Chapter 5 In Brief

The Physical hydroclimate system of the Amazon

Vista aérea da Terra Indígena Yanomami (Foto: Bruno Kelly/Amazônia Real)

THE AMAZON WE WANT
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The physical hydroclimate system of the Amazon

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Key Messages & Recommendations

1) Given its tropical location enclosed by the Andes, its huge spatial extent (approximately 7.3 million km^2), and extensive forest cover, the Amazon River basin is one of the most critical elements of the Earth's climate system. It exerts a strong influence on atmospheric dynamics and circulation patterns, both within and outside the tropics. It produces rainfall that results in the planet's largest river discharges, with a mean rate of 220,000 m^3/s, or 16-22% of the world's total river discharge.
2) The Amazon basin is mainly characterized by lowlands with a warm and rainy climate. The upper part of the basin includes the eastern slope of the Andes, characterized by a wide variety of mountain climates (cloud forest, *Páramos*, *Yungas*, *Punas*, etc.).
3) The El Niño-Southern Oscillation (ENSO) is the main cause of interannual variability in rainfall. El Niño is typically (but not exclusively) accompanied by droughts in the Amazon, with severe droughts in recent years resulting in low river water levels and increased risk of fires. In addition to ENSO, Atlantic and Pacific sea surface temperature (SST) variability influences the climate of the Amazon at interannual and interdecadal time-scales, including extreme events.
4) In the last 15 years, the Amazon has witnessed several climate extremes: droughts in 2005, 2010, and 2015–16; and floods in 2009, 2013, 2014, 2017 and 2021. Some of these have been classified as "once-in-a-century" events (see Chapter 22). Historical records show previous droughts in 1926, 1964, 1980, 1983, and 1998; and floods in 1953, 1988, and 1989.
5) Preserving and restoring the Amazon forest is essential to maintaining regionally-important processes, including convection, evapotranspiration (ET), mesoscale circulations, and land surface processes.

Abstract This chapter reviews the main features and large- to mesoscale mechanisms that contribute to the Amazon's climate, its interannual and interdecadal variability, and extreme drought and flood events. It examines the effects of extreme events on vegetation and the partitioning of precipitation into evapotranspiration, runoff, flow seasonality, and floodplain dynamics; and describes the floodplain´s role in the biogeochemical cycle.

Main characteristics of the Amazon's climate

Spatial distribution of temperature, atmospheric circulation, and rainfall Due to high, relatively constant incoming solar radiation, air temperatures in the Amazon are also relatively constant, with little variation throughout the year except in the southern Amazon (Rondônia, Mato Grosso, the Bolivian Amazon, and the southern Peruvian Amazon). Annual average temperatures exceed 27-29ºC in the central equatorial region. The seasonal thermal amplitude is 1-2ºC, and average values range from 24°C to 26ºC. Near the Andes, the maximum monthly mean temperature in Santa Cruz de la Sierra, Bolivia, is 26.1°C

