Drought and Flood Extremes on the Amazon River and in Northeast Brazil, 1790–1900

DANIELA GRANATO-SOUZA and DAVID W. STAHLE

a Department of Geosciences, University of Arkansas, Fayetteville, Arkansas

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ABSTRACT: Recent severe droughts, extreme floods, and increasing differences between seasonal high and low flows on the Amazon River may represent a twenty-first-century increase in the amplitude of the hydrologic cycle over the Amazon Basin. These precipitation and streamflow changes may have arisen from natural ocean–atmospheric variability, deforestation within the drainage basin of the Amazon River, or anthropogenic climate change. Tree-ring reconstructions of wet-season precipitation extremes, substantiated with historical accounts of climate and river levels on the Amazon River and in northeast Brazil found in the Brazilian Digital Library, indicate that the recent river-level extremes on the Amazon may have been equaled or possibly exceeded during the preinstrumental nineteenth century. The “Forgotten Drought” of 1865 was the lowest wet-season rainfall total reconstructed with tree-rings in the eastern Amazon from 1790 to 2016 and appears to have been one of the lowest stream levels observed on the Amazon River during the historical era according to first-hand descriptions by Louis Agassiz, his Brazilian colleague João Martins da Silva Coutinho, and others. Heavy rains and flooding are described during most of the tree-ring-reconstructed wet extremes, including the complete inundation of “First Street” in Santarem, Brazil, in 1859 and the overtopping of the Bittencourt Bridge in Manaus, Brazil, in 1892. These extremes in the tree-ring estimates and historical observations indicate that recent high and low flow anomalies on the Amazon River may not have exceeded the natural variability of precipitation and streamflow during the nineteenth century.

SIGNIFICANCE STATEMENT: Proxy tree-ring and historical evidence for precipitation extremes during the preinstrumental nineteenth century indicate that recent floods and droughts on the Amazon River may have not yet exceeded the range of natural hydroclimatic variability.

KEYWORDS: Amazon region; ENSO; Drought; Flood events; Climate variability; Paleoclimate

1. Introduction

The most severe and sustained drought in the history of instrumental precipitation and streamflow observations for the Amazon River basin occurred in 1925/26 when river commerce was brought to a standstill and several steamships became grounded in low water conditions between Iquitos and Manaus, Brazil, and on the lower Amazon River in the state of Pará [Commerce Yearbook 1926, p. 74; Jornal do Commercio 1925, supplemental Table 1 source 1770; Diario de Pernambuco 1926, supplemental Table 1 source 1750; Jornal do Commercio 1926a, supplemental Table 1 sources 1771, 1772, and 1773 (for supplemental Table 1 and all of its sources, see the online supplemental material); Williams et al. 2005]. Extreme droughts were also recorded over portions of the Amazon Basin in 2005, 2010, and 2015 (Marengo and Espinoza 2016; Jimenez et al. 2018). High discharge on the Amazon River was observed during the “Flood of the Century” in 2009, only to be followed by the extreme floods of 2012 (Marengo et al. 2013) and 2021 (Alves 2021; Espinoza et al. 2022). These recent drought and flood extremes, along with an apparent increase in the difference between the seasonal high and low water levels on the Amazon River (the flood stage vs the “terrestrial” phase), may represent an increase in the amplitude of the hydrologic cycle over the Amazon (Gloor et al. 2013; Barichivich et al. 2018). Deforestation in the drainage basin of the Amazon, natural variations in the large-scale circulation of the ocean and atmosphere, and anthropogenic climate change have all been implicated in the increasing frequency and magnitude of drought and flood extremes in the Brazilian Amazon (Sternberg 1987; Gloor et al. 2013; Barichivich et al. 2018). How unusual these recent extremes might be in the context of natural climate fluctuations is not clear because the record of hydroclimatic variability and change in the Amazon Basin is not well known prior to the initiation of stream level measurements for the Rio Negro at Manaus in 1902.

Proxy evidence and historical documents suggest that recent river-level extremes for the Amazon River may have been equaled or exceeded by conditions during certain droughts or floods of the nineteenth century. The magnitude of historical extremes is difficult to quantify because of the lack of direct observations of precipitation or streamflow during the preinstrumental period. The recent tree-ring reconstructions of
wet-season precipitation totals in the eastern Amazon (Granato-Souza et al. 2019, 2020) may help improve knowledge of preinstrumental droughts and floods, especially when combined with historical accounts describing these exactly dated hydroclimatic extremes in the dendroclimatic record. These proxy rainfall and historical records may provide useful benchmarks for extreme low and high river levels on the Amazon River during the preinstrumental nineteenth century.

Historical descriptions of weather and climate extremes in Brazil are limited before 1900 but include early compilations by Thomaz Pompeu Brasil (1877) and Alípio Luiz da Silva (1885), and the modern review by Joaquim Alves (2003). High-resolution proxy climate records are also limited in Brazil, but long precipitation-sensitive tree-ring chronologies have begun to emerge recently for the Amazon and elsewhere in tropical South America (e.g., Brienen et al. 2012; Lopez et al. 2017; Humanes-Fuente et al. 2020). This is despite the fact that Amazonia is the most biodiverse forest region in the world with some tree species potentially suitable for dendrochronology. In fact, 6727 tree species native to the Amazon have been described taxonomically (Cardoso et al. 2017). This impressive number certainly underestimates the true total because tree species entirely new to science are frequently discovered in the Amazon (Falcão and Mansano 2020; Vasconcelos et al. 2020; Thomas et al. 2021). Meta-analyses of forest plot-based data suggests that there could be nearly 16,000 tree species native to the Amazon (ter Steege et al. 2013). Unfortunately, most native trees in the Amazon and across the global tropics do not form anatomically simple annual growth rings that can also be exactly dated with dendrochronology and used for verifiable reconstructions of precipitation extending centuries before the beginning of instrumental observations. There are important exceptions, including Cedrela odorata (“cedro”), which is a commercially important tropical hardwood with a wide distribution across Amazonia and the neotropics (Cintron 1990; Paredes-Villanueva et al. 2019) and can live for more than 200 years.

Several ring width chronologies of C. odorata have been developed in the Amazon Basin region (Brienen et al. 2012; Baker et al. 2015), including two from the Rio Paru watershed in the eastern equatorial Amazon (Granato-Souza et al. 2019, 2020). The two Rio Paru Cedrela chronologies have been used to separately reconstruct wet-season precipitation over the eastern Amazon (February–November; Granato-Souza et al. 2019; February–July, Granato-Souza et al. 2020). The Cedrela wet-season precipitation reconstructions exhibit strong multidecadal variability that is only vaguely apparent in the available and relatively short instrumental observations from the eastern Amazon. Dry and wet extremes in the precipitation reconstructions for the eastern Amazon also co-occur with precipitation and tree growth extremes of opposite sign in the middle latitudes of North and South America, part of a pan-American interaction of climate and forest growth that is largely orchestrated by El Niño–Southern Oscillation (Stahle et al. 2020).

