The Drought of Amazonia in 2023-2024

Jose A Marengo, Ana P Cunha, Jhan-Carlo Espinoza, Rong Fu, Jochen Schöngart, Juan C Jimenez, Mabel C Costa, Joao M Ribeiro, Sly Wongchuig, Siyu Zhao

American Journal of Climate Change, 2024, 13, 567-597
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

The Drought of Amazonia in 2023-2024

Jose A. Marengo[1,2,3], Ana P. Cunha[1,2], Jhan-Carlo Espinoza[4,5], Rong Fu[6], Jochen Schöngart[7], Juan C. Jimenez[8], Mabel C. Costa[1], Joao M. Ribeiro[2], Sly Wongchuig[9], Siyu Zhao[6]

[1]National Center for Monitoring and Early Warning of Natural Disasters/CEMADEN, São José dos Campos, Brazil
[2]UNESP/CEMADEN, São José dos Campos, Brazil
[3]Graduate School of International Studies, Korea University, Seoul, South Korea
[4]Institut des Géosciences de l'Environnement (IGE), Institut de Recherche pour le Dévelopement (IRD), Saint Martin d'Heres, France
[5]Instituto de Investigación sobre la Enseñanza de las Matemáticas (IREM PUCP), Pontificia Universidad Católica del Perú, Lima, Peru
[6]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, CA, USA
[7]Departament of Environmental Dynamics, Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Brazil
[8]Global Change Unit (GCU) of the Image Processing Laboratory (IPL), Universitat de València Estudi General (UVEG), Paterna, Spain
[9]Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Université de Toulouse, CNES/CNRS/IRD/UT3, Toulouse, France
Email: jose.marengo@cemaden,gov.br, ana.cunha@ce,aden.gov.br, jcev09@gmail.com, rfu@atmos.ucla.edu, jochen.schongart@inpa.gov.br, Juancar.Jimenez@uv.es, mabel.costa@cemaden.gov.br, joao.mariano@unesp.br, xinox010@gmail.com, siyu_zhao@atmos.ucla.edu

How to cite this paper: Marengo, J. A., Cunha, A. P., Espinoza, J.-C., Fu, R., Schöngart, J., Jimenez, J. C., Costa, M. C., Ribeiro, J. M., Wongchuig, S., & Zhao, S. Y. (2024). The Drought of Amazonia in 2023-2024. *American Journal of Climate Change, 13,* 567-597.
https://doi.org/10.4236/ajcc.2024.133026

Received: May 22, 2024
Accepted: September 26, 2024
Published: September 29, 2024

Abstract

The Amazon basin has experienced an extreme drought that started in the austral summer of 2022-23 and extends into 2024. This drought started earlier than other previous droughts. Although some rain fell during the austral summer, totals remained below average. Higher temperatures during austral winter and spring 2023, which affected most of Central South America, then aggravated drought conditions. This coincided with an intense El Niño and abnormally warm tropical North Atlantic Ocean temperatures since mid-2023. Decreased rainfall across the Amazon basin, negative anomalies in evapotranspiration (derived from latent heat) and soil moisture indicators, as well as increased temperatures during the dry-to-wet transition season, September-October-November (SON) 2023, combined to delay the onset of the wet season in the hydrological year 2023-24 by nearly two months and caused it to be uncharacteristically weak. SON 2023 registered a precipitation deficit of the order of 50 to 100 mm/month, and temperatures +3˚C higher than usual in Amazonia, leading to reduced evapotranspiration and soil moisture indicators. These processes, in turn, determined an exceptionally late onset and a lengthening of the dry season, affecting the 2023-2024 hydrological year. These changes were aggravated by a heat wave from June to December 2023. Drought-heat compound events and their consequences are the most critical natural threats to society. River levels reached record lows, or dried up completely, affecting Amazonian ecosystems. Increased risk of wildfires is another concern exacerbated by these conditions.

Keywords

El Niño, SST in the Tropical Atlantic, Amazon, Drought, River Levels, Heatwave, Dry Season Length

1. Introduction

The Amazon region has the largest tropical rainforest in the world and contains a wealth of biodiversity. The interactions between forest and climate include the hydrological, energy, and carbon cycles (Artaxo, 2023). Accelerated deforestation and forest degradation in the Amazon are undermining its resilience, resulting in losses of critical wildlife and overall biodiversity (Boulton et al., 2022; Wunderling et al., 2023; Nobrega et al., 2023). It also disrupts delicate ecological balances, reduces atmospheric moisture recycling (Martinez & Dominguez, 2014; Eiras-Barca et al., 2020; Sierra et al., 2021), and decreases carbon sequestration of atmospheric CO_2 (Gatti et al., 2021; Chen et al., 2008).

Changes in large and regional-scale atmospheric heat and moisture cycles over the Amazon are also affecting interannual rainfall variability and, thus, increasing the number of extreme floods and droughts (Satyamurty et al., 2013a; Marengo & Espinoza, 2016; Barichivich et al., 2018; Heerspink et al., 2020; Espinoza et al., 2022). The main drivers of the droughts in the Amazon are El Niño and a warm tropical North Atlantic (Satyamurty et al., 2013b; Marengo & Espinoza, 2016; Towner et al., 2021, Marengo et al., 2021). Drought seems to be stronger during East Pacific-El Niño (Cai et al., 2020), as in the case of the 2023-24 El Niño event (Espinoza et al., 2024). Since the beginning of the 21st century, four intense droughts (2005, 2010, 2015-2016, and 2023-24) were classified as "once-in-a-hundred-years" events when they occurred. Yet each was surpassed in magnitude by the following event (Barichivich et al., 2018; Papastefanou et al., 2022; Espinoza et al., 2024).

The dry-season length (DSL) is a critical climate limitation for sustaining rainforests. This is especially true in southern Amazonia, where the rainforest is subject to relatively long dry seasons and rapidly changing land use (Salazar et al., 2007; Malhi et al., 2009; Arias et al., 2020; Gutierrez-Cori et al., 2021). The average dry season starts in June and ends in September. Reduced evapotranspiration (ET) in the Amazon rainforest due to the drought-driven legacy effect could be a crucial factor triggering wet season onset (WSO) delay in the transitional season following drought events (Wright et al., 2017; Shi et al., 2019).

Fu and Li (2004) explicitly show the connection between the dry season Bowen ratio and subsequent WSO.

A longer dry season delays its end date (and a delay in the WSO) or shortens the rainy season (Arvor et al., 2018). It is often accompanied by a prolonged fire season (Fu et al., 2013; Flores et al., 2021; Espinoza et al., 2021). Lengthening of the DSL in southern and eastern Amazonia since the late 1970s has been reported with rainfall and atmospheric data provided by multiple sources (Fu et al., 2013; Marengo et al., 2011, 2021; Espinoza et al., 2021). According to INPE (http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes), these two areas show the highest rate of deforestation. A similar tendency has been detected in the *Cerrado* region between eastern Amazonia and Northeast Brazil (Leite-Filho et al., 2021; Marengo et al., 2021). Expansion of deforested areas in southern Amazonia likely exacerbates the lengthening of the dry season, as documented in various observational and modeling studies (e.g., Leite-Filho et al., 2019; Sierra et al., 2023; Commar et al., 2023).

Recent decades have been the warmest on record in the Amazon, with four severe droughts since 2000. The 2023-24 drought is marked by exceptionally sparse rainfall and seven heat waves during the dry and dry-to-wet pre-rainy season. River levels are low and fires have increased (WMO, 2024; Jiménez et al., 2024). Deficits in soil moisture led to more frequent and severe summer high temperatures and heat waves, as climate models and observations both attest (Lorenz et al., 2010; Alexander, 2011).

In a companion study, Espinoza et al. (2024) show that these historical conditions in 2023 are associated with two main mechanisms. The first is an unprecedented southern anomaly of vertically integrated moisture flux (VIMF), VIMF divergence, and an extreme rainfall deficit over southwestern Amazonia during November 2022-February 2023, which corresponds to the first part of the 2022-23 hydrological year. These atmospheric anomalies are related to the impacts of the 2022-23 La Niña event in southern Amazonia. Second, a strong downward motion (atmospheric subsidence) observed over northern Amazonia relates to the warm conditions and rainfall deficit during June-August 2023. These atmospheric anomalies are connected to the impacts of the June-September El Niño on the Walker Circulation. Therefore, the transition from La Niña 2022-23 to El Niño 2023 was a major driver for this drought-heat situation, and its impacts were strongly amplified by global warming (Clarke et al., 2024).

These drought-heat alterations have led to increased fish and aquatic mammal mortality, lack of safe water and food for river-dwelling communities, halted river transportation, increased risk of waterborne diseases, and marked defoliation of river-margin vegetation, which may signal vegetation death and increase the risk of fires (Jiménez et al., 2024). These impacts on the aquatic Amazonian fauna, not observed during previous droughts, indicate the severity of the unprecedented drought in the Amazon in 2023-24. In 2023, Amazon waters suffered high mortality of fishes, river dolphins (in Portuguese, *boto cor de rosa*), and other mammals due to higher water temperature and decreased oxygen concentration (Ratier, 2023; Marmontel et al., 2024; Fleischmann et al., 2024). Droughts have long-lasting effects on aquatic fauna, such as the changes in fish species' composition and functional types caused by the 2005 event, which is still present nearly 10 years later (Arantes et al., 2017). Falling river levels in Amazonia impact the population living near the river (called *ribeirinhos*) and indigenous communities, limiting access to essential goods and basic services (Costa et al., 2024; de Lima et al., 2024). Between 2001 and 2018, extreme drought conditions degraded a total area of 2,740,647 km^2 in the basin (Lapola et al., 2023). Droughts greatly increase the incidence of fires in the Amazon, as reported in 2005, 2010, 2015, and 2023. This leads to positive feedback between fires and droughts (Aragão et al., 2018; Espinoza et al., 2024).

While previous studies have analyzed the regional climate features of the 2023 drought in Amazonia (Espinoza et al., 2024) and its impacts on vegetation (Jiménez et al., 2024), in this study, we examine the persistence of the drought during the first part of the 2023-2024 hydrological year. We compare it with previous droughts in 2005, 2010, and 2015-16. For this purpose, we investigate: 1) drought in the Amazon region caused by El Niño/warm tropical North Atlantic as compared to 2023-24; 2) the increased length of the dry season in 2023-24; and 3) changes in land surface-atmosphere interactions in the dry-to-wet transition 2023-24 that may have led to a longer dry season in 2023 and triggered a delay of the onset of the wet season in the 2023-2024 hydrological year.

2. Data and Methods

2.1. Selection of Study Regions

Spatial patterns of anomalies in hydrometeorological parameters are assessed over the whole Amazon Basin. We also select two specific regions located in southern and eastern Amazonia, delimited by the geographical coordinates [6˚S - 12˚S; 45˚W - 75˚W] and [2˚N - 2.5˚S; 45˚W -5 5˚W], respectively (**Figure 1**). Significant drying and warming trends have been reported in these two regions for the last four decades (Marengo et al., 2021). Although the areas delimited by boxes extend beyond the Amazon basin, the adjacent regions included are also considered representative of the Amazon forest biome.

2.2. Rainfall and River Water Levels

While previous studies have investigated rainfall variability in the Amazon region (Marengo et al., 2021 and references quoted therein), extensive, reliable, long-term, and homogeneous precipitation data from *in situ* stations in the region is lacking. Thus, global datasets such as Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and the Global Unified Gauge-Based Analysis of Daily Precipitation (CPC-NOAA) are the best alternatives available to estimate spatially distributed long-term precipitation trends.

CHIRPS is a rainfall product available at daily to annual time scales, with a spatial resolution of 0.05˚ × 0.05˚, starting from 1981 onwards. The dataset includes satellite imagery and rain gauge data to create gridded rainfall time series. The new dataset of CHIRPS version 2.0 has stations worldwide, including more than 11,000 in Brazil alone. This new dataset is available on https://data.chc.ucsb.edu/products/CHIRPS-2.0/. The CHIRPS-2.0 dataset has already been analyzed for other regions in Brazil (Baez-Villanueva et al., 2017; Paredes-Trejo et al., 2017; Anderson et al., 2018; Paca et al., 2020). Beck et al. (2017) evaluate precipitation accuracy and find that CHIRPS-2.0 generally performs better than other precipitation datasets in central Brazil. Its long-term climatology period is 1981-2010.

