn. Although ENSO and TNA are the 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 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 region, followed by north-south and east-west seesaw patterns (Builes-Jaramillo *et al.* 2018; Builes-Jaramillo and Poveda 2018).

Observed extreme climatic events in the region, such as droughts and floods, or changes in the rainy and dry seasons, augmented fire risk with associated impacts on climate, health, and biodiversity; these 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), and 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).

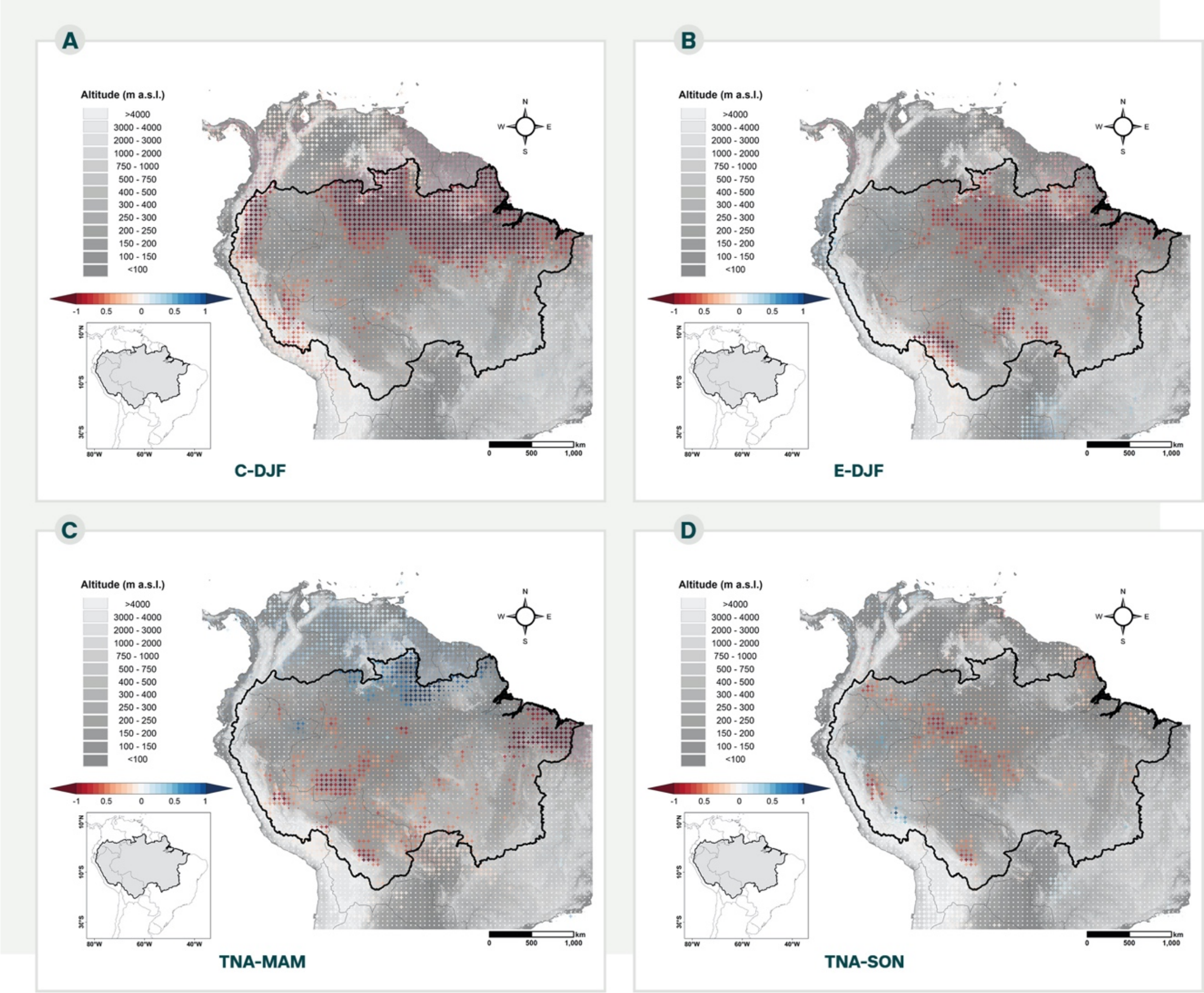

Figure 22.6 Slope of the linear regression coefficient between standardized SST indices (E, C, TNA) and precipitation anomalies for different seasons. Values are in mmday^{-1} per standard deviation. Pixels at the 95% confidence level are marked. Regions colored in red (blue) indicate a reduction (increase)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

Furthermore, in the beginning of the 21st-century there has been an unprecedented number of extreme drought events; this 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).