The tree-ring reconstruction reported by Granato-Souza et al. (2020) has been used to identify precipitation extremes in the eastern Amazon during the late-eighteenth and nineteenth centuries. The Brazilian Digital Library (BDL) was then searched for evidence to support or refute the occurrence of hydroclimate extremes in the specific years identified with the proxy data. Historical accounts, some exceptionally vivid, support most of the reconstructed wet and dry extremes from 1790 to 1900. Some of the historical documents also describe extreme high and low flows on the Amazon River and help identify the large-scale spatial pattern of precipitation during the reconstructed rainfall extremes. The proxy extremes that are well supported by historical accounts appear to have been major environmental events in Brazilian history and suggest that the modern instrumental record of Amazon precipitation and streamflow may not fully represent the range of natural hydroclimatic variability.

2. Data and methods

The tree-ring reconstruction of February–July precipitation totals in the eastern Amazon was described by Granato-Souza et al. (2020) and was based on the C. odorata chronology developed at the Rio Paru–Baixo site (RPB; located at 0.997522°S, 53.2667°W). The ring width chronology for the RPB collection was based on 50 dated radii from 22 Cedrela trees. The dendrochronologically dated ring widths (Douglass 1941; Stokes and Smiley 1996) were measured with a stage micrometer to a precision of 0.01 mm. The computer program COFECHA (Holmes 1983) was used to check dating and measurement accuracy. To minimize short-period growth excursions associated with nonclimatic stand dynamics in the closed canopy rain forests where the Cedrela were found, each dated time series was detrended and standardized by fitting a cubic smoothing spline with a 50% frequency response equal to two-thirds of the series length and calculating the ring width departures from the fitted curve using the ARSTAN program (Cook and Krusic 2005). The ring width index series for the 50 radii were then averaged on a year-by-year basis to produce the final robust mean index chronology (Cook and Krusic 2005).

The seasonal rainfall signal in the RPB chronology was identified using correlation analysis with monthly precipitation data from the eastern Amazon sector. The strongest signal was detected for the wet season (February–July) in a region near Santarém (0°–1°S and 56°–57°W) using gridded monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) V7 0.5° dataset (Becker et al. 2013; Schneider et al. 2014). The GPCC data totaled for February–July were then regionally averaged, and that instrumental time series was the predictand used for reconstruction.

The RPB ring-width chronology was calibrated using bivariate regression with February–July precipitation from 1978 to 2016 when the GPCC data from the eastern Amazon are based on several weather stations and appear to be most homogeneous. The derived reconstruction extends from 1759 to 2016 and was validated during the calibration interval using the leave-one-out cross-validation reduction of error (CVRE) statistic, a regression diagnostic similar to the prediction error sum of squares (Allen 1974). The reconstruction was also compared with the fewer single-station precipitation observations available for the eastern Amazon before 1978 (Granato-Souza et al. 2020), and with historical climate information from the
region during the late-eighteenth and nineteenth centuries (this report).

The years when reconstructed precipitation is estimated to have been in the upper 90th or lower 10th percentile for the wet season were identified for the period from 1790 to 1900 to narrow the search for historical reports concerning environmental conditions during just the most extreme years. The reconstructed extremes based on the RPB chronology were also compared with the February–November precipitation reconstruction reported by Granato-Souza et al. (2019) using the C. odorata chronology from the Rio Paru-Alto location (RPA). Time series values in the upper and lower 10th percentiles are unusual but may not be truly “extreme” in the normal sense of the word. However, historical reports found in the BDL justify the term because, as we will see below, several of these wet and dry years may have been among the most extreme hydroclimatic events in the history of the Amazon. Our purpose has been to both test the validity of the reconstruction against independent historical information and, when possible, to provide a more detailed description of the precipitation anomalies estimated with tree rings. The tree-ring reconstructions for the years prior to 1790 (i.e., 1759–89) were not included in this analysis due to low sample size in the available C. odorata chronology used to develop the reconstruction.

The Brazilian Digital Library was used to recover weather, climate, and streamflow information from Brazil and a few other South American countries during the tree-ring-reconstructed wet and dry years of the late-eighteenth and nineteenth centuries. The BDL was developed by the Brazilian National Library (BNL), the agency responsible for the collection, storage, preservation, and diffusion of Brazil’s intellectual production (BNL 2023). The BDL is served to the public via an internet portal (http://memoria.bn.br) and consists of digitally scanned documents that include historical newspapers, periodicals, and a diverse collection of government reports, personal and professional correspondence, and other documentary material. The BDL uses optical character recognition to facilitate keyword search of the documents. The BDL is believed to provide most of the historical newspapers printed in Brazil, but some early newspapers and documents known to exist in other repositories are not included (e.g., the Portuguese Digital Library as well as Brazilian libraries and museums containing nondigitized documents). The search function for the BDL is limited to keywords or phrases, and conditional keyword searching cannot currently be performed. Other historical reports were obtained from the University of Chicago digital archive (Latin American Materials Project; https://www.crld.edu/brazil) and various historical compilations and books, including Agassiz and Agassiz (1868), Brasil (1877), da Silva (1885), Le Cointe (1903, 1948), and Alves (2003).

Several keywords were used to recover relevant historical information about climate and streamflow extremes, including secca (drought), vazante (the ebb or seasonal low stand of the river), chuva copiosa (copious rain), cheia (high level or flood crest), and enchente (flood; see the complete keyword list in Table 1 in the online supplemental material). The 1733 historical citations from the BDL presented in this article (of 1777 citations) would certainly not have been as accessible without the keyword functionality of the BDL. Nevertheless, any keyword search of the BDL or other digital archives can go badly wrong. For example, the Portuguese word for “dry” is “secca,” and secca appears often in reference to dried meat, dried fruit, and many other contexts. Therefore, all keyword returns from the BDL were scrutinized for unambiguous reference to climate or streamflow conditions, or to the impacts of climate extremes on agriculture, environment, or society. Also, as vazante (the ebb, or low stand) and as enchente (the flood, or high stand) develop every year along the Amazon in response to strong precipitation seasonality in the basin, resulting in the dry-season low stand and the wet-season high stand of the river. Historical reference to these normal seasonal changes was not used as evidence for extremes, but many reports describing anomalies in the timing or magnitude of the vazante or the enchente were found and did relate to tree-ring-reconstructed precipitation extremes.

There are approximately 13 million sources in the BDL (BNL 2023). Because over 36,000 keyword returns were obtained for the decades beginning with 1870, we were only able to screen the first 3,000 listed for the reconstructed extreme years after 1870 for unambiguous reference to climate or streamflow. All keyword returns from the BDL were screened for the years prior to 1870. An automated retrieval and screening system is under development to recover Amazonian weather, climate, and streamflow information for every year of the historical era from the BDL but will not be completed soon and was beyond the scope of this article.

The historical citations to climate or streamflow during the tree-ring-reconstructed precipitation extremes are detailed in Tables 1–7 in the online supplemental material (pp. 1–115). These include selected quotations in the original Portuguese along with the English translation (just the English translations are reproduced below). Instructions for using the BDL to access and read each historical source cited in this article are provided in the caption to Table 1 in the online supplemental material.