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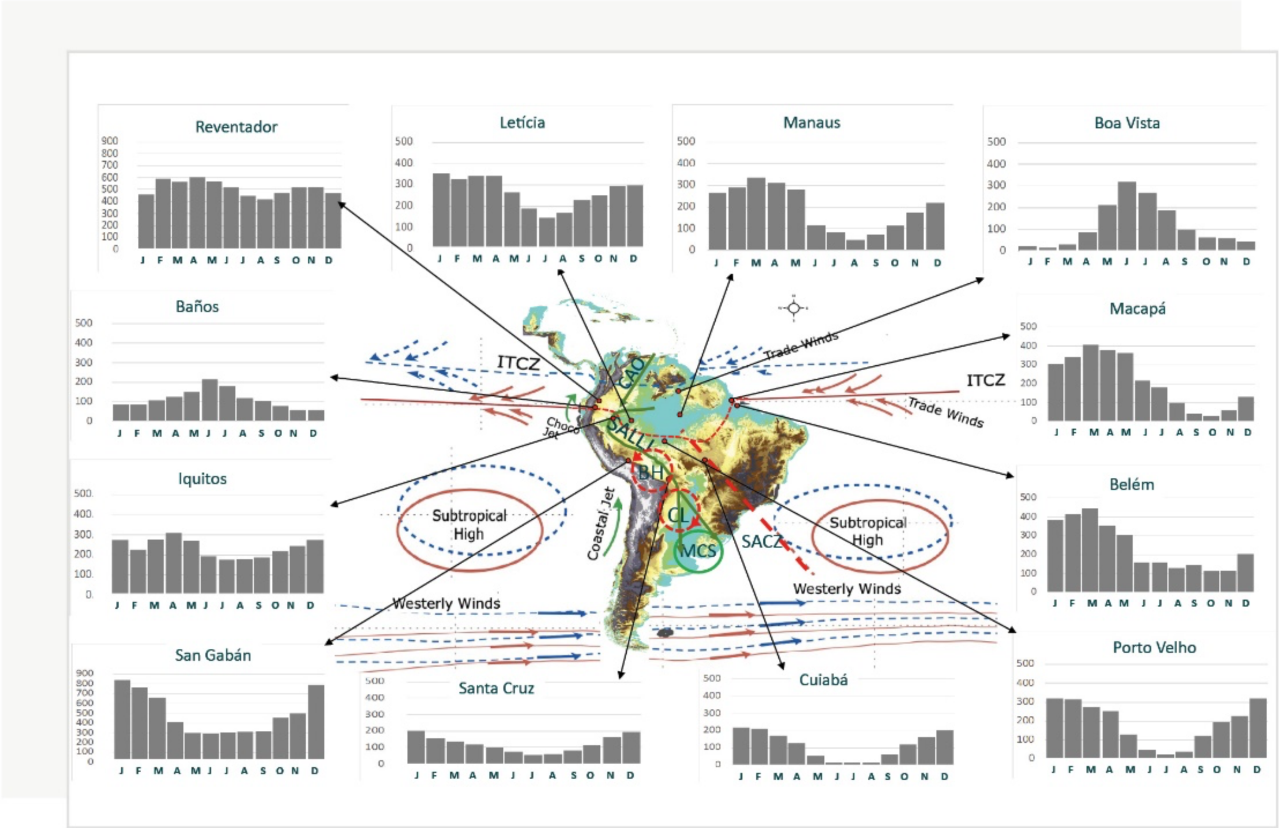

Figure 5.1 Schematic of the main climatological features in South America. The blue and red lines represent June-July-August (JJA) and December-January-February (DJF), respectively. The annual cycle of rainfall (bars, in mm) is shown for measurement stations located across the Amazon (indicated by dots). Abbreviations: CL, Chaco Low; BH, Bolivian High; ITCZ, Intertropical Convergence Zone; MCS, mesoscale convective system; SACZ, South Atlantic Convergence Zone; SALLJ, South American low-level jet. Sources of rainfall data: INMET and ANA (Brazil), SENAMHI (Peru), SENAMHI (Bolivia), INAMHI (Ecuador). Adapted from of Cai et al (Figure 1)[2]. Climatology of the period 1961-2010.

in September and 20°C in June. Despite small seasonal fluctuations, large temperature oscillations are typical of the diurnal cycle in this region, in association with that of rainfall.

Atmospheric circulation in the Amazon is driven by the annual cycle of solar radiation. Near the Amazon delta, maximum rainfall is observed during austral summer to fall, and dry conditions prevail during winter. This is due to the alternating warming of the two hemispheres and to variations in the location of the Intertropical Convergence Zone (ITCZ)[1]. Trade winds coming from the tropical North and South Atlantic converge along the ITCZ and are associated with subtropical anticyclones in the North and South Atlantic. Monsoonal rain over the Amazon basin during austral summer provides moisture to establish an active South Atlantic Convergence Zone (SACZ, Figure 5.1). The SACZ is characterized by a convective band that extends northwest to southeast from the Amazon basin to the subtropical South Atlantic Ocean. The SACZ´s northern edge merges with the Atlantic ITCZ[2]. Heating in the Amazon basin contributes to the formation of the Bolivian High (BH) in the upper atmosphere[3]. At the regional scale, moisture trans-port in and out of the Amazon basin is critical for the rainfall regime, particularly during the wet season. Moisture from the Amazon is exported out of the region via the South American Low-Level Jet (SALLJ); when it arrives at the eastern edge of the Andes, it interacts with the Chaco Low (CL) and drops precipitation over the La Plata basin[2,4–11].