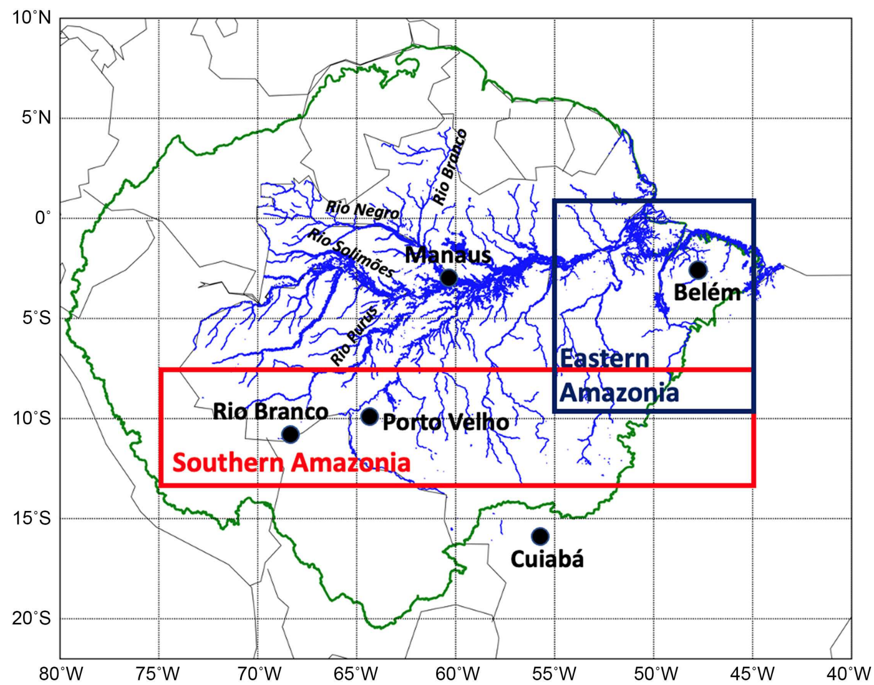

Figure 1. Location of southern and eastern Amazon areas in this study. Names of the stations with either temperature or rainfall/river records in 2023 are provided in the text.

The Global Unified Gauge-Based Analysis of Daily Precipitation (https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html; Xie et al., 2007; Chen et al., 2008) rainfall dataset is one of a suite of products from the Unified Precipitation Project underway at the United States National Oceanic and Atmospheric Administration Climate Prediction Center. Its spatial resolution is 0.5˚ × 0.5˚. It covers January 1979 onward. Its long-term climatology is 1981-2010.

Daily water level records of the Rio Negro for the Port of Manaus from September 1902 to October 2023 are provided by the Brazilian National Water Agency (ANA) and the Brazilian Geological Survey (SGB). In addition, meteorological reports and information from Brazil's federal institutions (INPE, INMET, and CEMADEN) are used as auxiliary resources.

2.3. Terrestrial Water Storage (TWS) and GLEAM Data Sets

The Gravity Recovery and Climate Experiment (GRACE) mission maps the temporal variations of the Earth's gravitational field (Tapley et al., 2004). GRACE data allows the detection of the variation in terrestrial water storage anomalies (TWSA) on the Earth's surface in approximately 30-day cycles, considering that water displacement on the continents is a leading cause of mass fluctuations on Earth (Rodell & Famiglietti, 2002; Strassberg et al., 2009). Numerous researchers have highlighted GRACE's applicability in large-scale hydrological investigations, emphasizing its consistent variation in water storage (de Paiva et al., 2013; Güntner, 2008). In this study, we use GRACE-FO Level-3 products due to their availability up to September 2023. The Jet Propulsion Laboratory (JPL) and the University of Texas Center for Space Research (CSR) developed all these products based on the latest version (GRACE-FO RL06v4). Since both centers report reasonably similar TWS anomalies, we use an average of the estimates. GRACE-FO RL06v4 products are available in pixel sizes of roughly 100 km at monthly intervals. We acknowledge that the equivalent water thickness represents the total TWSA from soil moisture, snow, surface water (including rivers, lakes, reservoirs, and the like), as well as groundwater and aquifers, associated with the variation between precipitation and evapotranspiration. Heerspink et al. (2020), De Paiva et al. (2013), and Pokhrel et al. (2013) find that TWSA components vary in the Amazon Basin. Therefore, TWSA is not an indicator *per se* of soil moisture.

The Global Land Evaporation Amsterdam Model (GLEAM, www.gleam.eu) provides data on the components of land evaporation (or *evapotranspiration*): transpiration, bare-soil evaporation, interception loss, and open-water evaporation and sublimation, in addition to other related variables such as surface and root-zone soil moisture, sensible heat flux, potential evaporation and evaporative stress conditions. In this work we use surface soil moisture from the GLEAMv4.1a version. This global dataset spans the 44-year period from January 1, 1980, to December 31, 2023. The dataset is based on satellite and reanalysis data. The surface soil moisture data is available at 0.1˚ resolution (Miralles et al., 2011, 2024; Hulsman et al., 2023).

2.4. Air Temperature, SST, Soil Water Content, and Latent Heat Flux

We use the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis Version 5 (ERA5) to extract additional information about surface and atmospheric properties. ERA5 provides land/sea and atmospheric fields from 1950 onwards at hourly intervals and monthly averages with a spatial grid of 0.25˚ (Albergel et al., 2018; Hersbach et al., 2023). Specifically, monthly sea surface temperature (SST) and monthly latent heat flux (LH) are drawn from ERA5. Monthly air temperature (at 2 m height) and volumetric soil water content for the uppermost layer of soil (0 - 7 cm) are from the land component of ERA5 (ERA5-Land). ERA5-Land includes a series of improvements over previous versions, including an enhanced grid resolution of 0.1˚ × 0.1˚, making it more accurate for all types of land applications (Muñoz-Sabater et al., 2021). Its long-term climatology is 1981-2020.

Sea surface temperature (SST) fields are also from ERA5 (Hirahara et al., 2016). This new reanalysis provides higher spatial and temporal resolutions and more recent model and data assimilation systems than the previous ERA-interim reanalysis (Albergel et al., 2018). Monthly SST at 0.25˚ spatial resolution is used in this study. Surface soil moisture data are taken from both ERA5-Land and the C3S satellite soil moisture product. These present conditions in the first few centimeters (~0 - 7 cm) of soil. Again, long-term climatology is 1981-2010.

Although we include information from a variety of sources: station data, gridded data sets, reanalyses, and satellite-derived data, we believe that any uncertainties caused by using different data sets do not reduce the credibility of our results.

2.5. Dry-Season Length (DSL)

We perform a quantitative analysis of the DSL from 1979 to 2023. We use daily rain rates from CPC to determine dry season onset (DSO) and dry season end (DSE) dates. DSE dates are the same as the wet season onset (WSO) dates. We start by finding average daily rain rates spatially over our chosen domains, e.g., the Southern Amazonian domain. We then temporally average the domain mean rain rates over five days (a pentad) to reduce synoptic noise. The observed DSE or WSO in Southern Amazonia is the first pentad in which the domain mean rain rate rises above the climatological value during two out of five pentads (Fu et al., 2013). Likewise, we define the DSO as the first pentad in which the domain mean rain rate drops below the climatological value during two out of five pentads. For the Eastern Amazonian domain, we define DSE and DSO in a way like the Southern Amazonian domain but using two out of six pentads as the threshold because the characteristics of rainfall seasonality there is somewhat different.

2.6. Integrated Drought Index (IDI)

To characterize drought, the integrated drought index (IDI) combines the standardized precipitation index (SPI), available soil water (ASW), and the vegetation water supply index (VSWI) or vegetation health index (VHI). Calculation of the IDI is based on the SPI for an accumulation period of three months (IDI-3). First, SPI (calculated from the CHIRPS dataset), VHI (from NOAA, www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_ftp.php), and ASW (from https://nasagrace.unl.edu) are rescaled to the same spatial resolution (5 km). In the second step, the indices are labeled to reflect equivalent drought intensity, as explained by Cunha et al. (2019) and Zeri et al. (2024). Finally, categorical maps of SPI, VHI, and ASW are combined to generate the final drought category. Each drought category is associated with a numerical and descriptive value (from 1—exceptional to 6—normal condition) so that the average is also meaningful.

3. Results

3.1. Large-Scale Circulation and Sea Surface Temperature Anomalies during the Drought of 2023-24 Relative to Previous Droughts

Extremes of interannual rainfall and river variability in the Amazon can be, in part, attributed to SST 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 Atlantic. Most of the severe droughts in the Amazon are associated with anomalous warm SST in the equatorial Pacific during El Niño events and warm SST anomalies in the tropical North Atlantic, as in 2010, 2015-16, and 2023-24, as well as in previous droughts in 1982-83 and 1997-98 (Marengo et al., 2018). The drought in 2005 was largely induced by high warm SST anomalies in the tropical North Atlantic. Both El Niño and warm tropical North Atlantic temperatures inhibit rainfall over the Amazon region, when the ITCZ is anomalously displaced northward and the Amazon basin is affected by strong subsidence induced by the warm SST anomalies in the equatorial Pacific (Marengo & Espinoza, 2016; Cai et al., 2020; Yoon & Zeng, 2010). The closest associations between SST anomalies in the equatorial Pacific and rainfall anomalies are during the peak of the austral summer between December and January, when El Niño is more intense, and the peak of the rainy season in the austral summer and fall in southern and central Amazonia, respectively.

SST anomalies in Niño 1+2 region showed neutral conditions starting in November 2022 and became positive in January 2023. Niño 3 showed positive SST anomalies starting in February 2023, and Niño 3.4 starting in March. **Figures 2(a)-(l)** show SST anomalies from September to March during several drought years in Amazonia: 2004-05, 2009-10, 2015-16 and 2023-24. The last three were El Niño years. In all these cases, warm conditions were observed in the equatorial Pacific, with highest intensity (SST > 3˚C) in SON and DJF in 2015-16 and 2023-24. Warm conditions were also observed in the tropical North Atlantic in 2005 and 2010. Perhaps the greatest difference between 2023-24 and the other drought years is that in addition to the tropical oceans, warm conditions were also observed in the subtropical North and South Pacific and in most of the Atlantic Ocean starting in September 2023. Warm conditions in the tropical Atlantic prevailed in DJF and MAM 2024. The warming of the tropical Pacific was more intense in SON 2023 as compared to DJF 2024 in the eastern Pacific. **Figure 2(m)** and **Figure 2(n)** show that considering Niño 3.4 region as indicator, El Niño 2023-24 was less intense than El Niño 2015-16. As for the Niño 1 + 2 region, warming was much higher in 2023-24, as compared to 2015-16. This region, Niño 1 + 2, in the eastern Pacific (Cai et al., 2020), is usually more important for the Amazon's rainfall. The tropical North Atlantic was almost 1˚C warmer than normal during all of 2023 and austral summer of 2024, much higher than in any other dry year in Amazonia. This determined an anomalously northward-displaced ITCZ, inhibiting rainfall and raising temperatures in Amazonia starting in spring 2023.

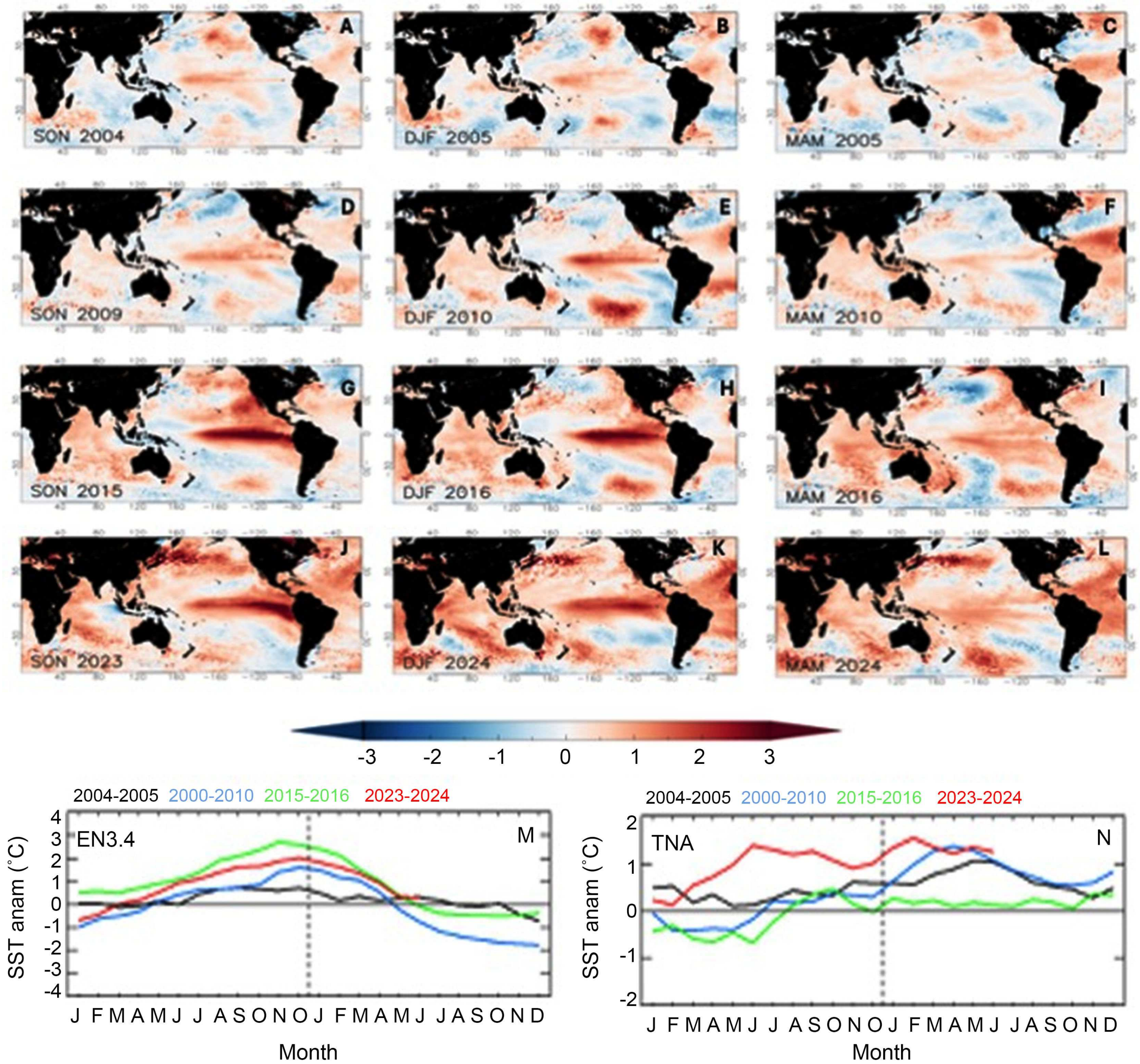

Figure 2. Sea surface temperature (SST) anomalies during drought years in Amazonia 2004-05, 2009-10, 2015-16 and 2023-24: (a-l) from SON 2009 to MAM 2024, (b) for Niño 3.4, and (c) for tropical North Atlantic. The climatological period is 1981-2020 (Source: ERA5).