To examine the potential forcing of tree-ring-reconstructed and historically documented precipitation anomalies during the preinstrumental era, the reconstructed wet and dry years in the eastern Amazon (i.e., upper and lower 10th percentiles), supported in several cases by historical reports (see Figs. 2 and 3, described in more detail below), were compared with the Gergis and Fowler (2009) reconstructions of El Niño and La Niña events and the Torbenson et al. (2019) reconstruction of the Multivariate ENSO Index (MEI), both of which fully cover our preinstrumental study period from 1790 to 1900 (Table 8 in the online supplemental material, p. 116). The Gergis and Fowler (2009) reconstruction is based on proxy estimates from tree rings, corals, and ice cores, and on historical documentary reports, all calibrated with an instrumental ENSO index. The Torbenson et al. (2019) reconstruction is based on tree-ring chronologies in southwestern North America that maintain a strong, temporally stable relationship with ENSO during the full instrumental era (in that case, 1901–91). The reconstructed wet and dry years were also compared with the Kaplan et al. (1998) gridded sea surface temperature (SST) dataset available monthly from January 1856 to present (currently updated to
January 2023) and with selected atmospheric variables in the Twentieth Century Reanalysis (2023) product (NOAA 2023).

3. Results

a. Reconstructed rainfall extremes in the eastern Amazon, 1790–1900

The single *C. odorata* chronology from the Rio Paru-Baixo site explained 42% of the variance in February–July precipitation totals from 1978 to 2016 ($R^2_{adj} = 0.42$; Granato-Souza et al. 2020). The reconstruction was validated during the calibration interval with the cross-validation reduction of error (CVRE = 0.39) and more weakly in correlations with an available four-station wet-season precipitation average during the precalibration interval from 1939 to 1977 when instrumental precipitation observations are limited in the Amazon basin ($r = 0.41$; Granato-Souza et al. 2020). The tree-ring reconstruction of wet-season rainfall totals for the eastern Amazon is plotted from 1790 to 2016 in Fig. 1a, along with the multi-decadal waveform (~35 yr; Granato-Souza et al. 2020) that represents approximately 20% of the variance of the reconstructed time series based on singular spectrum analysis (Ghil et al. 2002; St. George and Ault 2011). A photograph of dated annual rings in *C. odorata* is illustrated in Fig. 1b.

The tree-ring data used for this reconstruction are significantly correlated with wet-season precipitation totals for the eastern Amazon, especially during the wettest and driest years (Granato-Souza et al. 2020) when cold and warm sea surface temperatures (SSTs) in the tropical Pacific associated with extremes of El Niño–Southern Oscillation (ENSO) favor coherent precipitation anomalies over the eastern Amazon and the northeastern region of Brazil (Ropelewski and Halpert 1987, 1989; Wang et al. 2016). This coherence of moisture extremes over the eastern Amazon and northeast Brazil during warm and cold SSTs in the tropical Pacific is supported by moisture simulations in the CESM-Last Millennium Ensemble of paleoclimate models (Stahle et al. 2020). It is also supported by some of the historical accounts of weather, climate, and streamflow conditions found in the BDL during the years of reconstructed drought and wetness extremes in the late-eighteenth and nineteenth centuries [e.g., *O Cearense* 1877, Table 1 in the online supplemental material, source 1776; hereinafter all sources in supplemental Table 1 are specified as “Table 1: source number” (e.g., Table 1: 1776)].

![Fig. 1.](image-url)
The most extreme tree-ring-reconstructed dry years in the eastern Amazon from 1790 to 1900 occurred in 1791, 1795, 1804, 1825, 1826, 1833, 1839, 1853, 1865, 1875, 1876, and 1877 (i.e., the lowest 10th percentile of 111 years; Fig. 1a). The reconstructed wet extremes occurred in 1794, 1801, 1813, 1818, 1829, 1850, 1859, 1863, 1891, 1892, and 1897 (highest 10th percentile; Fig. 1a). The screening of the keyword returns resulted in 1733 reports referring to weather, climate, stream levels, crop conditions, or other impacts during the tree-ring-reconstructed dry or wet extremes from 1790 to 1900 (Tables 1–3 in the online supplemental material: 1729 primary, 4 secondary, and 44 other sources, for 1777 in total). Historical accounts found in the BDL that appear to be relevant to the reconstructed drought or wetness extremes, regardless of whether they agree with the sign of the tree-ring-reconstructed extreme, are referenced for each year in Table 1 in the online supplemental material. Supplemental Table 1 includes an identification number for each source, year of occurrence, location, and full bibliographic citation. These results are mapped sequentially in Figs. 2 and 3 (and in Fig. 6, described in more detail below), and the sources used in these figures are tabulated by identification number in Tables 4–6 in the online supplemental material.

Historical references to dryness were found in northeastern Brazil and/or the Amazon Basin for all 12 of the driest years in the tree-ring reconstruction (Table 7 in the online supplemental material), although historical reports from the Amazon Basin are absent for the dry extremes before 1853 (Fig. 2). Just a few climate-related reports were found for the reconstructed dry years of 1804 and 1839, and only one was found for 1795 but it described a “big drought” in Ceará (Table 1: 1062). The number of reports found for the tree-ring-reconstructed dry extremes are totaled by location and mapped in Fig. 2, excluding 1795. The precipitation estimates based on the Rio Paru-Alto chronology (Granato-Souza et al. 2019) are also included in Fig. 2 and indicate dryness in 10 of the 12 years of drought reconstructed with the RPB chronology for the eastern Amazon, particularly in 1791, 1833, 1853, and 1865.

Historical references to climate or stream level were found for 7 of the 11 tree-ring-reconstructed years of heavy precipitation (Table 7 in the online supplemental material), most indicating wetness in the Amazon and to a lesser extent over northeastern Brazil (Fig. 3). Precipitation estimates based on the RPA chronology also indicate some level of wetness for these seven years of heavy wet-season precipitation totals based on the RPB chronology (Fig. 3), and for 10 of the 11 wet year years from 1790 to 1900 (1794 was below average at RPA; Granato-Souza et al. 2019). The four years without any historical information occurred in the late-eighteenth and early-nineteenth centuries when historical documentation is limited in the BDL (i.e., 1794, 1801, 1813, and 1818). The tree-ring data indicate that 1818 may have been the highest wet-season rainfall total in 227 years (1790–2016; Fig. 1a; also very wet at RPA) but no citations to climate or streamflow conditions in 1818 have yet been found in the BDL. There are a few recollections of flooding on the Amazon River in 1819 but these were recorded many years later and it is not at all certain that they relate to 1818 as well (see Table 1: 28, 1664, 1698; and Table 7 in the online supplemental material for suggestions of flooding 1819 and 1814). However, this might be more than coincidental because consecutive high stands have occurred on the Amazon and Rio Negro, including in 1859/60 (Table 1: 443, 1774).

b. The forgotten drought of 1865

The droughts of 1791, 1825, and 1877 are well-known dry extremes in the history of Brazil (Brooks 1971; Kiladis and Diaz 1986; Alves 2003; Aceituno et al. 2009; Marengo et al. 2017; Lima and Magalhães 2019). All three of these historical droughts are in the lowest 10th percentile of the tree-ring reconstruction of wet-season rainfall totals for the eastern Amazon (Fig. 1a; Granato-Souza et al. 2020). However, the tree-ring data also indicate several other drought extremes during the late-eighteenth and nineteenth centuries that are less well known, but most of which can be supported by historical newspapers and other documents (Table 7 in the online supplemental material). The lowest reconstructed wet-season rainfall total in the eastern Amazon from 1790 to 2016 occurred in 1865 when less than half of normal wet-season precipitation is estimated from the tree-ring data (Granato-Souza et al. 2020; Fig. 1a).