Because it extends into both hemispheres, the alternating warming of each hemisphere causes several rainfall regimes in the Amazon. During a 'normal' year, rainfall in the region shows opposing phases between the northern and southern tropics, with a rainy season in austral winter in the North and austral summer in the South. In the southern Amazon, rainfall peaks during austral summer; in the central Amazon and near the delta, it peaks in austral autumn; and north of the Equator, it peaks in austral winter (Figure 5.1). The northwest equatorial region experiences low rainfall seasonality, with wet conditions throughout the year. The onset and demise of the rainy season in the Amazon varies gradually from south to north. The end of the rainy season is more regular than its onset. The rainy season in the southern Amazon ends in April, while in the northern part, it ends in September. SST anomalies in the Pacific or Tropical Atlantic play a dynamic role in controlling the beginning and end of the rainy season[12,13].

The Amazon Convection Alternating warming of the two hemispheres modulates seasonal displacement of the ITCZ, including its Amazonian part and the ascendant branch of the Hadley-Walker cells[i], which is associated with maximum rainfall over the equatorial Amazon Basin. At the peak of austral summer, following the southward migration of the sun, heating and convective activity moves toward the subtropical highlands. Rainfall peaks over the central Andes and the southern Amazon Basin during this season. Upward motion extends from near the surface to above 5,500 meters (500 hPa), reaching the level of free convection (LFC) where buoyant convection begins. At the large-scale (> 1000 km), seasonal changes in the thermal contrast between tropical South America and the Atlantic Ocean modulate wind circulation, which supplies the available energy and moist instability over the Amazon basin[1]. These features provide the convective available potential energy (CAPE), the gross moist instability, and the rising motion essential to deep atmospheric convection[14–16]. At regional (100-1000 km) to local (<100 km) scales, Amazon convection is also related to the land surface wet-bulb temperature, generally above 22 ° C[17], which is closely determined by surface humidity and by sensible and latent heat fluxes[ii]. from the local land surface. Deep atmospheric convection contributes about 80% of the total annual precipitation in the Amazon basin, while only 20% of yearly rainfall is associated with local systems[18].

Seasonal changes in Amazon convection are related to changes in the moistening of the planetary boundary layer (PBL) and changes in the temperature at the top of the PBL[19]. However, in the northwestern Amazon, deep convection is particularly intense year-round because the warmer land surface provides highly unstable atmospheric profiles. In addition, the concave shape of the Andes induces a low-level convergence over the northwestern Amazon basin, which causes the high annual rainfall (>3000 mm) in this region[20]. Because deep convection over the Amazon is related to a strong release of latent heat, the Amazon basin is an important source of energy and modulates regional atmospheric circulation in South America[21,22].

The role of ENSO and other large-scale mechanisms The El Niño-Southern Oscillation (ENSO) is the main cause of global interannual variability in water and energy budgets. ENSO extremes represent a reversal of the typical SST patterns in the Tropical Pacific,

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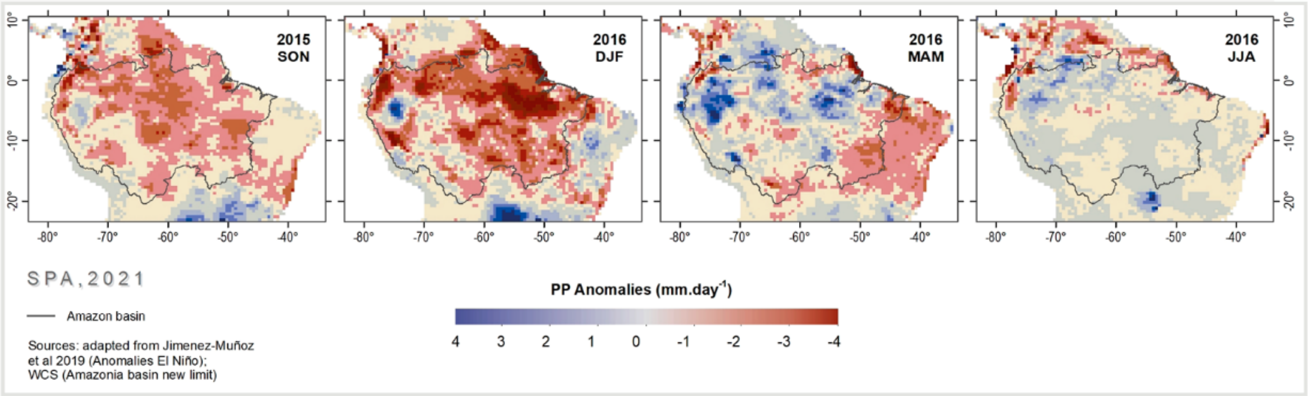
[i] Hadley and Walker cells are the two major circulation cells in the Earth´s atmosphere. The Hadley is essentially meridional, i.e., north-south winds, while the Walker cell is essentially zonal, i.e., east-west winds. In both cases, air rises near the Equator, but in the Hadley cell it sinks at about 30°, while in the Walker cell it sinks at other zones near the Equator.