22.3.4 Changes In evapotranspiration and possible 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 falling in the basin originated as ET (van der Ent *et al*. 2010). A review by Kunert *et al*. (2017) shows an estimated 25–56% of the precipitation falling on Amazon forests results from local to regional recycling within the ecosystem (see Chapter 7).

Deep-rooted vegetation pulls up soil moisture recharged during the wet season to maintain 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 (Rocha *et al*. 2009b; Sun *et al*. 2019). Constant or even elevated ET during the dry season is central for maintaining relatively humid atmospheric moisture and initiating the increase of rainfall during the dry to wet season transition (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 helps buffer again droughts across the Amazon (Staal *et al*. 2018).

Changes in ET 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, generally the eastern, southern, and southeastern transitional tropical forests 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 ET in the wet equatorial Amazon, whereas stomatal control is an important controller in regions with strong dry seasons (such as the 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 estimates of ET using the moisture budget approach also showed 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 a strong impact on ET, especially during the dry season. Flux tower measurements show an ET reduction over pastures as compared with two forest sites in the eastern Amazon (Santarem) from about 24% to 39% in the wet season and between 42% to 51% in the dry season, whereas in the 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 from 28% (Silva *et al*. 2019) to as much as 40% (Khandy *et al*. 2017) in the southern Amazon, whereas in the wet season the difference was not significant (Silva *et al*. 2019). The mechanisms of ET reduction resulting from changes in land cover, for example as occurs when forest is replaced by crops, or even in fragmented forests, are to some extent well-known, which supports a decrease of ET in the 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 on the temporal trends of ET. Therefore, it is difficult to extract a clear conclusion on ET trends over the Amazon basin based on literature review (Wu *et al*. 2020).

Changes of ET, especially during the dry season, have a significant impact on rainfall and wet season onset. For example, in terms of the surface energy balance, the relationship between sensible heat (used to warm or cool the air) and latent heat (used to evaporate or condensate atmospheric moisture), known as the Bowen ratio, during the dry season has strong impact on interannual variation in the onset of the wet season (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 show that the 2005 drought reduced dry season ET and contributed to the delay of wet season onset in 2006. Thus, the response of ET to drought could have a legacy impact on rainfall of the following wet season.

22.3.5 Long-term variability of atmosphereic moisture transport, moisture recycling from the Amazon, and inflences on 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 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 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 gain more moisture due to water recycling of the forest when crossing the Amazon (see 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 via the South American Low Level Jet East of the Andes (SALLJ). During the major drought in the 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 moisture transport from the tropical North Atlantic into the 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 (Zipser *et al.* 2006; Rassmussen and Houze 2016).

Evapotranspiration from the Amazon basin contributes substantially to precipitation regionally, as well as over 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 on the central branch. They showed significant increases in the SALLJ 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 the frequency and intensity of the SALLJ in the northern Andes.

At the interannual time scale, transport during a weak and a strong monsoon in the Amazon basin is 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 x10^7 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 Amazon forests in downwind regions, i.e., the south-western and southern Amazon region, but also reduce moisture export to 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 than previously thought. These authors further identify growth in 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.

Previous work by Nobre *et al.* (2009) showed that large-scale Amazon deforestation can severely reduce local rainfall through the cooperative processes of local reduction of evapotranspiration and enhanced atmospheric subsidence over the Amazon, due to increased ENSO activity associated with Amazonian deforestation. In addition, Staal *et al.* (2018) show that 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 area (Nobre *et al.* 2016; Staal *et al.* 2018).

22.4 Change Scenarios in the Amazon: Local and Remote Causes and Influences

This section summarizes future changes in temperature and precipitation across the Amazon, considering the temporal means and extremes. 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 representing high emissions of GHG by the end of the twenty-first century (2081-2100), relative to the 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 the Amazon's 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).

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 east 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 the southern Amazon (Bois-