The dry event of 1865 has been referred to as the “Forgotten Drought” (da Silva 1885) when one of the most profound vazantes (low stands) of the historical period occurred on the Rio Negro and Rio Solimões, the two tributaries that join at Manaus to form the Amazon River. The Diário de Pernambuco (Table 1: 452) described the vazante of 1864 on the Rio Negro as the lowest that had been witnessed (letter to editor written 24 December 1864; vazante on the Negro usually occurs in November but may persist into the next year). A government expedition aboard the steamer Pirajá on the Rio Negro could not proceed beyond the settlement of Carvoeiro near the confluence of the Rio Branco with the Rio Negro due to the extremely low water levels on 25 December 1864 (Table 1: 452). The Pirajá expedition also reported a delayed onset of the subsequent 1865 rainy season (Table 1: 452) and the seasonal change from vazante to enchente (lowest to highest stage) on the Rio Negro from 1864 to 1865 may have been the lowest of the historical or instrumental era (Diário de Pernambuco, Table 1: 454; discussed below).

The Rio Solimões was also well below average during the Forgotten Drought of 1865. The steamship Ycamiaba became grounded twice in trying to navigate the main channel of the Solimões from Tabatinga on the Peruvian frontier to Manaus (Table 1: 708):

“As the Ycamiaba grounded twice on the September trip as a result of the great ebb of the river, it could only reach Manaus on the 26th of that month.”

A steamship journey from Tabatinga to Manaus typically took 2 weeks in the midnineteenth century, but the Ycamiaba spent 2 months attempting to reach Manaus during the drought of 1865 (Table 1: 708; Agassiz and Agassiz 1868). Wet-season precipitation amount and duration may have both been lower than normal in 1865 because the vazante of the Rio Solimões reached its lowest level in mid-September (Table 1: 708, 1052; Diário de Pernambuco 1865c, Table 1: 1747), nearly 2 months
FIG. 2. Historical reports for moisture conditions in and near Brazil for the driest years in the precipitation reconstruction for the eastern Amazon from 1790 to 1900 (the lowest 10th percentile: large red cones with asterisk) based on the Rio Paru-Baixo chronology (Granato-Souza et al. 2020). The percentile rankings for the precipitation reconstruction based on the Rio Paru-Alto chronology during these same years are also plotted [red and blue cones; from Granato-Souza et al. (2019)]. Historical reports of dryness predominate in most of the tree-ring-reconstructed dry years. Only one historical climate report was found in the BDL for 1795 (“big drought” in Ceará; not mapped). The historical reports tallied here are cited for each year in Table 4 in the online supplemental material.
earlier than the normal seasonal low water level on the Solimões (e.g., *Jornal do Commercio* 1861, Table 1: 1769; *Estrella do Amazonas* 1862d, Table 1: 1767).

The Thayer Expedition was a zoological expedition to the central Amazon in 1865, headed by Louis Agassiz and his Brazilian counterpart João Martins da Silva Coutinho (“Major Coutinho”; Agassiz and Agassiz 1868, Table 1: 167). The Expedition was heading to the western Amazon near Tabatinga in 1865, but Agassiz elected to remain at Tefé on the Rio Solimões because the extreme *vazante* of 1865 had concentrated fish in many isolated pools, creating ideal conditions for collecting new species (Table 1: 1052; Agassiz and Agassiz 1868). Farther upstream near Tabatinga the low water levels on the Solimões in 1865 were described by Major Coutinho (*Diario de Pernambuco* 1865c, Table 1: 1747):

“The river is presently at its maximum ebb, here near Tabatinga. Large banks of sand and mud are discovered on the headlands of the islands, and even in the middle of the river, where the Indians and inhabitants of villages and parishes are camped out to fish for turtles, pracaos, etc.”

Agassiz and Coutinho were able to collect 800 freshwater species new to science in just 3 months during the unusual low water conditions in 1865. Agassiz compared that number with the 300 species of freshwater fish that were described worldwide by C. Linnaeus just 100 years earlier (Table 1: 1052; Agassiz and Agassiz 1868).
The obscurity of the Forgotten Drought in the Brazilian historical record is puzzling considering the profound low stand of the Amazon River in 1865. However, the economic impact of the drought in 1865 may have been mitigated in Brazil by the highly inflated price of cotton due to the collapse of production in the American South during the Civil War (da Silva 1885). These international economic conditions may have buffered the Brazilian economy from the negative consequences of drought such as crop failure and livestock losses and may help explain why the magnitude of the moisture deficit and the extreme low water conditions on the Amazon during the Forgotten Drought of 1865 have received limited historical or scientific attention (da Silva 1885).

c. The Amazon River floods of 1859/60 and 1892

Historical sources describing climate or climate impacts during the reconstructed heavy precipitation extremes are not as extensive as were noted for the dry extremes, and most sources refer to the more settled regions of eastern Brazil (Fig. 3). Nevertheless, the tree-ring-reconstructed wet extremes were associated with major flooding on the Amazon River system in 1859 and 1892. Extreme flooding on the Amazon River during the reconstructed wet year of 1859 was reported by several sources at both Manaus (Table 1: 1774) and Santarem (Table 1: 28, 97, 253, 254, 257, 259, 443, 1021, 1664), and was referred to as “The Great Flood of 1859” by Lacerda in 1865 (Table 1: 1698, 1774). Flooding occurred in 1859 and 1860 at both locations, although the highest flood level was observed in 1859 (Table 1: 443, 1774). A Epocha described the flooding along the lower Amazon River in June of 1859 (Table 1: 28):

“Santarem. The Amazon Flood. We would like to paint a living picture that would put well within reach of all the incalculable damages that the Amazonian people have suffered and continue to suffer from the great rise of the river, and in such an amazing way, that there is no tradition, taking with its ravenous current all that could hinder its impetuosity. The only tradition that exists about the great floods of the Amazon, are the ones of 1807 and 1819, and these that served as a rule to the farmers, for the search of their lands for agriculture, and building, were completely mistaken in the year of 1859 (!) in that the flood covered all the landmarks of those, covered all the lands, and even was to harm some establishments built in lands of the mainland and very high; and its invasion even went to towns like Santarem and Alemquer, where the first street was completely impassable, and now traffic can be made by canoe, whereas before it was done by land! In the districts of Santarem, Alemquer, Obidos, and Vila Franca, where establishments are built on the floodplains, there is not a single house whose floor is not flooded with two or more palms of water.” [one palm = 0.228 m; 1807 was not a reconstructed wet extreme].