[ii] Sensible heat flux is the transfer of heat caused by the difference in temperature between the surface and the air. Latent heat flux is the transfer of heat from the surface to the atmosphere that is associated with evaporation of water at the surface and subsequent condensation of water vapor in the atmosphere.



Sources: adapted from Jimenez-Muñoz et al 2019 (Anomalies El Niño); WCS (Amazonia basin new limit)

Figure 5.2 Spatial patterns of precipitation anomalies during seasons (DJF, MAM, JJA, and SON) for the drought years of 2015-2016 in the Amazon. Precipitation anomalies were obtained from the CHIRPSv2.0 dataset using the reference period 1981-2010. A black contour marks the Amazon basin. Adapted from Jimenez-Muñoz et al[28].

El Niño (EN) and La Niña (LN), when there is warming or cooling, respectively, in the eastern or central-eastern tropical Pacific. EN is typically (but not exclusively) accompanied by drought in the Amazon region. In general, recent severe droughts over the Amazon have resulted in low river water levels, increased risk of forest fire, and impacts on natural river ecosystems[2]. During drought and EN years, subsidence anomalies appear over areas with negative rainfall anomalies, with convection and intense rainfall over warm SST in the eastern Equatorial Pacific region. There are different "types" of EN depending on the location of anomalies over the tropical Pacific; the Eastern Pacific (EP) EN and Central Pacific (CP) EN[23] lead to different precipitation patterns over South America[24,25]. In addition to ENSO, there are two other modes of interannual and interdecadal variability that influence the climate of the Amazon: The Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO). They represent changes in air-sea interactions that vary at decadal scales and affect the sea surface, which in turn affects circulation and rainfall in the Amazon. Consistent with the ENSO (EN) positive phase, the PDO and AMO's positive phases intensified reductions in rainfall in the Amazon towards the end of 2015, during the 2015-16 EN event[26]. Positive phases of the PDO are associated with an increase in precipitation in the central and northern parts of the basin and a decrease in the southern regions[27]. Influenced by the Tropical North Atlantic, the drought of 2005, however, was characterized by a weaker-than-normal intra-seasonal oscillation, which favored drought conditions.

Extreme drought and flood events In the last 15 years, the Amazon basin has witnessed climate extremes, some of them characterized as 'events of the century', including droughts in 2005, 2010, and 2015–16 (Figure 5.2[28,29]); and floods in 2009, 2012, 2014, 2017, and 2021[30]. Historical records show previous droughts in 1926, 1964, 1980, 1983, and 1998; and floods in 1953, 1988, 1989, and 1999. These events have been linked to modes of natural climate variability (EN and warm TNA anomalies) with strong impacts on natural and human systems. Some of the Amazon's main cities were flooded or isolated by extremely low river levels during these events. 1999 and other wet years (1988-89, 2007-2008, 2011-2012) were LN years. It is worth mentioning that droughts and floods are not synchronous and do not affect the whole basin in the same way. Overall, droughts affect the south-central Amazon, but the spatial pattern differs from one EN event to another and even from one drought to another.