3.2. Observed Changes in Rainfall, Air Temperature, Drought Indicators, and River Level Extremes during the Drought of 2023

3.2.1. Rainfall

As explained above, between 2020 and mid-2023, tropical South America was under the effect of La Niña. After May 2023, the region was under the influence of El Niño. The spatiotemporal evolution of rainfall anomalies for September-November (SON) 2022, December 2022-February (DJF) 2023, March-May (MAM) 2023, June-July (JJA) 2023, SON 2023, DJF 2024 and MAM 2024 is depicted in **Figure 3**. From DJF to JJA 2022, above-average rainfall was observed over northern Amazonia, while southern Amazonia experienced below-normal rainfall. This pattern of rainfall anomalies agrees with the documented impacts of La Niña over Amazonia (Tedeschi et al., 2013; Espinoza et al., 2024). Drier conditions were observed in western and central Amazonia north of the equator in MAM and JJA 2023, and in MAM 2023, heavy rain was registered in western Amazonia, triggering an overflow of the Acre River that flooded vast areas of Rio Branco. The city recorded 124.4 mm of rainfall in 24 hours on March 23, 2023 (INMET, www.inmet.gov.br). With El Niño already in place, all of Amazonia experienced dry conditions in SON 2023, when the climatological onset of the rainy season in Amazonia occurs. SON 2023 was the only season with rainfall deficiency over the entire the basin. Eight Brazilian Amazon states recorded the lowest rainfall in over 40 years from July to September: 100 - 300 mm/month below normal (Toreti et al., 2023). In DJF and MAM 2024 the Amazon south of the equator recorded below-average rainfall.

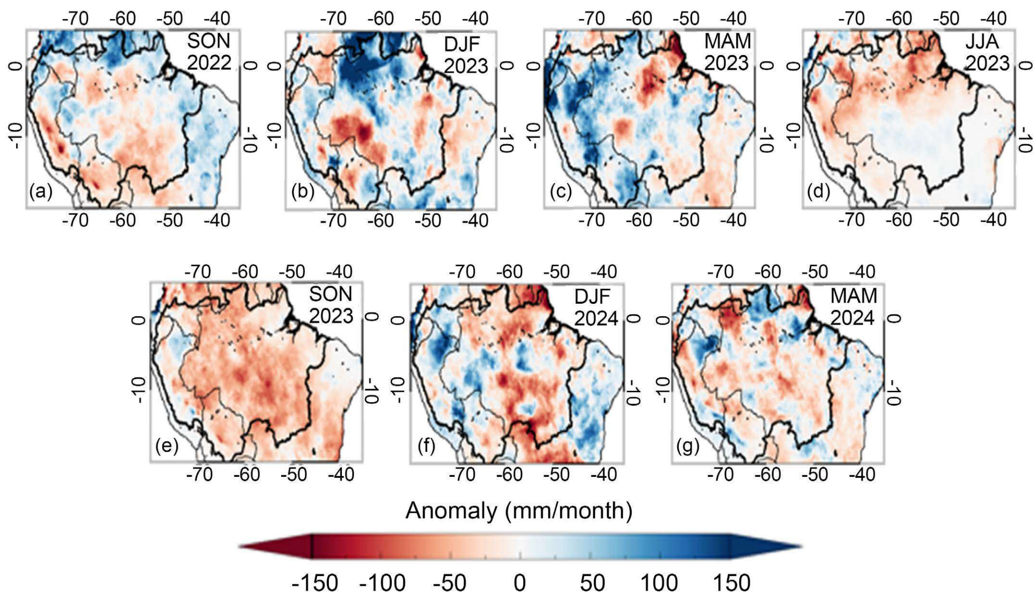

Figure 3. Seasonal average of the precipitation anomalies (in mm) from September-November (SON) 2022 to March-May (MAM) 2024 (a-g). The climatological period is 1981-2020. Values are in mm/month. Data is from CHIRPS.

3.2.2. Air Temperature

Figure 4 shows temperatures between +1˚C to +2˚C above average over central and western Amazonia in SON 2022. During DJF 2023, neutral conditions were observed over most parts of the Amazon Basin, but the warming in the region started to intensify in MAM 2023. The peak of the warming was in SON 2023, with temperature anomalies between +2˚C and +4˚C (or even higher), consistent with negative rainfall anomalies in the basin (**Figure 3**). In DJF and MAM 2024 warming was observed throughout the Amazon basin, between +2˚C to +3˚C. At the local scale, maximum and minimum temperatures in the Manaus station were well above average in 2023, almost 5˚C above normal in October 2023 (**Figure 5**). The highest temperature recorded in Manaus (**Figure 5**,

Figure 1 for location) in 2023 was 39.3˚C, higher than ever previously recorded (breaking the record of 39°C set on September 21, 2015, another El Niño year, INMET, 2023). The long-term mean (LTM) temperature there is 33.5˚C. According to INMET (2023), Belém reached a high of 36.6˚C in September 2023, the fourth-highest temperature recorded in 63 years. 2023 had the hottest September at this station in the last 33 years. Also in September 2023, higher temperatures were recorded in other nearby cities: Cuiabá at 41.2˚C (LTM: 34.3˚C) and Rio Branco at 37.1˚C (LTM: 33.2˚C). During the heat waves that affected central South America in SON 2023, the highest maximum was registered in Cuiabá with 39.6˚C (LTM: 33.6˚C), and in Porto Velho with 34.6˚C (LTM: 33.0˚C).

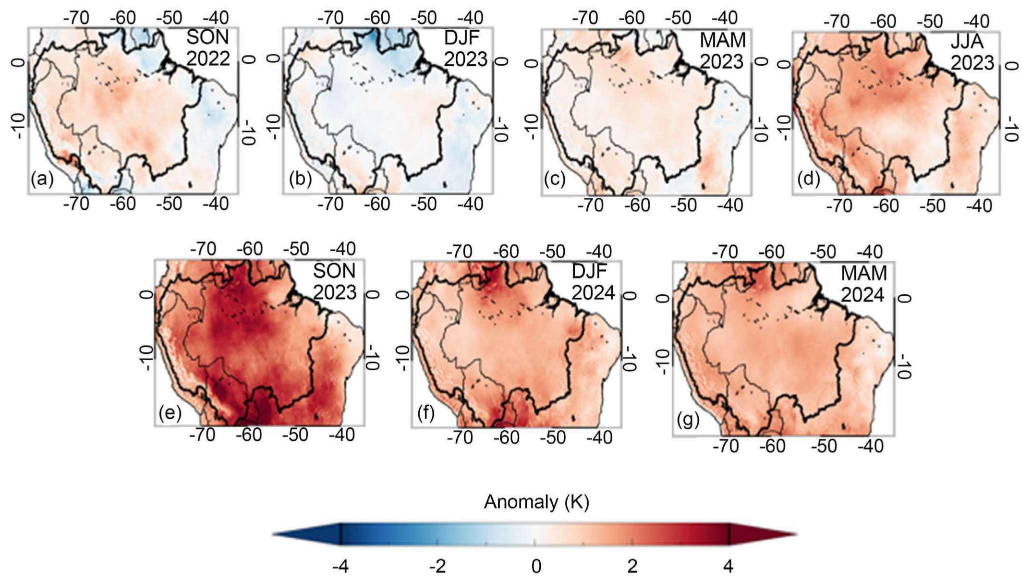

Figure 4. Seasonal average air temperature anomalies (in oC) from September-November (SON) 2022 to March-May 2024 (MAM) 2024 (a-g). The climatological period is 1981-2020. Values above are in oC. Data is from ERA5.

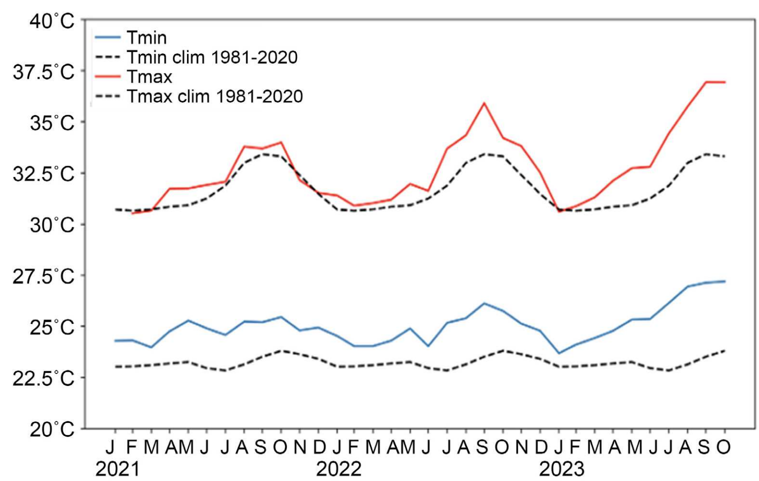

Figure 5. Maximum (red line) and minimum (blue line) air temperature in the Manaus station for 2021, 2022, and 2023. Values are in oC. Climatology is shown in black broken lines. Reference period is 1981-2020 (Source: INMET).

3.2.3. Drought Index

The drought in the Amazon in 2023 is classified according to the IDI (combining meteorological, hydrological, and agricultural features) as severe-extreme (Cunha et al., 2019; Toreti et al., 2023). As shown in **Figure 6**, from SON 2022 to DJF 2023 drought conditions appeared in southern Amazonia. In MAM 2023 consistent with positive rainfall anomalies, severe drought was concentrated in small locations in central Amazonia. In JJA and SON 2023, the Amazon experienced extreme drought and heat. The situation was exacerbated in SON for almost all of Amazonia, consistent with negative rainfall anomalies (**Figure 3**) and higher temperatures (**Figure 4**) in the region. The IDI of SON 2023 was classified as severe-extreme in the southern Amazon region of Brazil, over the Bolivian and Peruvian Amazon regions, and extending to most of the Amazon south of 5˚S. By DJF and MAM 2024, drought was mainly concentrated in southeastern Amazonia and the northernmost state of Roraima.

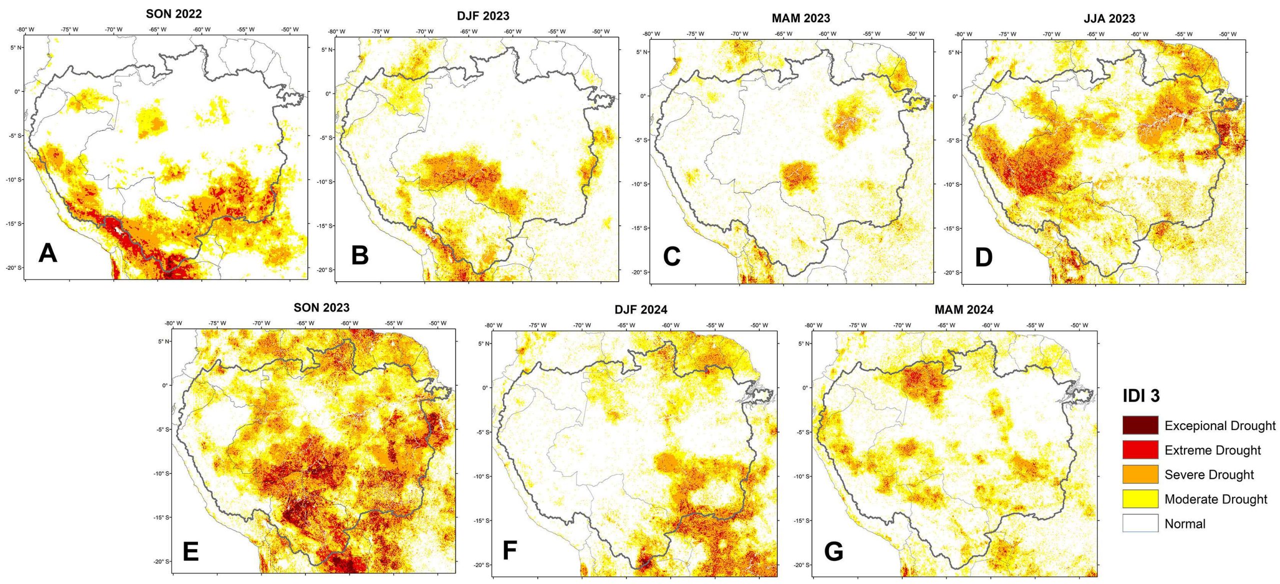

Figure 6. Seasonal average of the integrated drought index (IDI-3) from September-November (SON) 2022 to December-February (DJF) 2024 (a-g). The climatological period is 1981-2020. The IDI-3 is based on SPI-3 (3 months) (Source: Cunha et al., 2019).