The flood of the Rio Negro in 1892 occurred during the second highest wet-season precipitation total reconstructed for the eastern Amazon from 1790 to 2016 (Fig. 1a) and may have equaled or possibly exceeded the most extreme flood yet recorded at Manaus, which occurred in 2021 (Alves et al. 2021). Based on instrumental measurements at the Port of Manaus near the confluence with the Amazon, the crest of the Rio Negro reached 30.02 m on the gauge in 2021, which is equivalent to 23.19 m above mean sea level (MSL) (Alves et al. 2021; note that zero on the Rio Negro gauge at Manaus is 6.83 m MSL). A series of reports in the periodical Diario de Manaos from 21 May to 27 August 1892 (Table 1: 389, 390, 391), indicate that the bridge over Bittencourt Creek was overtopped by floodwaters from the Rio Negro. Bittencourt Creek and Manaus Creek are adjacent tributary streams between downtown Manaus (centro) and the Cachoeirinha neighborhood. Both drainageways are subject to backwater flooding from the Rio Negro and the Amazon River which joins the Negro only 13 km downstream. On 21 May 1892, Diario de Manaos reported:

“...we already put the illustrious stewardship on notice about the flooding of the river, which will cover the bridge of the Bittencourt Creek if it goes up one more palm: this warning is so that one fine day the residents of Cachoeirinha are not reduced to taking off their shoes to cross the bridge or have to look for other difficult and expensive means of transport for many.” (Table 1: 389).

Twelve days later on 2 June 1892, the Diario de Manaos declared in a headline that the bridge was “Inundada” (flooded) and:

“The bridge over the Bittencourt Creek, in the Cachoeirinha neighborhood, is finally taken by the river’s flood. It is urgent that the superintendent order as soon as possible the repairs that are needed on the said bridge, in order to reestablish public traffic. We are well aware that the superintendent is not responsible for the flooding of the bridge for the enormous flooding of the river, but he will be blamed if he does not take the measures that the case is demanding as soon as possible.” (Table 1: 390).

And on 27 August 1892, the Diario de Manaos described the damage caused by what appears to have been the overtopping or complete inundation of the bridge and roadway:

“The Bridges”

“It is another matter that lacks the care of the illustrious directors of the municipality. Almost all of them need repairs, especially the second bridge at Cachoeirinha [i.e., the Bittencourt Bridge]. Covered as it was by the waters of the stream that it crosses, by the huge flood this year, the nails oxidized by the long immersion dilated the places they cross in the wood of the bridge, as a result of which all the boards of the bed were detached and completely loose on the respective joists.” (Table 1: 391).

At least 24 reports in the BDL describe heavy precipitation or flooding in the Amazon River basin in 1892 (Tables 3 and 5 in the online supplemental material). The reporting by the Diario de Manaos is notable because it may help constrain the elevation (or stage height) of the Amazon River at Manaus during the flood of 1892. The Diario de Manaos indicates that the Bittencourt Bridge was immersed by the regional flooding of the Amazon River, which backed up the Rio Negro into Bittencourt Creek and submerged the roadway of the bridge for a period of days, possibly weeks. However, the flood of 1892 did not remove the bridge because Diario de Manaos states that boards on the joists of the bridge were only “loosened.” Nonetheless, the inundation damage was sufficient to require complete replacement of the original wooden bridge (Amasonas 1892ab
Table 1: 1739, 1740, 1742), a project that was not completed until 1896 [Diario Oficial (AM) 1896, Table 1: 1752; Duarte 2009]. These impacts to infrastructure, and references to measurements of the river-level change from seasonal low to high stand (vicente-enchente), may provide useful historical constraints on the elevation of the Amazon River during the floods of 1859/60 and 1892, and the Forgotten Drought of 1865.

d. Potential historical constraints on nineteenth-century river-level extremes of the Amazon River

Reports in A Epocha provide specific information on the elevation of the Amazon River at Santarem and three other towns nearby during the flood of 1859 (Table 1: 28). A Epocha discriminates between buildings on the “floodplains” and on the “mainland and very high” and noted that all structures built on the floodplain in Alenquer, Óbidos, Santarem, and Villa Franca were covered with at least two palms of floodwater (0.456 m). A Epocha also noted that “first street” in Santarem was completely flooded in 1859. The “first street” of 1859 in Santarem is now referred to as Rua 24 de Outubro (Lopes et al. 2019) and the modern road surface is approximately 10–12 m MSL based on four elevation measurements made in 2022 (i.e., 10.199, 10.935, 11.389, and 12.079 m MSL (Consultoria Norte Geo 2022); the sea level reference for the river gauge at Santarem was calculated by Moreira (2016)]. Because A Epocha stated that “first street in Santarem was completely impassable, and now traffic can be made by canoe” during the flood of 1859 (Table 1: 28), the level of the Amazon River may have reached 10.7 m MSL at Santarem (i.e., the lowest measured elevation of Rua 24 de Outubro (10.199 m MSL) plus the approximately 0.5 m needed to float a canoe.) If true, this would indicate that the flood of 1859 may have exceeded the highest flood of the instrumental era at Santarem (i.e., the record flood of 2009 reached 10.22 m MSL at Santarem (ANA 2019; Consultoria Norte Geo 2022; Moreira 2016)].

This, of course, depends on the elevation of First Street in Santarem in 1859. Is Rua 24 de Outubro in Santarem truly the First Street of 1859? Has the modern roadway on Rua 24 de Outubro been increased in elevation when compared with First Street of 1859? Does the elevation of the unaltered soil beneath Rua 24 de Outubro in Santarem provide a more realistic minimum stage height for the flood of 1859? These questions and others will need further investigation, potentially including “high water mark” analysis (e.g., Baker 2008; Koenig et al. 2016), to better constrain the flood stage of 1859.

The inundation of the Bittencourt Bridge may provide another useful benchmark for Rio Negro/Amazon River flood stage prior to the onset of instrumental observations. Because the Bittencourt Bridge is close to the confluence of the Rio Negro and Rio Solimões that join to form the Amazon River, the flood stage at the bridge is essentially equivalent to the level of the Amazon River below Manaus. As Oltman et al. (1964) note, the total fall of the Amazon River is only 65 m over 3000 km from the Peruvian border to the Atlantic Ocean, and the water level at the Rio Negro-Amazon River confluence during the average low stand each year ( vazante) is only 10.699 m (35.1 ft) MSL.

The first bridges over Bittencourt Creek and the adjacent Manaus Creek were built in 1881 based on engineering designs prepared by the “Engineer of the Municipal Chamber” in 1876 (Amasonas 1881abc, Table 1: 1736, 1737, 1738; Duarte 2009). Both bridges were severely damaged, and the Bittencourt Bridge was “covered” by the flood of 1892 (Table 1: 391, 392). Repairs began in November 1892 and replacement of the original wooden bridges by masonry structures was completed in 1896 (Duarte 2009). The bridges built in 1896 are still in use today (Fig. 4; Duarte 2009).

The precise elevation of the Bittencourt and Manaus Creek Bridges in 1892 is not currently known. However, the size and orientation of the bridges were discussed in the periodical Amasonas (1881c, Table 1: 1738; translated in Table 7 in the online supplemental material) and the modern bridges were reconstructed in the same location as the originals built in 1881 (Amasonas 1892d, Table 1: 1742). The modern bridge roadways are 27 m MSL (DMV Projetos e Servicos LTDA 2022), and the stream-bed elevation beneath the two bridges is estimated to have been 17.4 ± 2.0 m MSL before being backfilled and landscaped in 2006 (Duarte 2009), based on photogrammetric analysis of a circa-1970 photograph (H. Theiss 2022, personal communication; Fig. 4).