Spatial variability and seasonality of discharge. The discharge of the main stem of the Amazon River and its tributaries integrates hydrological fluctuations occurring upstream. At the Tabatinga station, the Amazonas-Solimões River Basin spans 890,300 km^2, of which ~ 40% are in the Andes. The mean annual discharge at Tabatinga is estimated at 38,000 m^3/s, with peak values around 51,000 m^3/s from April-May and the lowest discharge around 20,000 m^3/s in September[31]. These hydrological dynamics show strong seasonality that lags behind the rainfall cycle by a few months, with significant variations in the timing and magnitude of discharge across the Amazon's tributary watersheds[32]. The southern and western reaches of the Amazon River usually flood first, peaking between March and May. In the central Amazon, river levels are controlled by northern and southern tributaries, generally peaking in June.

Long-term discharge measurements recorded near the central Amazon city of Óbidos, for example, indicate a peak discharge approaching ~250,000 m^3/s during the high-water period in June, and a minimum discharge of ~100,000 m^3/s during the low-water period in November[33]. Because the northern headwaters of the Amazon are near the equator, their water levels fall between October and February, even as the Amazon River is rising due to contributions from its large southern tributaries. In contrast, most of the Amazon River's southern tributaries reach their highest levels in March or April (at points >300 km upstream from their mouths) and their lowest levels between August and October[33]. For example, discharge at Itaituba in the Tapajós River peaks at ~23,000 m^3/s in March and reaches its minimum (~5000 m^3/s) in October. To its west, the Purús River at Arumã-Jusante shows even more variability, with a peak discharge of ~11,000 m^3/s in April and a minimum discharge of ~1000 m^3/s in September[34]. The lower sections of these southern tributaries are heavily influenced by a backwater effect of the Amazon River itself, rising and falling in response to changes in the main stem[32,35,36].

Fluctuations in rainfall and river discharge drive pronounced seasonal changes in the water level of large Amazonian rivers, causing them to overflow their banks into adjacent floodplains. On a local scale, flooding can also result from rainfall in areas with poorly drained soils or rising groundwater levels, as in the case of the Llanos de Mojos in Bolivia. The periodic rise and fall of water levels – often referred to as the seasonal flood pulse – connects rivers and their floodplains during part of the year, resulting in heterogeneous habitat structure, rapid recycling of nutrients and organic matter, and high rates of biological production[37]. Flooding on the Amazon River has an average height of 10 m near Manaus, and ranges from 2 to 18 m depending on the location and year[38]. The greatest fluctuations occur in the southwestern Amazon, especially the Madeira, Purus, and Juruá Rivers, while the smallest changes happen in the east. Small streams in the Amazon lowlands are more complex, with backwater effects causing less predictability[39]. On average, the lowland rivers of the Amazon are flooded for 6-7 months of the year, with southern tributaries flooding from January to May and northern tributaries from June to August. Conversely, the southern Amazon undergoes a pronounced dry season from August to December, which generally coincides with the low-water period. In the north, floods can last until September[33]. Seasonally inundated wetlands cover an extensive area (17%) of the lowland Amazon[40].

Evapotranspiration About 50% of rainfall in the Amazon returns to the atmosphere through evapotranspiration (water returned to the atmosphere from the leaves of plants [transpiration] plus water evaporation from surfaces). The remainder recharges groundwater, which ultimately ends up in streams and rivers. The median value of evapotranspiration (ET) is 1,220 mm/yr±15%.

Shuttleworth (1988)[41] found limited seasonality in evapotranspiration (ET) in a forest reserve near Manaus, with peaks in March and September that coincided with net radiation extremes. In addition, actual ET rates were nearly equal to potentials throughout the year, suggesting that plenty of water was available even during dry periods. In the 1990s, data analysis of eddy-covariance (EC) flux towers monitored by the Large-Scale Biosphere-Atmosphere project (LBA), revealed some seasonality depending on the study site. Most sites showed a seasonal pattern similar to that observed at Manaus during the Amazon Region Micrometeorological Experiment (ARME), where ET correlates with net radiation (Rn), maintaining either a constant flux or showing a slight increase during the dry period[42–47]. A few studies, mostly located in the southwestern Amazon[48] or at the boundary between Amazon forests and cerrado savannas[49], observed higher ET in the rainy season. Hasler and Avissar (2007)[50] found strong seasonality in ET at stations near the equator (2°S-3°S), with ET increasing during dry periods and decreasing during wet periods, both correlated with Rn. In stations located further south (9°S-11°S), ET and Rn did not present clear seasonality. These studies found the best correlations between ET and Rn during wet periods, but no correlation during dry periods. The authors attributed this response to water stress during dry periods, especially at the drier southern sites. Costa et al. (2010)[51] analyzed three evergreen rainforest wet equatorial sites (2°S-3°S) and two seasonally dry rainforest sites (~11°S) and observed that ET was greater in the dry season. Following previous studies, they found that Rn was the main controlling factor of ET in wetter sites, followed by vapor pressure deficit and aerodynamic resistance. They also found ET seasonality in seasonally-dry forests was controlled by biotic parameters (e.g. stomatal conductance), but in humid equatorial forests it was controlled by environmental factors. (See Chapters 1 and 2 for more on links between groundwater, deep soil moisture, and the atmosphere.)