3.2.4. River Records

Over the last 120 years, twelve extreme hydrological droughts have been recorded by monitoring the Rio Negro levels at the port of Manaus. The number of extreme droughts has increased since 1995. Six extreme droughts occurred between 1995 and 2023, compared to seven from 1903-1994 (Barichivich et al., 2018; Espinoza et al., 2024). Because of the drought in 2023-24, the Rio Negro and many of the Amazon's major rivers reached historically low levels. Navigation was disrupted, isolating hundreds of riverine communities. In October 2023, the level at Manaus fell to 12.70 m, the lowest since measurements began in 1902 ((Brazilian Geological Survey) SGB (2023), www.sgb.gov.br). The barges that carry over 40% of Brazil's grain exports to northern ports have been running at half capacity because of the low river levels. Considering the critical level of emergency at the Manaus Port for floods (>29 m) and hydrological droughts (<15.8 m) (Maciel et al., 2020), a significant increase in the annual amplitude of about 150 cm has developed during the last 30 years (Schöngart & Junk, 2020; Espinoza et al., 2022), compared to earlier periods (**Figure 7**).

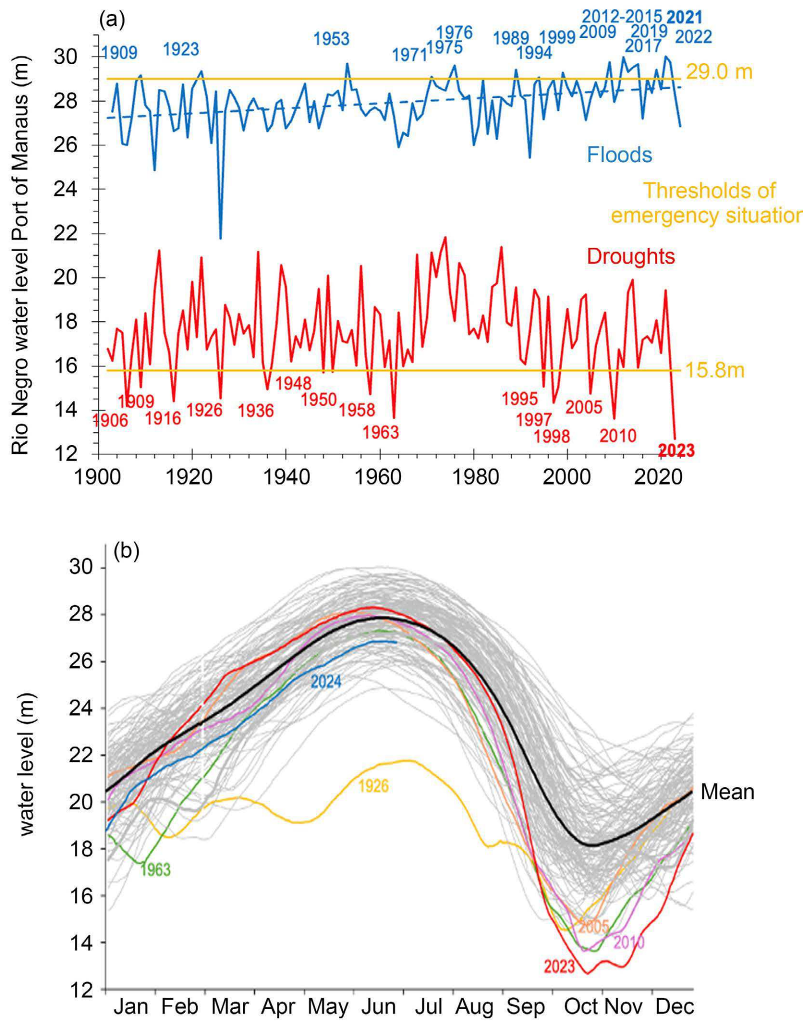

Figure 7. (a) Maximum (blue lines) and minimum (red lines) levels of the Rio Negro at the Port of Manaus from 1902 to November 2023. Blue and red numbers indicate record floods and droughts, respectively. Values are in meters. (b) Rio Negro water levels measured at the Port of Manaus. Solid red line shows the levels in drought years 1963, 2005, 2010, 2023, and 2024 (Source: J. Schongart, INPA).

The frequency of severe floods has more than doubled, compared to hydrological droughts, over the last 120 years (Barichivich et al., 2018; Espinoza et al., 2022). Since 2010, no severe hydrological drought occurred (considering the threshold of 15.8 m). The severe El Niño 2015-16 and subsequent drought in Amazonia did not impact the minimum water level in Manaus. Droughts related to El Niño have a greater effect on rivers with headwaters in the northern hemisphere, as the period of reduced rainfall coincides with the natural low-water period. However, the 2023 drought started much earlier, due to the many synergistic effects reviewed above. Thus, it affected a broader range of rivers across the Amazon (Costa et al., 2024). According to the Port of Manaus, the Rio Negro recorded a tide of 12.70 m at Manaus on October 26, 2023, its lowest since 1902 (**Figure 7(b)**). Levels fell below normal in June 2023, and 2024 river levels were even lower than those of 2023—and lower than the LTM starting in February.

As for the changes in water levels in 2024, after the low point in October 2023 in the Port of Manaus, the water level rose 14.15 m. It reached its maximum level on June 16, 2024, at 26.85 m. This is 1.07 m below the mean (1903-2023). In July 2024, the river reached 25.71 m, according to SGB (www.sgb.gov.br). Prior to June 2024, the levels at Manaus were below the mean and below 2023 levels (**Figure 7(b)**). The upper Rio Solimões at Tabatinga has nearly the lowest water levels ever recorded for this region. **Figure 8(a)** and **Figure 8(b)** show the consequences of the drought in the rivers and on population activities.

(a)

(b)

Figure 8. Pictures depict Lake Tefé and the city of Tefé (Brazil) during the drought in October 2023. Credits for Débora Hymans/Instituto Mamirauá.

3.3. Observed Trends in the Dry Season Length and Onset of the Rainy Season in Southern and Eastern Amazonia

Lengthening of the dry season and changes in the frequency and intensity of extreme drought episodes are probably the most critical factors affecting the Amazon (Sampaio et al., 2018). **Figure 9(b)** and **Figure 9(d)** show that WSO over the southern Amazon shows a significant delay trend (p = 0.001). Possibly due to a strong interannual variability, the delay trend is less significant for eastern Amazonia for WSO or DSL, with wet onsets delayed during some El Niño years (**Figure 10**). For eastern Amazonia, WSO (in other words, DSE) was undetectable in 2015 and 2023. The rainfall in these two years never exceeded the annual mean. Hence, **Figure 9(a)** shows gaps for these two years. Since our analysis focuses on the years 1979-2023, we define the DSE date as the last pentad (i.e., the 73rd pentad) if the dry season continues, which means the DSE date will not proceed to the next year. According to our method, for the years 2015 and 2023 (i.e., gaps shown in **Figure 9(a)**), the DSE dates are set to the 73rd pentad. DSL is computed between this DSE date (the 73rd pentad) and the DSO date. In practice, this eliminates any gap in DSL in **Figure 9(c)**. Therefore, according to **Figure 9**, for both eastern and southern Amazonia, statistically significant trends suggest that the rainy season is gradually starting later, and the dry season has become longer during 1979-2023. Years with drought show late onsets and long dry seasons, and interannual variability of those dates is high due to El Niño or the warm tropical Atlantic.

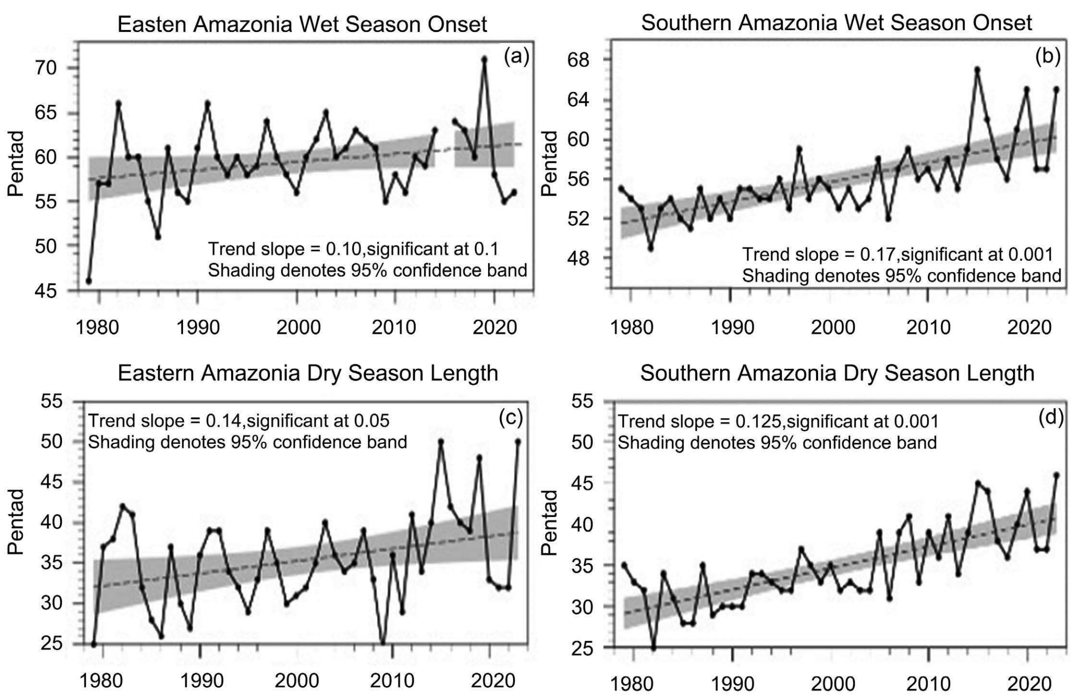

Figure 9. Interannual variability (1979-2023) of the wet season onset (WSO) in (a) eastern and (b) southern Amazonia, and dry season length (DSL) in (c) eastern and (d) southern Amazonia. Unit is pentad (5-day). DSL and DSE are derived from the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center's (CPC) daily rainfall data. The linear trend is determined by a least-square fitting in ray shading. Trends are significant ($p < 0.01$). The shading shows the 95% confidence intervals for the trends.

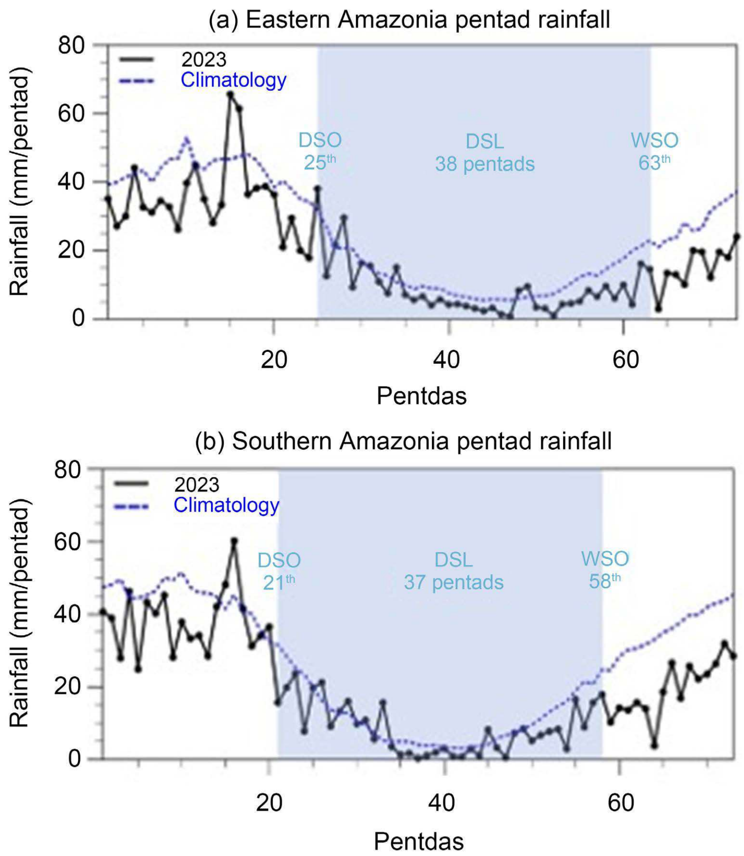

Figure 10. Seasonal variation of pentad rainfall (mm/pentad) in 2023 (solid black curve) and its climatology averaged over 1981-2020 (dashed blue curve) over eastern (a) and southern (b) Amazonia. The climatological DSO, WSO (DSE), and dry season length (DSL) are marked with blue labels. The DSO, DSL, and DSE are derived from the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center's (CPC) daily rainfall data.

3.4. Observed Changes in the Onset of the Rainy Season 2023-24 and the Effect of Land-Surface Interactions

Figure 10(a) shows the pentad climatological (dashed blue line) and 2023 (solid black line) rainfall over eastern Amazonia. The climatological DSO, DSL, and WSO are denoted with blue shading. Figure 10(b) is the same as Figure 10(a). But for southern Amazonia, comparing the two regions, the dates of DSO and WSO are earlier over southern Amazonia than over eastern Amazonia. This reflects an anomalous latitudinal migration of the Intertropical Convergence Zone over Amazonia to the north.