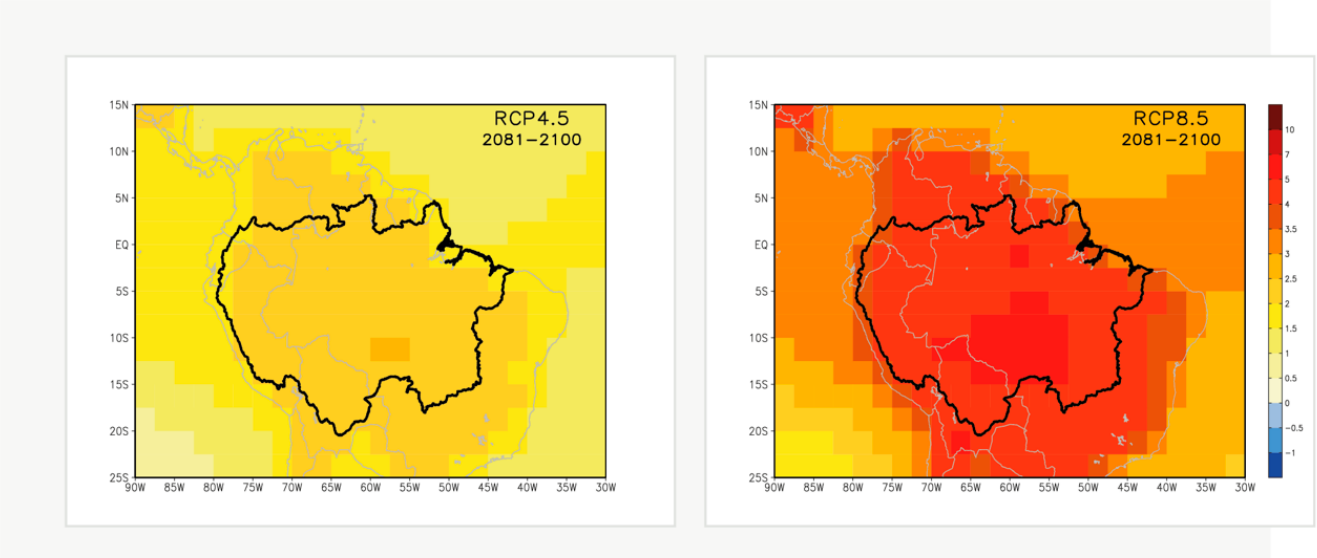

Figure 22.7 Multi-model CMIP5 average percentage change in annual mean near-surface air temperature relative to the reference period 1986–2005 averaged over the period 2081–2100 under the RCP4.5 and 8.5 forcing scenarios.

ier *et al.* 2015).

Spracklen and Garcia-Carreras (2015) assessed relevant peer-reviewed literature published over the last 40 years 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 leads to a reduction in rainfall. However, there are some differences between models, 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 the northwestern Amazon (Colombia, Ecuador and the 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 the 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 the Bolivian Amazon and Southern Peruvian Amazon during the low-water season for the middle and end of the 21st Century. In summary, 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 intensification of wet conditions in the north and dry conditions in the south, as observed during the last decades (Section 22.3).

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

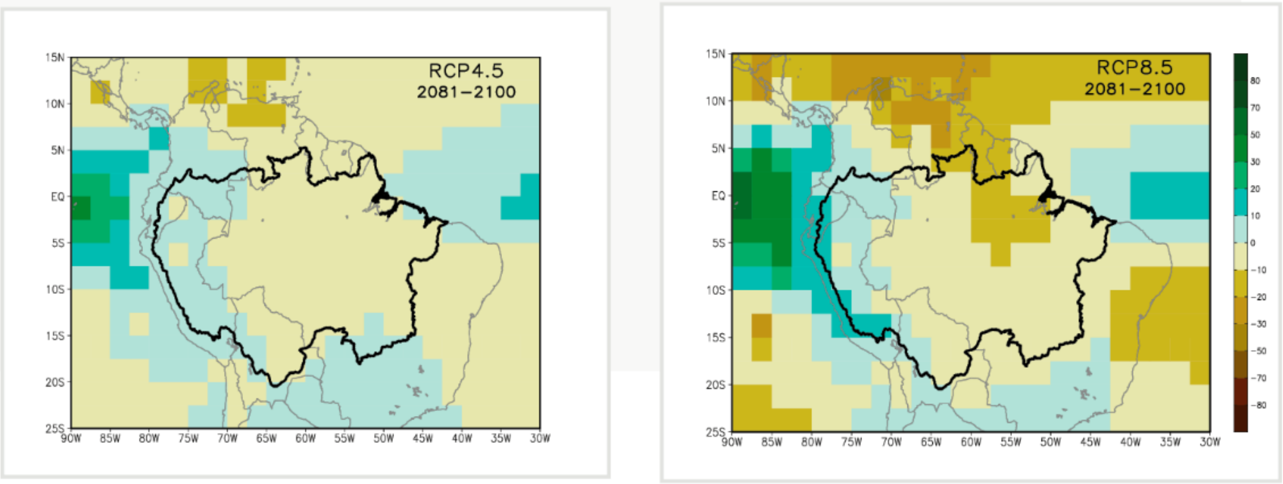

Figure 22.8 Multi-model CMIP5 ensemble percentage change in annual mean precipitation relative to the reference period 1986–2005 averaged over the period 2045–2081–2100 under the RCP4.5 and 8.5 forcing scenarios.

temperature 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 upper Andean valleys.