Conclusions The physical hydroclimate system of the Amazon operates on several spatial and temporal scales. Given its tropical location enclosed by the Andes, its huge spatial extent, and vast forest cover, the Amazon River basin is the largest and most intense land-based convective center, exerting a strong influence on atmospheric dynamics and circulation patterns both within and outside the tropics. It is a critical energy source for the atmosphere, removing latent heat from the surface through evapotranspiration and releasing it to the atmosphere as condensation and cloud formation. It produces rainfall that results in the largest river discharges on Earth, 187,000-253.000 m^3/s, or 16-22% of the world's total river discharge. ENSO is the main cause of interannual variability in rainfall. EN is typically (but not exclusively) accompanied by droughts in the Amazon region, with recent severe droughts producing low river water levels, increased risk of forest fires, and ecosystem impacts. In addition to ENSO, Atlantic and Pacific SST variability influences the climate of the Amazon at interannual and interdecadal scales, including extreme events. These events affect ecosystems and the carbon cycle, changing the balance in the southern and eastern transition zones between forests and savannas, and affecting biomass stocks by favoring softwooded species vulnerable to disturbance.

References

1. Vera, C. *et al.* Toward a Unified View of the American Monsoon Systems. *J. Clim.* **19**, 4977–5000 (2006).
2. Cai, W. *et al.* Climate impacts of the El Niño-Southern Oscillation on South America. *Nat. Rev. Earth Environ.* **1**, 215–231 (2020).
3. Lenters, J. D. & Cook, K. H. On the Origin of the Bolivian High and Related Circulation Features of the South American Climate. *J. Atmos. Sci.* **54**, 656–678 (1997).
4. Marengo, J. A., Soares, W. R., Saulo, C. & Nicolini, M. Climatology of the low-level jet east of the Andes as derived from the NCEP--NCAR reanalyses: Characteristics and temporal variability. *J. Clim.* **17**, 2261–2280 (2004).
5. Drumond, A. *et al.* The role of the Amazon Basin moisture in the atmospheric branch of the hydrological cycle: a Lagrangian analysis. *Hydrol. Earth Syst. Sci.* **18**, 2577–2598 (2014).
6. Arraut, J. M., Nobre, C., Barbosa, H. M. J., Obregon, G. & Marengo, J. Aerial Rivers and Lakes: Looking at Large-Scale Moisture Transport and Its Relation to Amazonia and to Subtropical Rainfall in South America. *J. Clim.* **25**, 543–556 (2012).
7. Vera, C. *et al.* The South American low-level jet experiment. *Bull. Am. Meteorol. Soc.* **87**, 63–78 (2006).
8. Jones, C. & Carvalho, L. M. V. The influence of the Atlantic multidecadal oscillation on the eastern Andes low-level jet and precipitation in South America. *NPJ Clim. Atmos. Sci.* **1**, 1–7 (2018).
9. Gimeno, L. *et al.* Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events. *Annu. Rev. Environ. Resour.* **41**, 117–141 (2016).
10. Jones, C. Recent changes in the South America low-level jet. *npj Clim. Atmos. Sci.* **2**, 20 (2019).
11. Gimeno, L. *et al.* Recent progress on the sources of continental precipitation as revealed by moisture transport analysis. *Earth-Science Rev.* **201**, 103070 (2020).