The wet season in 2023-24 arrived late in both regions because rainfall in 2023 was consistently lower than that of climatology. Thus, the climatological WSO over eastern Amazonia occurred in the 59^{th} pentad, with rainfall varying between 20 - 35 mm/pentad between September-December. The WSO of the 2023-24 hydrological year started late and was very weak in December 2023. Rainfall observed from September to December varied between 0 and 20 mm/pentad. In southern Amazonia the mean WSO occurred in the 65th pentad. Rainfall in September-December was between 20 - 45 mm/pentad. As in eastern Amazonia in 2023, the WSO occurred late, and rainfall between September and December varied between 10 and 25 mm/pentad (Figure 10(a)).

Austral winter and spring (when the WSO typically occur) of 2023 had warmer and drier than normal conditions over southern and eastern Amazonia (Figure 4 and Figure 6). Figure 2 and Figure 3 show that in 2023, broad areas of Amazonia were affected by drought and warm temperatures, and the rainy season was delayed (Figure 9 and Figure 10).

Reduced dry-season and dry-to-wet season rainfall (as in JJA 2023 and SON 2023) (Figure 3) diminishes atmospheric moisture transport (Espinoza et al., 2024) and reduces surface soil moisture and latent heat flux (Figures 11(a)-(g), Figures 12(a)-(g)) in those two seasons in the Amazon region. This increases sensible heat flux due to the more significant portion of radiative energy available for land and air heating (Sillmann et al., 2013). It thus reduces precipitation and raises temperatures. Lack of rain and higher temperatures dried the soil of the Amazonian forest during the JJA 2023 dry season, diminishing ET. Moisture will recharge once heavy rains return (Arias et al., 2020). Like 2023, Liu et al. (2024) identify below-average TWS in 2005 and 2010 due to below-average precipitation during the fall and JJA dry season.

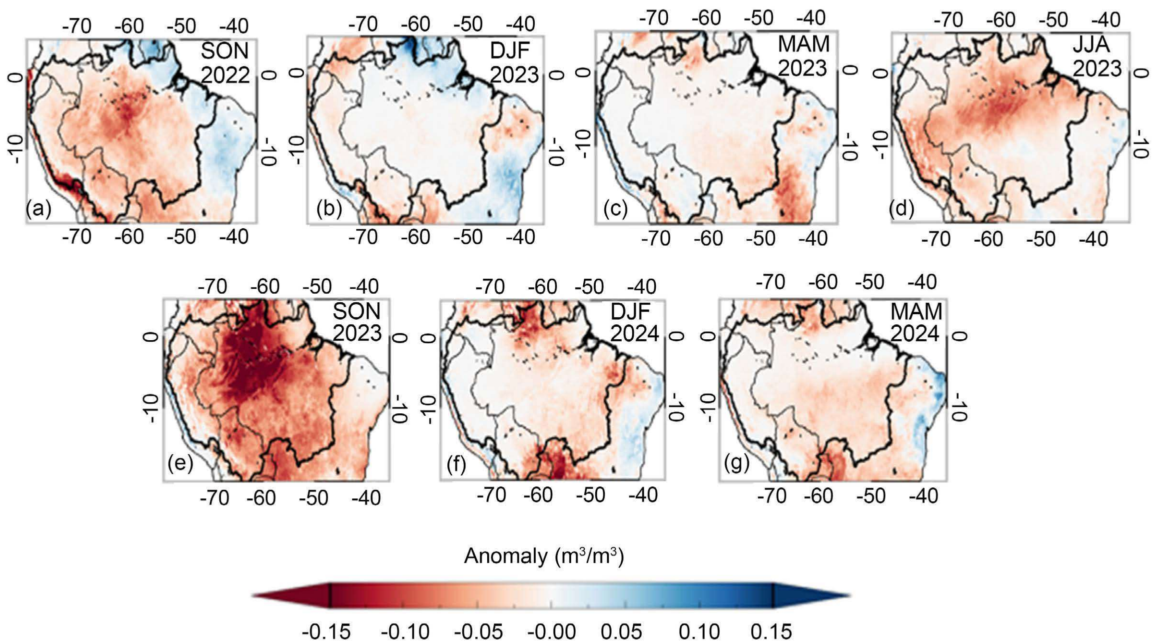

Figure 11. Seasonal average of the surface soil moisture (in m³/m³) from September-November (SON) 2022 to March-May 2024 (MAM) 2024 (a-g). The climatological period is 1980-2020. Data is from ERA5.

We have evidence of reduced TWSA in JJA and SON 2023 from GRACE (Figures 13(a)-(f)) and surface soil moisture from GLEAMv4.1a (Figures 14(a)-(f)) due to diminished precipitation in JJA and SON 2023. This is consistent with negative rainfall and ET anomalies. This combination shows reduced surface soil moisture, modifying energy distribution to increase sensible heat flux and temperature, as **Figure 4** shows. This change correlates with amplified Bowen ratios, according to Fu & Li (2004), Good et al. (2015), and Sierra et al. (2023). Therefore, the WSO of 2023 began at least two months late. Rainfall was below normal, with dry and warm conditions prevailing during the SON 2023 dry-to-wet season.

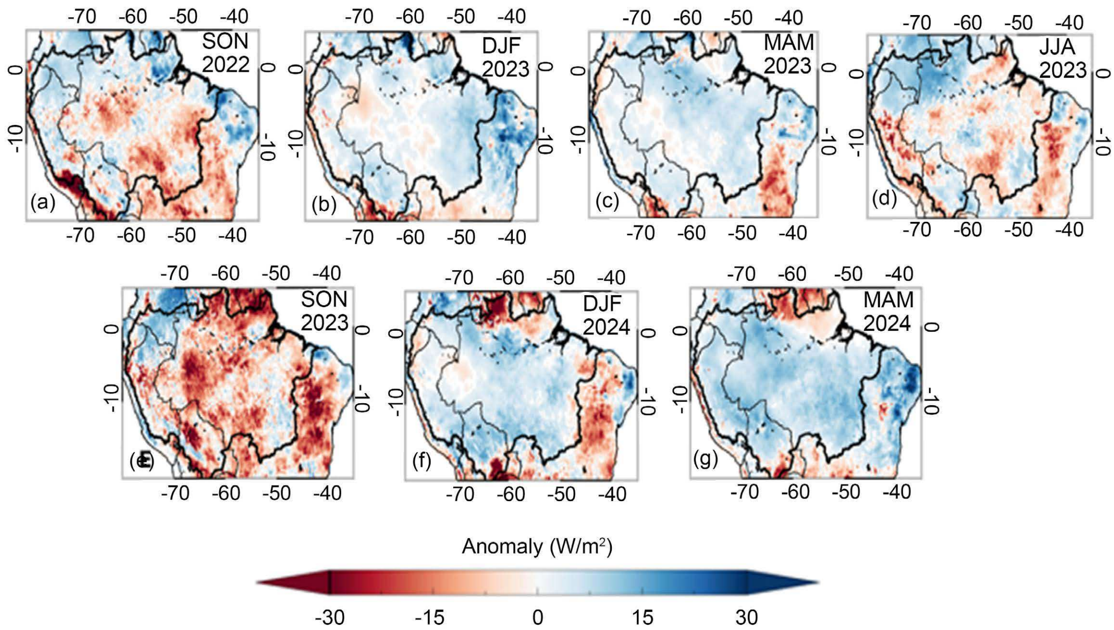

Figure 12. Seasonal average of the latent heat (in W/m^2) from September-November (SON) 2022 to March-May (MAM) 2024 (a-f). The climatological period is 1980-2020. Data is from ERA5.

According to Wright et al. (2017), ET is the primary moisture source for shallow convection during the dry-to-wet season transition. The TWSA derived from GRACE, surface soil moisture from ERA5 and GLEAMv4.1a, and latent heat show negative anomalies in the SON 2023 dry-to-wet season. Positive anomalies or near-normal conditions in MAM in 2023 are consistent with positive rainfall anomalies in western and central Amazonia. In JJA 2023, the dry season in Amazonia and the high air temperatures were related to anomalous atmospheric subsidence, associated with the impacts of El Niño on the Walker circulation (Espinoza et al., 2024). TWSA and surface soil moisture started to show negative anomalies in JJA 2023 and SON 2023. The soil dried out, and ET was reduced (negative anomalies of latent heat).

Figures 11-14 show negative anomalies of latent heat, surface soil moisture, and TWS in SON 2023, when the rainy season normally starts. Thus, the onset of the rainy season was delayed. Decreased ET reduces atmospheric moisture and cloud cover, raising temperatures. The impact of the six heat waves increased air temperature, particularly during the dry JJA and SON dry-to-wet seasons. Fu and Li (2004), Wright et al. (2017) and Sierra et al. (2023) propose that a lower ET may induce a late onset of the rainy season in both southern and eastern Amazonia, contributing to a longer dry season. This situation was observed mainly in southern Amazonia. Uncertainties about the ET in other parts of the Amazon basin are still high due to the lack of systematic observations.

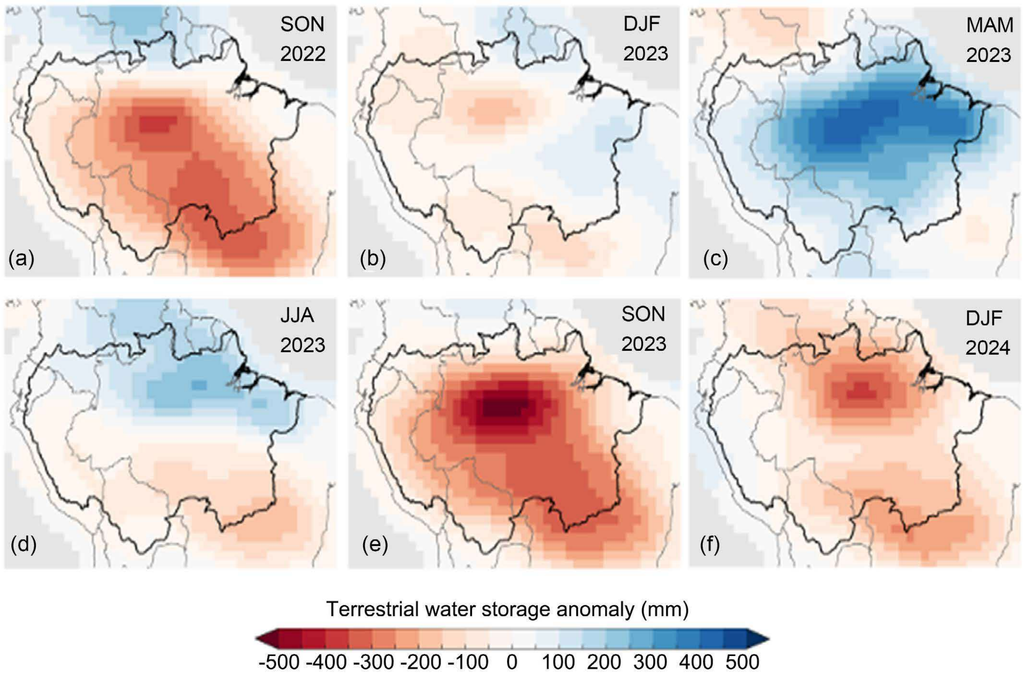

Figure 13. Seasonal average of the terrestrial water balance (TWS) (mm) from September-November (SON) 2022 to December-February (DJF) (a-f). No data available for MAM 2024. The climatological period is 1980-2020. Data is from GRACE.

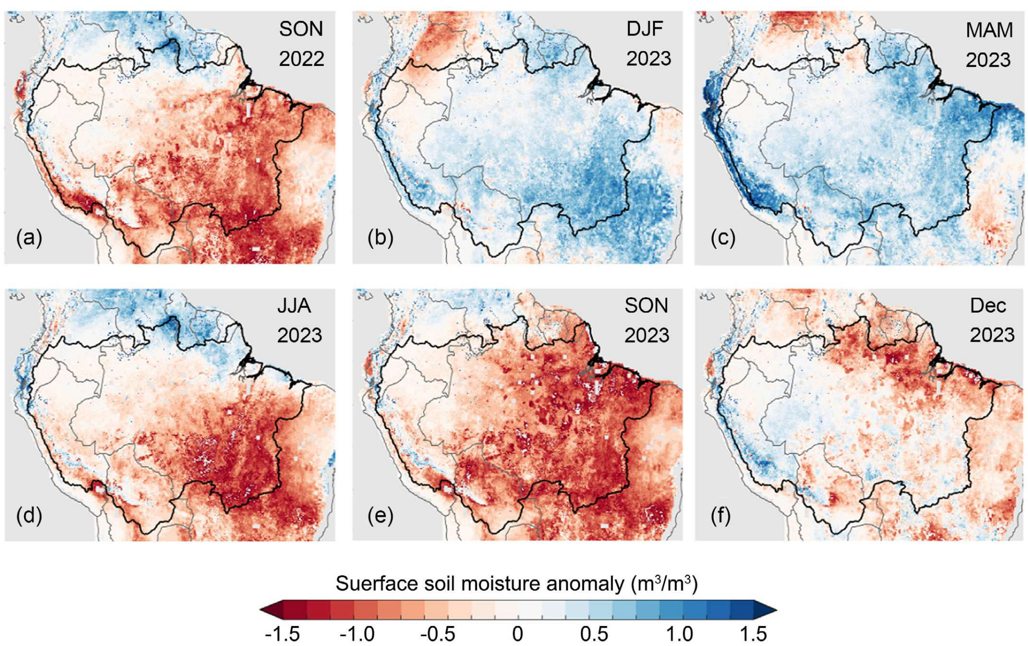

Figure 14. Seasonal average of the surface soil moisture (in m^3/m^3) from September-November (SON) 2022 to December 2023 (a-f). The climatological period is 1980-2020. No data available for MAM 2024. Data is from GLEAMv4.1a.