The road surface on the Bittencourt Bridge is estimated to have been 9.6 m (±2.0 m) above the stream bed in the 1970 photograph (Fig. 4), so the original elevation of the streambed beneath the bridge would have been 27 minus 9.6 m, or approximately 17.4 m (±2.0 m) MSL. This approximates the specifications for the replacement bridge published in Diario de Manaus on 27 August 1892 (i.e., “12 meters wide and 8 meters high above the water level,” Amasonas 1892c, Table 1: 1741). The stream-bed elevation therefore provides a minimum estimate for the height of the 1892 flood, assuming that the Bittencourt “Bridge” that was overtopped by the flood of 1892 was nothing more than a low water crossing. However, the Bittencourt Bridge was indeed a timber-framed structure (Jornal do Amazonas 1876; Amasonas 1881abc, Table 1: 1736, 1737, 1738) and 17.4 m MSL is below the average seasonal enchente (high-stand) of the Rio Negro at Manaus (the instrumental mean minimum, average, and maximum for the Rio Negro level at Manaus are 10.699, 15.86, and 21.02 m MSL, respectively, and the modern gauge is 1.32 km west of the bridge). Consequently, the original 1881 wooden bridge must have been at least 3.62 m above Bittencourt Creek to be above the modern mean seasonal high stand (i.e., 21.02 minus 17.4 = 3.62). If it was ≥5.79 m above the creek bed then the flood of 1892 may have equaled or exceeded the record flood of 2021 (i.e., 17.4 + 5.79 = 23.19 m MSL, the stage height measured in 2021). Additional documentary descriptions of the Bittencourt Bridge during or before 1892, if they can be found, would be critically relevant to the question of flood extremes on the Amazon River.

The nineteenth-century documentary records of Major Coutinho are also potentially relevant to hydroclimatic extremes on the Amazon River. Major Coutinho (1830–89) was an officer and engineer in the Brazilian army who traveled...
extensively in the Amazon River basin the midnineteenth century making scientific collections and observations (Silva et al. 2013; Diario de Pernambuco 1865ab, Table 1: 1745, 1746, 1867ab, Table 1: 1748, 1749; Diario do Rio de Janeiro 1866, Table 1: 1751; Correio Mercantil 1862, Table 1: 1744; Mello 1866, Table 1: 1774; Table 1: 167, 1052). Coutinho made meteorological and hydrological observations near Manaus (Estrella do Amazonas 1861a–j, 1862a–d, Table 1: 1753–67), including of Rio Negro stream level at “Ponte dos Remédios” (da Silveira 1984), one of the first bridges built in Manaus (Duarte 2009). The Ponte dos Remédios was in central Manaus between Tenreiro Aranha Square and Miranda Léão Street, only about 0.5 km from the modern stream level gauge at the Port of Manaus maintained by the Amazonas State Administration (Duarte 2009). The bridge no longer exists, and the Igarapé dos Remédios (Remedios Creek) has been backfilled and landscaped (Duarte 2009). However, the Port of Manaus was located at the Ponte dos Remédios in the midnineteenth century, and Coutinho’s measurements were made there (da Silveira 1984).

We have found reference to only a few of Coutinho’s measurements cited in some of the other historical documents (e.g., Estrella do Amazonas 1861a–j, 1862a–d, Table 1: 1753–67). The complete set of Coutinho’s measurements and the crucial potential link to absolute elevation are apparently not included in the BDL, nor in the selected papers of Major Coutinho housed at the Museu Emilio Goeldi in Belém, Brazil (da Silveira 1984) and our personal inspection of the Coutinho papers in Belém in 2022]. Nevertheless, Coutinho’s available measurements of river-level change by may be useful even without reference to absolute elevation.

The change from the annual maximum to minimum level of the Rio Negro at Manaus is plotted from 1859 to 1862 (Fig. 5a). Coutinho reported very high levels of the Rio Negro during the floods in both 1859 and 1860 (Lacerda 1865; Table 1: 1774; see Table 7 in the online supplemental material under 1859 for a transcription and further explanation of the Coutinho reference). According to Coutinho, the difference between the highest level measured during the enchente of 1860 and the lowest level during the vazante of 1861 was “67 palms” or approximately 15.28 m (Mello 1866, Table 1: 1775). Note that he was measuring the interannual change from high to low stand for 1860/61 and not the seasonal intra-annual change in the level of the Rio Negro. Nonetheless, the 15.28-m change from the enchente of 1860 and the vazante of 1861 was exceeded only once in the modern instrumental record from 2009 to 2010, when the difference was 16.13 m [the instrumental mean year-to-year change is 10.35 m, std dev 2.14 m, as compared with the average within-year seasonal change of 10.28 (std dev 1.89 m), 1903–2022; ANA 2023]. The maximum range from the highest to lowest levels yet observed in the gauged record for the Rio Negro was 16.38 m, or 71.65 palms, comparing the vazante of 1963 (and 2010) with the enchente of 2021 (ANA 2023). This record range in the instrumental observations might have been approached from the enchente of 1860 (or 1859) to the vazante of 1864, because the vazante was lower in 1864.
e. ENSO associations with the occurrence and large-scale patterns of reconstructed precipitation extremes

ENSO events can have a major impact on the spatial pattern and intensity of precipitation and temperature anomalies over South America (Aceituno et al. 2009; Garreaud et al. 2009). Drought over the eastern Amazon and northeast Brazil has been linked with El Niño events and with warm SSTs in the tropical North Atlantic (Hastenrath 2012), while wetness often prevails during La Niña events. Precipitation over southern Brazil also tends to be out of phase with northern Brazil (Garreaud et al. 2009), particularly during El Niño events (e.g., Stahle et al. 2020). The tree-ring reconstruction of wet-season precipitation in the eastern Amazon is associated with El Niño conditions for the period 1856–2016 when instrumental SST observations are available, with warm, statistically significant SST anomalies in the central and eastern tropical Pacific during the 10 worst reconstructed droughts (Granato-Souza et al. 2020). The sample size is low, but several interesting observations can be made about the possible ENSO forcing of certain wet and dry years during the preinstrumental period from 1790 to 1900 and concerning the composite spatial patterns of historical climate reports during these same years over Brazil.

The reconstructed driest and wettest years in the eastern Amazon were compared with the list of El Niño or La Niña years reconstructed by Gergis and Fowler (2009) and with the reconstructed Multivariate ENSO Index reported by Torbenson et al. (2019) during the preinstrumental era from 1790 to 1900 (Table 8 in the online supplemental material). There are notable hits and misses in comparing the Gergis and Fowler (2009) ENSO event lists with the reconstruction of Amazon precipitation extremes that are discussed below. However, a Wilcoxon...
rank sum test (Gibbons and Chakraborti 2011) indicates that the medians of reconstructed MEI values are modestly but significantly different between the two groups of years (i.e., the 12 dry years in the lower and 11 wet years in the upper 10th percentiles of reconstructed precipitation; \( z \) value = 2.123; \( p = 0.0337 \)). Similarly, a two-tailed \( t \) test (Fay and Proschan 2010) shows statistically significant differences in the MEI means for these two groups (\( t = 2.152, p = 0.0432 \)). The MEI reconstruction is based entirely on tree-ring chronologies from the ENSO teleconnection province of southwestern North America that exhibit a strong temporally stable correlation with the instrumental MEI (Torbenson et al. 2019). Instrumental and reconstructed wet-season precipitation totals in the Amazon have both been previously related with precipitation and tree growth anomalies across subtropical North America, which is also believed to be primarily due to ENSO forcing of hydroclimate in both regions of the Americas (Stahle et al. 2020).