12. Arias, P. A., Fu, R., Vera, C. & Rojas, M. A correlated shortening of the North and South American monsoon seasons in the past few decades. *Clim. Dyn.* **45**, 3183–3203 (2015).
13. Liebmann, B. *et al.* Onset and end of the rainy season in South America in observations and the ECHAM 4.5 atmospheric general circulation model. *J. Clim.* **20**, 2037–2050 (2007).
14. Garstang, M., Massie Jr, H. L., Halverson, J., Greco, S. & Scala, J. Amazon coastal squall lines. Part I: Structure and kinematics. *Mon. Weather Rev.* **122**, 608–622 (1994).
15. Cohen, J. C. P., Silva Dias, M. A. F. & Nobre, C. A. Environmental conditions associated with Amazonian squall lines: A case study. *Mon. Weather Rev.* **123**, 3163–3174 (1995).
16. Zhou, J. & Lau, K. M. Does a monsoon climate exist over South America? *J. Clim.* **11**, 1020–1040 (1998).
17. Eltahir, E. A. B. & Pal, J. S. Relationship between surface conditions and subsequent rainfall in convective storms. *J. Geophys. Res. Atmos.* **101**, 26237–26245 (1996).
18. Greco, S. *et al.* Rainfall and surface kinematic conditions over central Amazonia during ABLE 2B. *J. Geophys. Res. Atmos.* **95**, 17001–17014 (1990).
19. Liebmann, B. & Marengo, J. Interannual Variability of the Rainy Season and Rainfall in the Brazilian Amazon Basin. *J. Clim.* **14**, 4308–4318 (2001).
20. Espinoza, J. C. *et al.* Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador). *Int. J. Climatol.* **29**, 1574–1594 (2009).
21. Figueroa, S. N., Satyamurty, P. & Da Silva Dias, P. L. Simulations of the summer circulation over the South American region with an eta coordinate model. *J. Atmos. Sci.* **52**, 1573–1584 (1995).
22. Junquas, C., Li, L., Vera, C. S., Le Treut, H. & Takahashi, K. Influence of South America orography on summertime precipitation in Southeastern South America. *Clim. Dyn.* **46**, 3941–3963 (2016).
23. Takahashi, K., Montecinos, A., Goubanova, K. & Dewitte, B. ENSO regimes: Reinterpreting the canonical and Modoki El Niño. *Geophys. Res. Lett.* **38**, (2011).
24. Tedeschi, R. G. & Collins, M. The influence of ENSO on South American precipitation: simulation and projection in CMIP5 models. *Int. J. Climatol.* **37**, 3319–3339 (2017).
25. Sulca, J., Takahashi, K., Espinoza, J.-C., Vuille, M. & Lavado-Casimiro, W. Impacts of different ENSO flavors and tropical Pacific convection variability (ITCZ, SPCZ) on austral summer rainfall in South America, with a focus on Peru. *Int. J. Climatol.* **38**, 420–435 (2018).
26. Aragão, L. E. O. C. *et al.* 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nat. Commun.* **9**, 536 (2018).
27. Gloor, M. *et al.* Intensification of the Amazon hydrological cycle over the last two decades. *Geophys. Res. Lett.* **40**, 1729–1733 (2013).
28. Jiménez-Muñoz, J. C. *et al.* The role of ENSO flavours and TNA on recent droughts over Amazon forests and the Northeast Brazil region. *Int. J. Climatol.* **41**, 3761–3780 (2021).
29. Venticinque, E. *et al.* An explicit GIS-based river basin framework for aquatic ecosystem conservation in the Amazon. *Earth Syst Sci Data* 651–661 https://knb.ecoinformatics.org/view/doi%3A10.5063%2FF1BG2KX8#snapp_computing.6.1 (2016).
30. Espinoza, J.-C., Marengo, J. A., Schongart, J. & Jimenez, J. C. 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 Clim. Extrem.* **35**, 100406 (2022).
31. Lavado-Casimiro, W. S., Ronchail, J., Labat, D., Espinoza, J. C. & Guyot, J. L. Basin-scale analysis of rainfall and runoff in Peru (1969–2004): Pacific, Titicaca and Amazonas drainages. *Hydrol. Sci. J.* **57**, 625–642 (2012).