4. Discussion

This study underlines the complex atmosphere-soil interactions of precipitation, ET, temperature, latent heat, surface soil moisture, TWS, and the DSL. This is key to understand the possible impacts of droughts on the physiology and functioning of the Amazon forest. Analysis suggests a close association between latent heat, surface soil moisture, and TW. These are indicators of soil moisture available for plants during intense drought events. However, it is not always the case that a soil water deficit impacts tropical forests (Liu et al., 2024).

On a large scale, warming of the northern tropical Atlantic Ocean contributed to the subsequent anomalously northward position of the ITCZ. It reduced the intensity of northerly trade winds and moisture flow from SON 2023 to MAM 2024. The 2023-24 El Niño was an eastern Pacific type, with large positive SST anomalies in the Niño 3.4 and most particularly in the Niño 1 + 2 region. Subsidence conditions in central South America and the Amazon region in JJA and SON 2023 determined dry and warm conditions in central and northern Amazonia (Espinoza et al., 2024), with reduced soil moisture and latent heat particularly in those two seasons. SON is normally when the climatological rainy season begins. On the regional scale, local ET during the late dry season is key to initiate the dry-to-wet transition season over the southern Amazon (e.g., Wright et al., 2017; Commar et al., 2023; Sierra et al., 2023). So, late onsets could be related to reduced rainfall and warm conditions, reducing ET and soil moisture during the dry-to-wet transition.

Another contributor to droughts is the warm phase of the Atlantic Multidecadal Oscillation (AMO) (Yoon & Zeng, 2010; Espinoza et al., 2019a, 2019b; Aragão et al., 2018). AMO is a cyclical variation of the large-scale oceanic and atmospheric conditions in the tropical North Atlantic. The majority (80%) of the historical severe hydrological droughts in the Amazon basin coincide with warm phases of AMO (1925-1970 and 1995 onwards). Moisture transport into and inside the Amazon east of the Andes by means of atmospheric rivers or "flying rivers" weakens (Liu et al., 2023; Galaz & Meacham, 2024). The Indian Ocean also plays a role in droughts in Amazonia (Espinoza et al., 2024). Decadal changes in Amazonian precipitation have been attributed to phase shifts of the Pacific Decadal Oscillation (PDO), and Interdecadal Pacific Oscillation (IPO) (Andreoli & Kayano, 2005; Espinoza et al., 2019a, 2019b; Aragão et al., 2018). Fernandes et al. (2015) show that rainfall decadal fluctuations over the western Amazon closely correlate with those of the north-south gradient of tropical and subtropical Atlantic SST.

The year 2023 was marked by major heatwaves across the globe. Record-breaking air temperatures and prolonged heat waves reached the Amazon region (Perkins-Kirkpatrick et al., 2024). In SON 2023, the drought intensified in the Amazon. Six heat waves raised the temperatures by 4˚C - 5˚C warmer than average over the region in JJA and SON 2023, inducing a drought-heat event (WMO, 2024). Perkins-Kirkpatrick et al. (2024) and Jiménez et al. (2024) analyze the heat waves that occurred in 2023 in central South America: exceptional heat in winter and early spring 2023 that in some places broke all-time temperature records. This exacerbated the drought and was associated with the warming observed in **Figure 3** in JJA and SON 2023 and summer 2024.

Considering river data as an indicator, this drought in 2023 is the most intense ever seen in the instrumental record. The levels of the Rio Negro in Manaus in October 2023 were the lowest in 121 years of observations. Most of the main rivers in the Amazon, including the Solimões, Purus, Acre, and Branco, suffered record lows or dried up completely. According to the National Water Agency of Brazil, ANA (www.ana.gov.br) and the Brazilian Geological Survey, the Madeira River in Porto Velho fell to 1.09 m on October 15, which is the minimum level observed in the 56 years of measurements, and on August 3, 2024, the level at Porto Velho reached 1.02 m, the lowest since the beginning of measurements in 1967. The Santo Antônio and Jirau hydroelectric along the Madeira River recorded negative flow records for October 2023 (ANA, 2023). In the Peruvian Amazon, the flows and levels of Amazonas, Marañón, Huallaga, and Ucayalí Rivers ranged from average to much lower than usual. The Huallaga River at Tingo María showed an anomaly of −45% in its discharge in October 2023 (SENAMHI, 2023). In Bolivia, the Mamoré-Guaporé and Madeira Rivers remain very low due to insufficient rainfall from July 2022 to June 2023 (SENAMHI-www.senamhi.gob.bo). By December 2023 the Rio Negro increased its levels and reached values near normal (SGB, https://www.sgb.gov.br/w/bacia-do-amazonas-nivel-do-rio-negro-em-manaus-se-aproxima-da-faixa-da-normalidade) with 18.34 m. A similar tendency was observed in other rivers in the region due to increased rainfall.

In the dry season between 2023 and 2024, the minimum level of the Rio Negro at São Gabriel da Cachoeira occurred on November 9, 2023, when the river dropped to 492 cm. At the end of 2023, the river level rose and then fell again. In March 2024, the drought situation worsened again, with the river reaching 533 cm on March 1. This level is less than the previous record drought (in March 1992, the river was at 573 cm). According to the SGB, between August 2023 and February 2024, the Rio Negro and Solimões basin had a 30% deficit in rainfall. Only 925 mm of rain fell, compared to an average of 1,290 mm. River levels reflected this deficit (https://www.socioambiental.org/en/socio-environmental-news/prolonged-drought%2C-rationing-and-smoke-marked-the-dry-season-in-the-middle-and). By July 19, 2024 the Madeira River dropped to 3.8 m in Porto Velho Station (LTM 10.4 m). The Brazilian Navy prohibited nighttime navigation (https://www.sgb.gov.br/w/rio-madeira-atinge-menores-niveis-historicos-para-o-mes-de-julho) due to deficient rainfall in the basin in previous months.

Previous drought events occurred during the summertime peak of the rainy season in December-February. Southeast and southern Amazonia suffered from concurrent thermal stress due to heat waves and water stress, as shown by negative TWS anomalies and longer dry seasons in 2023. Espinoza et al. (2024) highlight the lack of rain and subsequent drought in the 2022-2023 austral summer. Anomalous vertically integrated moisture flux was displaced south, associated with the extreme rainfall deficit over southwestern Amazonia. These results suggest that dry conditions in southwestern Amazonia have prevailed for at least one year.

The dry-to-wet season SON 2023 showed negative rainfall anomalies (−50 to −100 mm/month), positive air temperature anomalies (+3˚C) including four intense heat waves. In terms of soil moisture content, SON showed negative TWM, soil moisture content and latent heat anomalies, characteristics of water deficiency. This led to drought conditions in Amazonia, particularly in southern and eastern Amazonia (including the *Cerrado*-Amazon transition zone). Warm SST anomalies due to El Niño and the warm tropical North Atlantic started in May 2023 and intensified in SON 2023, helping to induce these changes. This situation led to a delay of the WSO, occurring in DJF 2024 rather than in SON 2023. Low evapotranspiration and soil moisture, together with high temperatures and deficient rainfall, induced drought conditions These conditions then inhibited the timely onset of the rainy season. It occurred almost two months later, and had very low rainfall, as shown by Wright et al. (2017) and Fu and Li (2004).

In addition, recent analysis by Clarke et al. (2024) shows that climate change has been exacerbating the El Niño impacts over central and northern Amazonia. El Niño and climate change were each responsible for 50% of the reduction in precipitation of austral winter and spring 2023. The intensity of the drought of 2015-16 has also been linked to anthropogenic causes (Ribeiro et al., 2022).

5. Conclusion

A severe drought affected large sections of the Amazon River basin and most of northern South America due to a severe dry period from the austral summer 2022-23 and extending well into 2024. In the dry-to-wet SON 2023 season, the basin recorded below-average rainfall, mostly across the Solimões, Purus, Juruá, and Madeira River headwaters. Meteorologically, the drought situation started in southwestern Amazonia in November 2022. It intensified in central and northern Amazonia during austral winter of 2023, exacerbated by El Niño and a warm tropical North Atlantic. We find that drought conditions continued during the first part of the 2023-24 hydrological year, growing more intense during September-November (SON) 2023 and extending into 2024. Large-scale rainfall anomalies started with El Niño and a very warm tropical North Atlantic during the second half of 2023. This was like other drought years in Amazonia. The difference is that the most affected season was the SON spring season in 2023, and not the austral summer DJF as in other dry years.

Evapotranspiration derived from latent heat diminished during the second half of 2023. The decrease of latent heat and the warming of the near-surface, together with reduced rainfall and soil moisture content, generated a drought-warm situation in Amazonia in JJA. It grew more extreme during the dry-to-wet season SON 2023. ET should also diminish during a warmer spring if the dry season continues. Heat wave events increased air temperature and thermal stress even more during JJA and SON 2023. The dry soil generated by the drought-heat situation in Amazonia delayed the onset of the wet season of the hydrological year 2023-24 by at least two months, making the dry season longer. Generally, ET is higher at the beginning of the dry season because there may be some rain. In 2023, reduced ET during the dry and dry-to-wet transition seasons led to late onset of the rainy season. It did so by inhibiting the formation of shallow convection. Thus, the delayed WSO means a longer dry season, with thermal stress due to heat waves and reduced rainfall and soil moisture content. The drought reported for Amazonia in SON 2023 extended into DJF 2024.

Interactions between dry soil, high temperatures, reduced evapotranspiration, and lack of rainfall explain changes in DSL and a late and weak WSO during the drought of 2023 in Amazonia. Therefore, land surface-climate interactions in the dry-to-wet season SON 2023 were key to determining drought conditions in Amazonia during summer and fall of 2024. The lengthening of the dry season and changes in the frequency and intensity of extreme drought episodes aggravated by heat wave occurrences fueled fires and low river levels in the region, extending into 2024.

The synergy of droughts, deforestation, fire, and degradation reduces the Amazon's capacity to recycle water and act as a carbon sink. As seen in previous intense droughts, either related to El Niño or to a warm tropical North Atlantic, the Amazon's ecosystem and population are highly vulnerable to extremes of climate variation. The drought legacy may include tree mortality and a high risk of fire in the next couple of years, with notable signs already evident in 2024. This drought illustrates an extreme climate anomaly that might become more frequent and intense if no action is taken to stop climate change. Adaptation to droughts requires multisectoral approaches and strong governance. Interventions in infrastructure, agriculture, sanitation, potable water access, and health, and the establishment of early warning systems of droughts could help to minimize socio-economic and environmental impacts and losses.

There are still some gaps to the knowledge of climate extremes in the Amazon, and whether to attribute them to climate variability or to climate change (e.g. land use changes, increased greenhouse gas emissions). However, we likely already have enough information to respond to climate crises. The countries that make up the Amazon still lack the means to comprehensively monitor climate and hydrology systems. Improved understanding of these systems could aid in developing and implementing adaptation programs directed towards vulnerable populations, such as indigenous people. To cope with drought impacts, climate and hydrology monitoring programs and early warning systems for droughts must be implemented. Other programs should include seasonal climate and continental hydrology predictions, as well as data sharing across Amazon countries. Another alternative is the adoption of diversified agroforestry and agroecological systems to improve food security and natural resources management.

Adaptation strategies and policies must be based on a comprehensive understanding of the local realities of different socio-economic groups and regions.

Acknowledgements

We thank Vitor Miranda (EOU/PISA Portugal; GCU/IPL Universitat de València, Spain) for the processing and elaboration of the latent heat flux maps. This work was supported by Brazil's National Institute of Science and Technology for Climate Change Phase 2 under CNPq Grant 465501/2014-1; FAPESP Grants 2014/50848-9, and the National Coordination for Higher Education and Training (CAPES) Grant 88887.136402/2017-00. JCE was supported by the French AMANECER-MOPGA project funded by ANR and IRD (ref. ANR18-MPGA-0008). JAM acknowledges the support of the Newton Fund through the Met Office Climate Science for Service Partnership Brazil (CSSP Brazil). We also thank Ayan Santos Fleischmann from Instituto Mamirauá for providing photographs of drought in Amazonia.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Albergel, C., Dutra, E., Munier, S., Calvet, J., Munoz-Sabater, J., de Rosnay, P., et al. (2018). ERA-5 and ERA-Interim Driven ISBA Land Surface Model Simulations: Which One Performs Better? *Hydrology and Earth System Sciences, 22,* 3515-3532. https://doi.org/10.5194/hess-22-3515-2018

Alexander, L. (2011). Extreme Heat Rooted in Dry Soils. *Nature Geoscience, 4,* 12-13. https://doi.org/10.1038/ngeo1045

ANA (2023). *Subsídios técnicos à proposta de Declaração de situação crítica de escassez quantitativa dos recursos hídricos no Rio Madeira. Nota Técnica Conjunta N° 1/2023/SRE/SFI/SHE/SGH-IS.* Agencia Nacional de Aguas ANA.