The tree-ring-reconstructed wet years of 1801, 1863, and 1892 did co-occur with strong to very strong La Niña events in the Gergis and Fowler (2009) record and extensive historical evidence for heavy precipitation and flooding in the Amazon was found in the BDL for 1863 and 1892 (Fig. 3). Very strong El Niño conditions were identified during the reconstructed dry years of 1853 and 1877 (Table 8 in the online supplemental material), also supported by historical reports of drought over Northeast Brazil (including Aceituno et al. 2009) as well as in a few areas of the Amazon River basin (Fig. 2). Note also that the precipitation anomalies indicated for Brazil in 1875 and 1891 were of opposite sign between the Amazon and Northeast Brazil (Figs. 2 and 3). In these two cases the more numerous historical observations over the Northeast were consistent with the expected sign of ENSO forcing (i.e., La Niña and wetness over the Northeast in 1875 (Fig. 2), El Niño and dryness over the Northeast in 1891 (Fig. 3; supplemental Table 8).

Surprisingly, no strong La Niña conditions were estimated by Gergis and Fowler (2009) or Torbenson et al. (2019) for the year 1859 as might be expected for what may have been one of the largest floods in the history of the Amazon River. Intense La Niña values are reconstructed for the period 1860–63 just after 1859, which includes documented flooding of the Amazon River in 1860 and 1863 (Lacerda 1865; Table 1: 1774; Fig. 3, Table 7 in the online supplemental material). The gridded SST data of Kaplan et al. (1998) indicate warm SSTs in the tropical Pacific during the reconstructed dry years of 1859 (La Niña like), but these anomalies were very weak and not spatially extensive, and the eastern tropical Pacific began to warm modestly by May of 1859. SSTs in the tropical North Atlantic were below average in February of 1859, but were otherwise near normal to above average in that sector from October 1858 to July 1859. Last, the composite map of precipitation rate over the global tropics computed with the Twentieth Century Reanalysis (NOAA 2023) from December 1858 to July 1859 indicates an El Niño–like pattern not at all consistent with extreme flooding on the Amazon River in 1859.

In fact, it appears that the large-scale forcing responsible for two of the largest hydroclimate extremes in the history of the Amazon River is not well represented in the available ENSO data, “The Great Flood of 1859” and the “Forgotten Drought” of 1865. Gergis and Fowler (2009) indicate a moderate El Niño event in 1865 consistent with dryness over the eastern Amazon (Table 8 in the online supplemental material), but hardly commensurate with what may have been one of the most severe droughts in the history of the region [the Torbenson MEI reconstruction indicates slightly positive MEI for 1865 (El Niño), but it was the only positive reconstructed value in a decade (1859–68)]. Kaplan et al. (1998) indicate warm SSTs in the tropical Pacific from September 1864 through July of 1865, although again not as intense as was measured during major El Niño events. These epic Amazon Basin hydroclimate extremes of 1859 and 1865 therefore suggest that the anomalies apparent in the coupled ocean–atmospheric field may be underestimated during the midnineteenth century when the global instrumental climate record was in the very early stages of development.

A stark nineteenth-century contradiction between the hydroclimate extremes in the Amazon and northeast Brazil and simultaneous conditions in the large-scale climate field occurred in 1897 when instrumental weather and SST measurements had become reasonably abundant globally. The tree-ring reconstruction indicates that the wet season of 1897 was the third wettest of the entire reconstruction from 1790 to 2016 (Fig. 1a), supported by scattered reports of wetness in the Amazon and over northeast Brazil (Fig. 3), yet strong El Niño conditions are indicated by Gergis and Fowler (2009) and Kaplan et al. (1998) for 1897. Nowhere in South America does ENSO explain more than two-thirds of the interannual variance in instrumental precipitation totals (Garreau et al. 2009) and 1897 may provide a useful example of dryness developing over northern Brazil despite the prevailing SST field in the tropical Pacific and Atlantic Oceans.

The summary maps of historical climate reports during tree-ring-reconstructed precipitation extremes in the eastern Amazon produce interesting large-scale patterns that may also reflect the underlying forcing of South American climate, particularly ENSO (Figs. 2 and 3). Historical accounts during most of the extremely dry years indicate that dry conditions often extended from the Amazon into northeastern Brazil typical of El Niño forcing (Fig. 2). To search for this pattern during the late-eighteenth and nineteenth century, and the opposite pattern of wetness linked with La Niña conditions, all reports found in the Brazilian Digital Library were summed and mapped for the tree-ring-reconstructed dry and wet years (Figs. 6a,b). Historical reports of dryness prevailed in the Amazon and the Northeast during the reconstructed drought extremes (Fig. 6a), a spatial pattern typical during El Niño conditions. Wet conditions were exclusively reported in the available documents for the central and lower Amazon Basin during the reconstructed wet years, but wetness did not extend into the Northeast as would often occur during La Niña events (Fig. 6b).

Anti-correlation between northern and southern Brazil has also been noted in modern precipitation observations in response to ENSO forcing, with drought in the north and wetness in the south during El Niño conditions (the opposite during La Niña; Garreau et al. 2009). The tree-ring-reconstructed dry years of 1853, 1865, and 1877 in the Amazon were associated with wet reports from southern Brazil (Figs. 2g,h,k), and 1877/78 was
one of the largest El Niño events in instrumental history (Kiladis and Diaz 1986; Huang et al. 2020). Likewise, dry reports from southern Brazil prevailed during the reconstructed wet years of 1859, 1863, and 1892 in the Amazon (Figs. 3c,d,f), and 1892 was a strong La Niña year (Wolter and Timlin 2011). Nevertheless, the full composite pattern does not indicate an unambiguous north–south dipole for these tree-ring-reconstructed wet and dry extremes in the nineteenth century (Figs. 6a,b).