Recent studies have revealed the strong dependence of Andean hydroclimatology on the Amazonian rainforest (e.g., Espinoza *et al.* 2020 and cited articles). Indeed, loss of Amazonian rainforests will probably 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 general model agreement for an increment in precipitation for 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 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 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 22.9a). 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 22.9a) (Seneviratne *et al.* 2021; Ranasinghe *et al.* 2021; Gutiérrez *et al.* 2021).

It is also important to note that the impacts of deforestation are frequently reflected in changes in the amount, intensity, and frequency of precipitation. Alves *et al.* (2017) conducted a modeling study to examine possible connections between changes in land cover in the Amazon and the spatiotemporal variability of precipitation in South America. They also found more extreme precipitation events and, as compensation, a longer 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 the 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

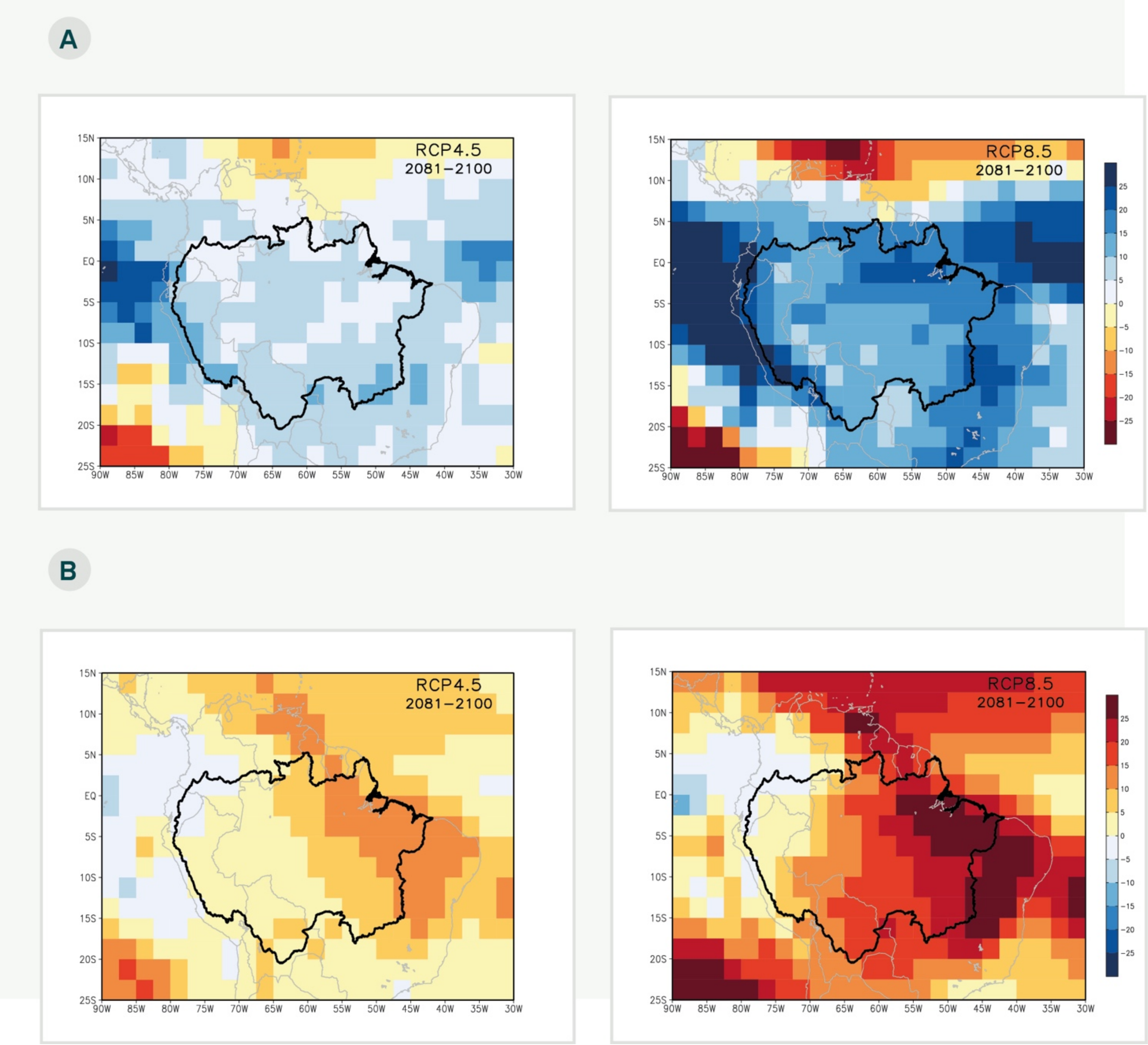

Figure 22.9 (a) Projected percent changes in annual RX5day, the annual maximum five-day precipitation accumulation and (b) projected change in annual CDD, the maximum number of consecutive dry days when precipitation is less than 1 mm, over the 2081–2100 period in the RCP4.5 and 8.5 scenarios (relative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

water were also observed.