Anderson, L. O., Ribeiro Neto, G., Cunha, A. P., Fonseca, M. G., Mendes de Moura, Y., Dalagnol, R., et al. (2018). Vulnerability of Amazonian Forests to Repeated Droughts. *Philosophical Transactions of the Royal Society B: Biological Sciences, 373,* Article ID: 20170411. https://doi.org/10.1098/rstb.2017.0411

Andreoli, R. V., & Kayano, M. T. (2005). ENSO-Related Rainfall Anomalies in South America and Associated Circulation Features during Warm and Cold Pacific Decadal Oscillation Regimes. *International Journal of Climatology, 25,* 2017-2030. https://doi.org/10.1002/joc.1222

Aragão, L. E. O. C., Anderson, L. O., Fonseca, M. G., Rosan, T. M., Vedovato, L. B., Wagner, F. H., et al. (2018). 21st Century Drought-Related Fires Counteract the Decline of Amazon Deforestation Carbon Emissions. *Nature Communications, 9,* Article No. 536. https://doi.org/10.1038/s41467-017-02771-y

Arantes, C. C., Winemiller, K. O., Petrere, M., Castello, L., Hess, L. L., & Freitas, C. E. C. (2017). Relationships between Forest Cover and Fish Diversity in the Amazon River Floodplain. *Journal of Applied Ecology, 55,* 386-395. https://doi.org/10.1111/1365-2664.12967

Arias, P. A., Martínez, J. A., Mejía, J. D., Pazos, M. J., Espinoza, J. C., & Wongchuig-Correa, S. (2020). Changes in Normalized Difference Vegetation Index in the Orinoco and Amazon River Basins: Links to Tropical Atlantic Surface Temperatures. *Journal of Climate, 33,* 8537-8559. https://doi.org/10.1175/jcli-d-19-0696.1

Artaxo, P. (2023). Amazon Deforestation Implications in Local/Regional Climate Change. *Proceedings of the National Academy of Sciences of the United States of America, 120,* e2317456120. https://doi.org/10.1073/pnas.2317456120

Arvor, D., Funatsu, B., Michot, V., & Dubreuil, V. (2018). Addendum: Arvor, D., et al. Monitoring Rainfall Patterns in the Southern Amazon with PERSIANN-CDR Data: Long-Term Characteristics and Trends. Remote Sens. 2017, 9, 889. *Remote Sensing, 10,* Article 128. https://doi.org/10.3390/rs10010128

Baez-Villanueva, O. M., Zambrano-Bigiarini, M., Ribbe, L., Nauditt, A., Giraldo-Osorio, J. D., & Thinh, N. X. (2017). Temporal and Spatial Evaluation of Satellite Rainfall Estimates over Different Regions in Latin-America. *Atmospheric Research, 213,* 34-50. https://doi.org/10.1016/j.atmosres.2018.05.011

Barichivich, J., Gloor, E., Peylin, P., Brienen, R. J. W., Schöngart, J., Espinoza, J. C., et al. (2018). Recent Intensification of Amazon Flooding Extremes Driven by Strengthened Walker Circulation. *Science Advances, 4,* eaat8785. https://doi.org/10.1126/sciadv.aat8785

Beck, H. E., Vergopolan, N., Pan, M., Levizzani, V., van Dijk, A. I. J. M., Weedon, G. P., et al. (2017). Global-Scale Evaluation of 22 Precipitation Datasets Using Gauge Observations and Hydrological Modeling. *Hydrology and Earth System Sciences, 21,* 6201-6217. https://doi.org/10.5194/hess-21-6201-2017

Boulton, C. A., Lenton, T. M., & Boers, N. (2022). Pronounced Loss of Amazon Rainforest Resilience since the Early 2000s. *Nature Climate Change, 12,* 271-278. https://doi.org/10.1038/s41558-022-01287-8

Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., et al. (2020). Climate Impacts of the El Niño-Southern Oscillation on South America. *Nature Reviews Earth & Environment, 1,* 215-231. https://doi.org/10.1038/s43017-020-0040-3

Chen, M., Shi, W., Xie, P., Silva, V. B. S., Kousky, V. E., Wayne Higgins, R., et al. (2008). Assessing Objective Techniques for Gauge-Based Analyses of Global Daily Precipitation. *Journal of Geophysical Research: Atmospheres, 113,* D04110. https://doi.org/10.1029/2007jd009132

Clarke, B. Barnes, C., Rodrigues, R., Zachariah, M., Stewart, S., Raju, E., Baumgart, N., D., Libonati, R., Santos, D., Albuquerque, R., Alves, L.M., Otto, F. (2024) *Climate Change, Not El Niño, Main Driver of Exceptional Drought in Highly Vulnerable Amazon River Basin.* https://spiral.imperial.ac.uk/bitstream/10044/1/108761/7/Scientific%20Report%20-%20Amazon%20Drought.pdf

Commar, L. F. S. A., Abrahão, G. M., & Costa, M. H. (2023). A Possible Deforestation-Induced Synoptic-Scale Circulation That Delays the Rainy Season Onset in Amazonia. *Environmental Research Letters, 18,* Article ID: 044041.

Costa, F., Marengo, J., Albernaz, A., et al. (2024). *Policy Brief: Droughts in Amazonia, Science Panel for Amazon SPA.* https://www.theamazonwewant.org/spa_publication/pb-droughts/

Cunha, A. P. M. A., Zeri, M., Deusdará Leal, K., Costa, L., Cuartas, L. A., Marengo, J. A., et al. (2019). Extreme Drought Events over Brazil from 2011 to 2019. *Atmosphere, 10,* Article 642. https://doi.org/10.3390/atmos10110642 de Lima, L. S., Silva, F. E. O. e., Dorio Anastácio, P. R., Kolanski, M. M. d. P., Pires Pereira, A. C., Menezes, M. S. R., et al. (2024). Severe Droughts Reduce River Navigability and Isolate Communities in the Brazilian Amazon. *Communications Earth & Environment, 5,* Article No. 370. https://doi.org/10.1038/s43247-024-01530-4

de Paiva, R. C. D., Buarque, D. C., Collischonn, W., Bonnet, M., Frappart, F., Calmant, S., et al. (2013). Large-Scale Hydrologic and Hydrodynamic Modeling of the Amazon River Basin. *Water Resources Research, 49,* 1226-1243. https://doi.org/10.1002/wrcr.20067

Eiras-Barca, J., Dominguez, F., Yang, Z., Chug, D., Nieto, R., Gimeno, L., et al. (2020). Changes in South American Hydroclimate under Projected Amazonian Deforestation. *Annals of the New York Academy of Sciences, 1472,* 104-122. https://doi.org/10.1111/nyas.14364

Espinoza, J. C., Ronchail, J., Marengo, J. A., & Segura, H. (2019b). Contrasting North–South Changes in Amazon Wet-Day and Dry-Day Frequency and Related Atmospheric Features (1981-2017). *Climate Dynamics, 52,* 5413-5430. https://doi.org/10.1007/s00382-018-4462-2

Espinoza, J. C., Sörensson, A. A., Ronchail, J., Molina-Carpio, J., Segura, H., Gutierrez-Cori, O., et al. (2019a). Regional Hydro-Climatic Changes in the Southern Amazon Basin (Upper Madeira Basin) during the 1982-2017 Period. *Journal of Hydrology: Regional Studies, 26,* Article ID: 100637. https://doi.org/10.1016/j.ejrh.2019.100637

Espinoza, J., Arias, P. A., Moron, V., Junquas, C., Segura, H., Sierra-Pérez, J. P., et al. (2021). Recent Changes in the Atmospheric Circulation Patterns during the Dry-To-Wet Transition Season in South Tropical South America (1979-2020): Impacts on Precipitation and Fire Season. *Journal of Climate, 34,* 1-56. https://doi.org/10.1175/jcli-d-21-0303.1

Espinoza, J., Jimenez, J. C., Marengo, J. A., Schongart, J., Ronchail, J., Lavado-Casimiro, W., et al. (2024). The New Record of Drought and Warmth in the Amazon in 2023 Related to Regional and Global Climatic Features. *Scientific Reports, 14,* Article No. 8107. https://doi.org/10.1038/s41598-024-58782-5

Espinoza, J., Marengo, J. A., Schongart, J., & Jimenez, J. C. (2022). The New Historical Flood of 2021 in the Amazon River Compared to Major Floods of the 21st Century: Atmospheric Features in the Context of the Intensification of Floods. *Weather and Climate Extremes, 35,* Article ID: 100406. https://doi.org/10.1016/j.wace.2021.100406

Fernandes, K., Giannini, A., Verchot, L., Baethgen, W., & Pinedo-Vasquez, M. (2015). Decadal Covariability of Atlantic SSTs and Western Amazon Dry-Season Hydroclimate in Observations and CMIP5 Simulations. *Geophysical Research Letters, 42,* 6793-6801. https://doi.org/10.1002/2015gl063911

Fleischmann, A., Papa, F., Hamilton, S., Melack, J., et al. (2024). *Extreme Warming of Amazon Waters in a Changing Climate.*

Flores, B. M., & Holmgren, M. (2021). White-Sand Savannas Expand at the Core of the Amazon after Forest Wildfires. *Ecosystems, 24,* 1624-1637. https://doi.org/10.1007/s10021-021-00607-x

Fu, R., & Li, W. (2004). The Influence of the Land Surface on the Transition from Dry to Wet Season in Amazonia. *Theoretical and Applied Climatology, 78,* 97-110. https://doi.org/10.1007/s00704-004-0046-7

Fu, R., Yin, L., Li, W., Arias, P. A., Dickinson, R. E., Huang, L., et al. (2013). Increased Dry-Season Length over Southern Amazonia in Recent Decades and Its Implication for Future Climate Projection. *Proceedings of the National Academy of Sciences, 110,* 18110-18115. https://doi.org/10.1073/pnas.1302584110

Galaz, V., & Meacham, M. (2024). *Redirecting Flows—Navigating the Future of the Am-*

azon. arXiv: 2403.18521.

Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., et al. (2021). Amazonia as a Carbon Source Linked to Deforestation and Climate Change. *Nature, 595,* 388-393. https://doi.org/10.1038/s41586-021-03629-6

Good, P., Lowe, J. A., Andrews, T., Wiltshire, A., Chadwick, R., Ridley, J. K., et al. (2015). Nonlinear Regional Warming with Increasing CO_2 Concentrations. *Nature Climate Change, 5,* 138-142. https://doi.org/10.1038/nclimate2498

Gutierrez-Cori, O., Espinoza, J. C., Li, L. Z. X., Wongchuig, S., Arias, P. A., Ronchail, J., et al. (2021). On the Hydroclimate-Vegetation Relationship in the Southwestern Amazon during the 2000-2019 Period. *Frontiers in Water, 3,* Article 648499. https://doi.org/10.3389/frwa.2021.648499

Güntner, A. (2008). Improvement of Global Hydrological Models Using GRACE Data. *Surveys in Geophysics, 29,* 375-397. https://doi.org/10.1007/s10712-008-9038-y

Heerspink, B. P., Kendall, A. D., Coe, M. T., & Hyndman, D. W. (2020). Trends in Streamflow, Evapotranspiration, and Groundwater Storage across the Amazon Basin Linked to Changing Precipitation and Land Cover. *Journal of Hydrology: Regional Studies, 32,* Article ID: 100755. https://doi.org/10.1016/j.ejrh.2020.100755

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Hornyi, A., Muoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., & Thepaut, J. N. (2023). *ERA5 Hourly Data on Single Levels from 1940 to Present.* Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Hirahara, S., Balmaseda, M. A., de Boisseson, E., & Hersbach, H. (2016). *Sea Surface Temperature and Sea Ice Concentration for ERA5.* ERA Report Series No. 26.