Two years in particular are impacting the expected ENSO-like patterns in the composite maps of reconstructed extremes for the nineteenth century. If 1875 (Fig. 2i) is removed from the dry composite (Fig. 6a), then the typical El Niño pattern of dryness over the eastern Amazon and northeast Brazil strengthens and some mixed evidence for wetness is observed in southern Brazil and adjacent areas (i.e., the dipole pattern; Fig. 6c). If 1891 (Fig. 3e) is removed from wet composite (Fig. 6b), then a La Niña–like pattern of wetness prevails in the Amazon and northeast Brazil along with some dryness to the south (Fig. 6d). ENSO forcing is not the only factor responsible for the spatial variability of precipitation over South America, of course, and the interesting non-ENSO related patterns of variability (e.g., 1897) deserve investigation in both the instrumental and preinstrumental historical record. But even at the continental scale, historical references to climate in

Fig. 6. The number of historical reports of dry or wet conditions in and near Brazil for (a) 11 of the 12 driest and (b) 7 of the 11 wettest years from 1790 to 1900 in the precipitation reconstruction. The number of historical sources used to produce these maps is tallied in Table 6 in the online supplemental material. The tree-ring-reconstructed wet-season precipitation totals based on the *C. odorata* chronology from Rio Paru-Baixo (Granato-Souza et al. 2020) are also indicated for the (c) dry and (d) wet extremes (upper and lower 10th percentiles; red and blue, respectively). The year 1875 is omitted from the composite map for the dry years [in (c)], and 1891 is omitted from the map for the wet years [in (d)].
the BDL provide broad support for the precipitation extremes reconstructed with tree rings (Figs. 2 and 3), particularly in the Amazon River basin (Fig. 6), a result that would not be possible without the exact calendar year dating of the C. odorata tree rings with dendrochronology.

4. Discussion and conclusions

The Brazilian Digital Library is a large archive of historical information, including descriptions of extreme high and low flow conditions on the Amazon River and drought or wetness over northeastern Brazil. The most extreme years of tree-ring-reconstructed wet-season rainfall in the eastern Amazon have been used to focus the search of the BDL for relevant climate and streamflow information, which has provided strong historical support for some of the extremes identified with the independent proxy tree-ring data. A much larger effort is under way to recover all relevant hydrometeorological information for every year covered by the BDL in the eighteenth and nineteenth centuries and might provide valuable insight into climate and environmental variability in the Amazon Basin and across Brazil.

The historical comparisons with reconstructed wet-season rainfall extremes in the eastern Amazon have helped validate the fidelity of the climate signal in the C. odorata tree-ring chronologies from the Rio Paru. The tree-ring data only explain 42% of the instrumental precipitation variance during the 1978–2016 calibration period, but high-quality instrumental observations of precipitation are not numerous in the vicinity of the tree-ring collection site even in the late-twentieth and early-twenty-first centuries. Because the tree-ring data respond most strongly to the driest and wettest rainfall extremes, the derived reconstruction of rainfall tends to relate to precipitation anomalies broadly over the Amazon, even extending into the northeastern states of Brazil where nineteenth-century historical reports are reasonably numerous. Precipitation extremes during the modern and historical eras tend to be driven by very large-scale ocean–atmospheric forces related to ENSO. However, ENSO is not the only driver of hydroclimate in the Amazon Basin and some of the preinstrumental extremes documented here may provide a useful perspective on independent variability between the tropical Pacific and Amazonian climate systems.

Ring-width chronologies of C. odorata have proven to be valuable rainfall proxies in the Amazon, but more are certainly needed to improve the temporal and spatial reconstruction of precipitation over what is the largest watershed on Earth. There may also be opportunities to recover additional historical benchmarks regarding drought and flood extremes in the Amazon that are not currently included in the Brazilian Digital Library, including the 1876 engineering specifications for the Bittencourt Bridge and any professional papers of Major Coutinho that may yet survive. Coutinho was in Manaus in the midnineteenth century and made instrumental observations of precipitation, river levels, and seasonal river-level changes (selected monthly precipitation totals for Manaus were included in Estrella do Amazonas 1861a–k, 1862a–d, Table 1, sources 1753–67). A dedicated search for any surviving professional records is needed because the available information suggests that the floods of 1859, 1860, and 1892 may have been among the highest in the history of the Amazon River. Coutinho’s benchmark in Manaus was the gauge at Ponte dos Remédios, which was destroyed in the late-nineteenth century (A Federação 1896, Table 1: 1735; Duarte 2009; cause of bridge destruction not known). Nevertheless, it might be possible to constrain the relationship between the Ponte dos Remédios gauge and the modern gauge at the Port of Manaus with further historical, archaeological, and geomorphological research.

The most important specific benchmark yet discovered in the BDL may be the flooding in Santarem during 1859 when “First Street” was inundated sufficiently deep to float canoes. The lowest elevation measured for the modern day First Street in Santarem (Rua 24 de Outubro) is 10.199 m, which, along with the water depth needed to float a canoe (perhaps 0.5 m), could represent a river stage of 10.7 m MSL, exceeding even the flood of 2009 that reached 10.22 m MSL, the highest yet observed on the gauge at Santarem. This “Great Flood of 1859” at Santarem may have also exceeded the record flood at Manaus in 2021 (23.19 m MSL) because the two gauges are so highly correlated ($r = 0.89; 1999–2022$) that a regression estimate extrapolated from a high-water mark of 10.7 m at Santarem (estimated for 1859) would correspond to a level of 23.65 m MSL on the Rio Negro at Manaus. Recognizing that Amazon River discharge at Santarem, below the confluence with the Rio Tapajos, is larger than the mean discharge at Manaus, Obidos, or other gauging stations upstream, a record flood stage at Santarem would normally involve a greater water volume than any upstream stations. Because the Amazon River is the largest river on earth by a lot, “The Great Flood of 1859” at Santarem may have been the largest meteorological flood on earth in the past 164 years (e.g., O’Conner and Costa 2004).

The extraordinary possibility that the Amazon River flood of 1859 in Santarem, and perhaps the flood of 1892 at Manaus, may have nearly equaled or exceeded the record highest floods of the instrumental era will require further historical, hydrological modeling, and on-site engineering and archaeological research to support or refute. Flood crests along the Amazon River can be affected by several factors (e.g., de Paiva et al. 2013), including spatial variability in precipitation and runoff within the drainage basin, channel width and depth, sediment distribution in the channel and on the floodplain, water exchange between the main channel and large floodplain lakes, soil moisture, evapotranspiration, deforestation, crustal deformation due to water mass loading (Moreira 2016; Fossoni-Andrade et al. 2021), and ocean tides in the lower ~800 km of the stream (the Amazon estuary; Yamazaki et al. 2012). Nonetheless, improved characterization of the floods of 1859 and 1892, if feasible, would help to place the recent years of high-magnitude Amazon River floods into a longer context of natural hydroclimatic variability.

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Data availability statement. The tree-ring data used in this article, including the raw ring-width data for each core and cross section and the derived precipitation reconstruction, are available from the NOAA National Centers for Environmental Information (https://www.ncei.noaa.gov/pub/data/paleo/treering/reconstructions/southamerica/amazon2020precip.txt). Every historical report concerning climate tallied in Figs. 2 and 3 is available from the Brazilian Digital Library and the University of Chicago. The instructions for accessing each citation are provided in the caption to Table 1 in the online supplemental material. Note that images of the original citations are copyrighted protected by the BDL and therefore could not be reproduced in the online supplemental material.

REFERENCES


Alves, J., 2003: História Das Secas: Séculos XVII a XIX. Ed. fac. símil. Fundação Waldemar Alcântara, 630 pp. (Table 1 in the online supplemental material, source 1).


Brasil, T. P. S., 1877: Memória sobre o clima e as secas do Ceará. Nono Livro Das Secas, V.-U. Rosado, Eds., Fundação Vingt-Un Rosado/Colecção Mossoroense (Acervo virtual Oswaldo Lamartine de Faria), 4–125. (Table 1 in the online supplemental material, source 2).