Decreases in precipitation are countered by declines in evapotranspiration and total runoff, leading to an almost neutral trend in the terrestrial water flux over the Amazon (Figure 22.9b). Results also indicated that soil moisture will become lower over the 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 of runoff to precipitation indicated dramatic changes from June to September over the Amazon for the period 2081-2100, which is attributed to 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 the southern and southeastern Amazon for the period 2071-2100.

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, that favours an increased 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., higher 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 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.

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 (see Chapters 19, 23 and 24). Such services include 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 services provided by the Amazon forest is water. Evapotranspiration from the forest across the basin provides moisture for the downwind region, including the Andean mountains, helps buffer again droughts across the Amazon, and also contributes to rainfall in the southern Amazon, Pantanal, and La Plata basin. In these downwind regions a suppression of moisture transport from the Amazon may lead to rainfall reductions and warmer temperatures, increasing the risk of drought and fire, as well as 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 almost 50%. The higher temperatures and increased human water use, together with reduced rainfall, triggered a water crisis that lasted until 2015 (Nobre *et al.* 2006). In the summer of 2019, 2020, and 2021 the summer rainy season the in Pantanal was very weak, with moisture transport from the Amazon. Reduced rainfall in the west central and southeastern Brazil induced drought in the region, increased the risk of fire, and lowered river levels in the basin (Marengo *et al.* 2021) and this is also reflected in the water crisis situation that is affecting these regions in 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 the 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 (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 under global warming (Ukkola *et al.* 2020). Specially, CMIP6 models show drying across the 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).

Under different global warming scenarios, the Amazon, particularly the central Amazon, is projected to experience a 75% increase in the number of hot days and a decrease in Rx5day. This region is also projected to have increased droughts (Santos *et al.* 2020). Lastly, Oliveira *et al.* (2021) show that the combined effects of large-scale Amazon deforestation and global warming can subject millions of people in the Amazon region to a heat stress index beyond the level of survivability by the end of the 21st century. Furthermore, their results indicate that the effects of deforestation alone are comparable to those of the worst-case scenarios of global warming under the RCP8.5 scenario.

Recent work by Baudena *et al.* (2021) identified that loss of tree transpiration from the Amazon causes a 13% drop in column water vapor, and could result in a 55%–70% decrease in precipitation annually. They conclude that although the effects of deforestation may be underestimated, forest restoration may be more effective for precipitation enhancement than previously assumed. Furthermore, Oliveira *et al.* (2021) showed through numerical simulations with the Brazilian Earth System Model that the combined effects of climate change under the RCP8.5 scenario and large-scale Amazon deforestation can impact annual rainfall over the central portion of the Amazon Basin with a reduction of up to 70% of its annual rainfall total.

22.5 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 the details of 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 it 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 datasets suggesting that 2020 may be the warmest year over particular sections of the basin. In a region where measurements are very scarce, the uncertainty in the size and direction of any temperature trend is 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 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).

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 reconstruct past climatic and hydrological features in the basin. The role of vegetation and land use in the region on 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 the graphical abstract of this chapter. 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 or more intense rainfall events. The level of confidence is determined by the level of convergence among model signals of change from CMIP5 models (Kirtman *et al.* 2013).

22.6 Recommendations

Our knowledge of temperature and rainfall trends is limited because of the lack of complete, homogeneous, and long-term climate records to identify changes in extremes, such as droughts and floods, due to increasing 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 this particular 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. High-resolution climatic and hydrological gridded datasets for the Amazon should be generated by means of a cooperation between state and national meteorological services, international climate agencies, universities, and private datasets.

When considering the policy and practical implications of our assessment, it is important to note that despite the fact that 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 will be able to enhance 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 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. In sum, we have to 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. These efforts may need support from national and/or international funding agencies.

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 forests, especially in the eastern and southern Amazon basin. This is despite large uncertainties in precisely defining thresholds for tipping points (see Chapter 24).

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