Hulsman, P., Keune, J., Koppa, A., Schellekens, J., & Miralles, D. G. (2023). Incorporating Plant Access to Groundwater in Existing Global, Satellite-Based Evaporation Estimates. *Water Resources Research, 59,* e2022WR033731. https://doi.org/10.1029/2022wr033731

INMET (2023). *Balanço de setembro de 2023 em Manaus (AM).* https://portal.inmet.gov.br/noticias/balan%C3%A7o-manaus-am-teve-chuva-acima-da-m%C3%A9dia-em-setembro-2023

Jiménez, J. C., Miranda, V., Trigo, I., Libonati, R., Albuquerque, R., Peres, L. F., et al. (2024). Vegetation Warming and Greenness Decline across Amazonia during the Extreme Drought of 2023. *Remote Sensing, 16,* Article 2519. https://doi.org/10.3390/rs16142519

Lapola, D. M., Pinho, P., Barlow, J., Aragão, L. E. O. C., Berenguer, E., Carmenta, R., et al. (2023). The Drivers and Impacts of Amazon Forest Degradation. *Science, 379,* eabp8622. https://doi.org/10.1126/science.abp8622

Leite-Filho, A. T., de Sousa Pontes, V. Y., & Costa, M. H. (2019). Effects of Deforestation on the Onset of the Rainy Season and the Duration of Dry Spells in Southern Amazonia. *Journal of Geophysical Research: Atmospheres, 124,* 5268-5281. https://doi.org/10.1029/2018jd029537

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., & Börner, J. (2021). Deforestation Reduces Rainfall and Agricultural Revenues in the Brazilian Amazon. *Nature Communications, 12,* Article No. 2591. https://doi.org/10.1038/s41467-021-22840-7

Liu, S., McVicar, T. R., Wu, X., Cao, X., & Liu, Y. (2024). Assessing the Relative Importance of Dry-Season Incoming Solar Radiation and Water Storage Dynamics during the 2005, 2010 and 2015 Southern Amazon Droughts: Not All Droughts Are Created

Equal. *Environmental Research Letters, 19,* Article ID: 034027. https://doi.org/10.1088/1748-9326/ad281e

Liu, T., Chen, D., Yang, L., Meng, J., Wang, Z., Ludescher, J., et al. (2023). Teleconnections among Tipping Elements in the Earth System. *Nature Climate Change, 13,* 67-74. https://doi.org/10.1038/s41558-022-01558-4

Lorenz, R., Jaeger, E. B., & Seneviratne, S. I. (2010). Persistence of Heat Waves and Its Link to Soil Moisture Memory. *Geophysical Research Letters, 37,* L09703. https://doi.org/10.1029/2010gl042764

Maciel, J. S. C., Simões Alves, L. G., Dos Santos CorrÊA, B. G., Rodrigues De Carvalho, I. M., & Oliveira, M. A. (2020). Flood Forecast in Manaus, Amazonas, Brazil. *WIT Transactions on The Built Environment, 194,* 63-72. https://doi.org/10.2495/friar200061

Malhi, Y., Aragão, L. E. O. C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., et al. (2009). Exploring the Likelihood and Mechanism of a Climate-Change-Induced Dieback of the Amazon Rainforest. *Proceedings of the National Academy of Sciences of the United States of America, 106,* 20610-20615. https://doi.org/10.1073/pnas.0804619106

Marengo, J. A., & Espinoza, J. C. (2016). Extreme Seasonal Droughts and Floods in Amazonia: Causes, Trends and Impacts. *International Journal of Climatology, 36,* 1033-1050. https://doi.org/10.1002/joc.4420

Marengo, J. A., Espinoza, J., Fu, R., Jimenez Muñoz, J. C., Muniz Alves, L., Ribeiro da Rocha, H., et al. (2021). Chapter 22: Long-Term Variability, Extremes, and Changes in Temperature and Hydro Meteorology. In C. Nobre, et al. (Eds.), *Amazon Assessment Report 2021.* UN Sustainable Development Solutions Network (SDSN). https://www.theamazonwewant.org/spa-reports/ https://doi.org/10.55161/zgjg8060

Marengo, J. A., Souza, C. M., Thonicke, K., Burton, C., Halladay, K., Betts, R. A., et al. (2018). Changes in Climate and Land Use over the Amazon Region: Current and Future Variability and Trends. *Frontiers in Earth Science, 6,* Article 228. https://doi.org/10.3389/feart.2018.00228

Marengo, J. A., Tomasella, J., Alves, L. M., Soares, W. R., & Rodriguez, D. A. (2011). The Drought of 2010 in the Context of Historical Droughts in the Amazon Region. *Geophysical Research Letters, 38,* L12703. https://doi.org/10.1029/2011gl047436

Marmontel, M., Fleischmann, A., Val, A., & Forsberg, B. (2024). Safeguard Amazon's Aquatic Fauna against Climate Change. *Nature, 625,* 450-450. https://doi.org/10.1038/d41586-024-00114-8

Martinez, J. A., & Dominguez, F. (2014). Sources of Atmospheric Moisture for the La Plata River Basin. *Journal of Climate, 27,* 6737-6753. https://doi.org/10.1175/jcli-d-14-00022.1

Miralles, D. G., Holmes, T. R. H., De Jeu, R. A. M., Gash, J. H., Meesters, A. G. C. A., & Dolman, A. J. (2011). Global Land-Surface Evaporation Estimated from Satellite-Based Observations. *Hydrology and Earth System Sciences, 15,* 453-469. https://doi.org/10.5194/hess-15-453-2011

Miralles, D. G., Koppa, A., Baez-Villanueva, O. M., Tronquo, E., Bonte, O., Zhong, F., Beck, H. E., Hulsman, P., Haghdoost, S., & Dorigo, W. A. (2024). *GLEAM4: Global Evaporation and Soil Moisture Datasets at 0.1˚ Resolution from 1980 to Near Present, in Review.*

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., et al. (2021). ERA5-Land: A State-of-the-Art Global Reanalysis Dataset for Land Applications. *Earth System Science Data, 13,* 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

Nobrega, R. L. B., Alencar, P. H. L., Baniwa, B., Buell, M., Chaffe, P. L. B., Munduruku Pinto Correa, D., et al. (2023). Co-developing Pathways to Protect Nature, Land, Territory, and Well-Being in Amazonia. *Communications Earth & Environment, 4,* Article No. 364. https://doi.org/10.1038/s43247-023-01026-7

Paca, V. H. D. M., Espinoza-Dávalos, G., Moreira, D., & Comair, G. (2020). Variability of Trends in Precipitation across the Amazon River Basin Determined from the CHIRPS Precipitation Product and from Station Records. *Water, 12,* Article 1244. https://doi.org/10.3390/w12051244

Papastefanou, P., Zang, C. S., Angelov, Z., de Castro, A. A., Jimenez, J. C., De Rezende, L. F. C., et al. (2022). Recent Extreme Drought Events in the Amazon Rainforest: Assessment of Different Precipitation and Evapotranspiration Datasets and Drought Indicators. *Biogeosciences, 19,* 3843-3861. https://doi.org/10.5194/bg-19-3843-2022

Paredes-Trejo, F. J., Barbosa, H. A., & Lakshmi Kumar, T. V. (2017). Validating Chirps-Based Satellite Precipitation Estimates in Northeast Brazil. *Journal of Arid Environments, 139,* 26-40. https://doi.org/10.1016/j.jaridenv.2016.12.009

Perkins-Kirkpatrick, S., Barriopedro, D., Jha, R., Wang, L., Mondal, A., Libonati, R., et al. (2024). Extreme Terrestrial Heat in 2023. *Nature Reviews Earth & Environment, 5,* 244-246. https://doi.org/10.1038/s43017-024-00536-y

Pokhrel, Y. N., Fan, Y., Miguez-Macho, G., Yeh, P. J., & Han, S. (2013). The Role of Groundwater in the Amazon Water Cycle: 3. Influence on Terrestrial Water Storage Computations and Comparison with Grace. *Journal of Geophysical Research: Atmospheres, 118,* 3233-3244. https://doi.org/10.1002/jgrd.50335

Ratier, R. (2023). *Água a 38˚C, peixe podre e jacaré morto: Cientistas mostram colapso no AM.* https://www.uol.com.br/ecoa/colunas/rodrigo-ratier/2023/10/17/agua-a-38-oc-peixe-podre-e-jacare-morto-cientistas-mostram-colapso-no-am.htm accessed 11.19.23

Ribeiro, G. G., Anderson, L. O., Barretos, N. J. C., Abreu, R., Alves, L., Dong, B., et al. (2022). Attributing the 2015/2016 Amazon Basin Drought to Anthropogenic Influence. *Climate Resilience and Sustainability, 1,* e25. https://doi.org/10.1002/cli2.25

Rodell, M., & Famiglietti, J. S. (2002). The Potential for Satellite-Based Monitoring of Groundwater Storage Changes Using GRACE: The High Plains Aquifer, Central US. *Journal of Hydrology, 263,* 245-256. https://doi.org/10.1016/s0022-1694(02)00060-4

Salazar, L. F., Nobre, C. A., & Oyama, M. D. (2007). Climate Change Consequences on the Biome Distribution in Tropical South America. *Geophysical Research Letters, 34,* L09708. https://doi.org/10.1029/2007gl029695

Sampaio, G., Borma, L. S., Cardoso, M., Alves, L. M., von Randow, C., Rodriguez, D. A., et al. (2018). Assessing the Possible Impacts of a 4 °C or Higher Warming in Amazonia. In C. A. Nobre, J. A. Marengo, & W. R. Soares (Eds.), *Climate Change Risks in Brazil* (pp. 201-218). Springer International Publishing. https://doi.org/10.1007/978-3-319-92881-4_8

Satyamurty, P., da Costa, C. P. W., & Manzi, A. O. (2013b). Moisture Source for the Amazon Basin: A Study of Contrasting Years. *Theoretical and Applied Climatology, 111,* 195-209. https://doi.org/10.1007/s00704-012-0637-7

Satyamurty, P., da Costa, C. P. W., Manzi, A. O., & Candido, L. A. (2013a). A Quick Look at the 2012 Record Flood in the Amazon Basin. *Geophysical Research Letters, 40,* 1396-1401. https://doi.org/10.1002/grl.50245

Schöngart, J., & Junk, W. J. (2020). Clima e hidrologia nas várzeas da Amazônia Central. In W. J. Junk, M. T. F. Piedade, F. Wittmann, & J. Schöngart (Eds.), *Várzeas Amaz Desafios para um Manejo Sustentável* (pp. 44-65). INPA—Instituto Nacional de Pesquisas da Amazonia.

SENAMHI (2023). *Boletín Hidrológico Mensual a Nivel Nacional.* https://www.senamhi.gob.pe/load/file/02609SENA-147.pdf

SGB (2023). https://www.sgb.gov.br/publique/Hidrologia/Eventos-Criticos/Seca-na-Regiao-Amazonica-8328.html

Shi, M., Liu, J., Worden, J. R., Bloom, A. A., Wong, S., & Fu, R. (2019). The 2005 Amazon Drought Legacy Effect Delayed the 2006 Wet Season Onset. *Geophysical Research Letters, 46,* 9082-9090. https://doi.org/10.1029/2019gl083776

Sierra, J. P., Espinoza, J., Junquas, C., Wongchuig, S., Polcher, J., Moron, V., et al. (2023). Impacts of Land-Surface Heterogeneities and Amazonian Deforestation on the Wet Season Onset in Southern Amazon. *Climate Dynamics, 61,* 4867-4898. https://doi.org/10.1007/s00382-023-06835-2

Sierra, J. P., Junquas, C., Espinoza, J. C., Segura, H., Condom, T., Andrade, M., et al. (2021). Deforestation Impacts on Amazon-Andes Hydroclimatic Connectivity. *Climate Dynamics, 58,* 2609-2636. https://doi.org/10.1007/s00382-021-06025-y

Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X., & Bronaugh, D. (2013). Climate Extremes Indices in the CMIP5 Multimodel Ensemble: Part 2. Future Climate Projections. *Journal of Geophysical Research: Atmospheres, 118,* 2473-2493. https://doi.org/10.1002/jgrd.50188

Strassberg, G., Scanlon, B. R., & Chambers, D. (2009). Evaluation of Groundwater Storage Monitoring with the GRACE Satellite: Case Study of the High Plains Aquifer, Central United States. *Water Resources Research, 45,* W05410. https://doi.org/10.1029/2008wr006892

Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., & Watkins, M. M. (2004). GRACE Measurements of Mass Variability in the Earth System. *Science, 305,* 503-505. https://doi.org/10.1126/science.1099192

Tedeschi, R. G., Cavalcanti, I. F. A., & Grimm, A. M. (2013). Influences of Two Types of ENSO on South American Precipitation. *International Journal of Climatology, 33,* 1382-1400. https://doi.org/10.1002/joc.3519

Toreti, A., Bavera, D., Acosta Navarro, J., Arias Muñoz, C., Barbosa, P., Branco, A., Cunha, A. P., de Jager, A., Fioravanti, G., Grimaldi, S., Hrast Essenfelder, A., Libertà, G., Maetens, W., Magni, D., Marengo, J. A., Masante, D., Mazzeschi, M., McCormick, N., Meroni, M., Oom, D., Rembold, F., Salamon, P., & San Miguel, J. (2023). *Drought in the Amazon Basin.* Publications Office of the European Union.

Towner, J., Ficchí, A., Cloke, H. L., Bazo, J., Coughlan de Perez, E., & Stephens, E. M. (2021). Influence of ENSO and Tropical Atlantic Climate Variability on Flood Characteristics in the Amazon Basin. *Hydrology and Earth System Sciences, 25,* 3875-3895. https://doi.org/10.5194/hess-25-3875-2021

WMO (2024). *State of the Climate in Latin America and the Caribbean 2023 WMO-No. 1351.* World Meteorological Organization.

Wright, J. S., Fu, R., Worden, J. R., Chakraborty, S., Clinton, N. E., Risi, C., et al. (2017). Rainforest-Initiated Wet Season Onset over the Southern Amazon. *Proceedings of the National Academy of Sciences of the United States of America, 114,* 8481-8486. https://doi.org/10.1073/pnas.1621516114

Wunderling, N., Staal, A., Sakschewski, B., Hirota, M., Tuinenburg, O. A., Donges, J. F., et al. (2022). Recurrent Droughts Increase Risk of Cascading Tipping Events by Outpacing Adaptive Capacities in the Amazon Rainforest. *Proceedings of the National Academy of Sciences of the United States of America, 119,* e2120777119. https://doi.org/10.1073/pnas.2120777119

Xie, P., Arkin, P. A., & Janowiak, J. E. (2007). CMAP: The CPC Merged Analysis of Precipitation. In V. Levizzani, P. Bauer, & F. J. Turk (Eds.), *Measuring Precipitation from Space* (pp. 319-328). Springer. https://doi.org/10.1007/978-1-4020-5835-6_25

Yoon, J., & Zeng, N. (2010). An Atlantic Influence on Amazon Rainfall. *Climate Dynamics, 34,* 249-264. https://doi.org/10.1007/s00382-009-0551-6

Zeri, M., Cunha, A., Cunningham, C., Guedes, M., & Costa, L. (2024). *A Long-Term Database of the Integrated Drought Index for Brazil from 2003 to 2023.* Mendeley Data.