32. Sorribas, M. V. *et al.* Projections of climate change effects on discharge and inundation in the Amazon basin. *Clim. Change* **136**, 555–570 (2016).
33. Goulding, M., Barthem, R. & Ferreira, E. J. G. The Smithsonian atlas of the Amazon. (2003).
34. Coe, M. T., Costa, M. H. & Howard, E. A. Simulating the surface waters of the Amazon River basin: impacts of new river geomorphic and flow parameterizations. *Hydrol. Process. An Int. J.* **22**, 2542–2553 (2008).
35. Heerspink, B. P., Kendall, A. D., Coe, M. T. & Hyndman, D. W. Trends in streamflow, evapotranspiration, and groundwater storage across the Amazon Basin linked to changing precipitation and land cover. *J. Hydrol. Reg. Stud.* **32**, 100755 (2020).
36. Espinoza Villar, J. C. *et al.* Contrasting regional discharge evolutions in the Amazon basin (1974-2004). *J. Hydrol.* **375**, 297–311 (2009).
37. Junk, W. J., Piedade, M. T. F., Schöngart, J. & Wittmann, F. A classification of major natural habitats of Amazonian white-water river floodplains (várzeas). *Wetl. Ecol. Manag.* **20**, 461–475 (2012).
38. Melack, J. M. & Coe, M. T. Climate change and the Floodplain Lakes of the Amazon Basin. *Amaz. Glob. Chang. (eds Goldman CR, Kumagai M, Robarts R)* 295–310 (2013).
39. Piedade, M. T. F., Worbes, M. & Junk, W. J. Geoecological Controls on Elemental Fluxes in Communities of Higher Plants. *Biogeochem. Amaz. Basin* 209 (2001).
40. Hess, L. L. *et al.* Wetlands of the lowland Amazon basin: Extent, vegetative cover, and dual-season inundated area as mapped with JERS-1 synthetic aperture radar. *Wetlands* **35**, 745–756 (2015).
41. Shuttleworth, W. J. Evaporation from Amazonian rainforest. *Proc. R. Soc. London. Ser. B. Biol. Sci.* **233**, 321–346 (1988).
42. Costa, M. H., Souza-Filho, J. C. & Ribeiro, A. Comments on "The Regional Evapotranspiration of the Amazon". *J. Hydrometeorol.* **5**, 1279–1280 (2004).
43. Hutyra, L. R. *et al.* Climatic variability and vegetation vulnerability in Amazônia. *Geophys. Res. Lett.* **32**, L24712 (2005).
44. Negrón Juárez, R. I. N., Hodnett, M. G., Fu, R., Goulden, M. L. & von Randow, C. Control of Dry Season Evapotranspiration over the Amazonian Forest as Inferred from Observations at a Southern Amazon Forest Site. *J. Clim.* **20**, 2827–2839 (2007).
45. Da Rocha, H. R. *et al.* Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. *Ecol. Appl.* **14**, 22–32 (2004).
46. Souza Filho, J. D. da C., Ribeiro, A., Costa, M. H. & Cohen, J. C. P. Mecanismos de controle da variação sazonal da

transpiração de uma floresta tropical no nordeste da amazônia. *Acta Amaz.* **35**, 223–229 (2005).

47. Vourlitis, G. L. *et al.* Seasonal variations in the evapotranspiration of a transitional tropical forest of Mato Grosso, Brazil. *Water Resour. Res.* **38**, 30–31 (2002).
48. Aguiar, R. G. *et al.* Fluxos de massa e Energia em uma Floresta Tropical do Sudoeste da Amazônia. (2006).
49. Borma, L. S. *et al.* Atmosphere and hydrological controls of the evapotranspiration over a floodplain forest in the Bananal Island region, Amazonia. *J. Geophys. Res.* **114**, G01003 (2009).
50. Hasler, N. & Avissar, R. What Controls Evapotranspiration in the Amazon Basin? *J. Hydrometeorol.* **8**, 380–395 (2007).
51. Costa, M. H. *et al.* Atmospheric versus vegetation controls of Amazonian tropical rain forest evapotranspiration: Are the wet and seasonally dry rain forests any different? *J. Geophys. Res.* **115**, G04021 (2010).