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Multidecadal Changes in Wet Season Precipitation Totals Over the Eastern Amazon

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Key Points:
- Drought and flood extremes in the Amazon River basin have increased in frequency during the last 40 years
- A new tree-ring chronology of *Cedrela odorata* confirms the dating and climate signal of a previous chronology for the eastern Amazon
- Multidecadal variability of tree-ring reconstructed rainfall suggests that recent eastern Amazon rainfall extremes may not be unprecedented

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Abstract Instrumental observations indicate that Amazon precipitation and streamflow extremes have increased during the last 40 years, possibly due to anthropogenic changes and natural variability. How unprecedented these changes might be is difficult to determine because some paleoclimatic, instrumental, and climate model simulations suggest that Amazonian precipitation and streamflow may be subject to multidecadal variability with return intervals longer than most direct observations. A new 258-**year** long tree-ring chronology of *Cedrela odorata* has been developed in the eastern Amazon and has been used to reconstruct wet season precipitation totals from 1759–2016. Reconstructed drought extremes are associated with significant sea surface temperature anomalies over the tropical Pacific and Atlantic Oceans. Strong multidecadal variance is identified in the reconstruction that may reflect a component of natural rainfall variability relevant to forest ecosystem dynamics and suggesting that recent hydroclimate changes over the eastern Amazon may not be unprecedented over the past 258 years.

Plain Language Summary Drought and flood extremes in the Amazon River basin have increased in frequency during the last 40 years, but how unprecedented these recent changes might be is difficult to determine because most instrumental records do not extend before 1950. A new tree-ring chronology of *Cedrela odorata* has been developed in the eastern equatorial Amazon, confirming the exact dating and climate signal of the single existing tree-ring chronology from the region. A tree-ring reconstruction of wet season precipitation based on this new chronology extends from 1759–2016 and documents strong multidecadal variability that impacted the frequency of reconstruction precipitation extremes over the past 258 years.

1. Introduction

The vast Amazon basin still preserves the largest tropical forests on Earth and plays a significant role in the general circulation of the atmosphere and the global energy balance (Nobre et al., 2016). Climate model simulations of hydroclimatic variability in the Amazon indicate that anthropogenic forcing may amplify the hydrologic cycle, resulting in more severe drought, extreme floods, and a decline in annual precipitation over most of the watershed (Feng & Fu, 2013). Some of these hydroclimatic changes may already be evident in observational records (Espinoza et al., 2014; Gloor et al., 2013; Marengo & Espinoza, 2016). Precipitation and streamflow extremes have increased in the Amazon during the last 40 years, possibly due to interactions between deforestation and climate (Khanna et al., 2017), intensification of the Walker Circulation (Barichivich et al., 2018), or global climate change (Nobre et al., 2016). How unprecedented these recent changes in extremes might be is difficult to determine because instrumental precipitation records have become widely available across the Amazon in only the last 50 years and high-resolution paleoclimate proxies are scarce.

The El Niño/Southern Oscillation (ENSO) strongly modulates the interannual variability of rainfall over Amazonia, with drought often developing during El Niño events (Marengo & Espinoza, 2016; Ronchail et al., 2002; Ropelewski & Halpert, 1987; Zeng, 1999). Lower-frequency variability may also modulate precipitation over the equatorial Amazon, and multidecadal regimes have been identified in speleothem proxies, instrumental observations, and climate model simulations over the basin (Ault et al., 2012; Chelliah & Bell, 2004; Fernandes et al., 2015; Labat et al., 2004; Marengo, 2004; Wang et al., 2011; Wang et al., 2017).

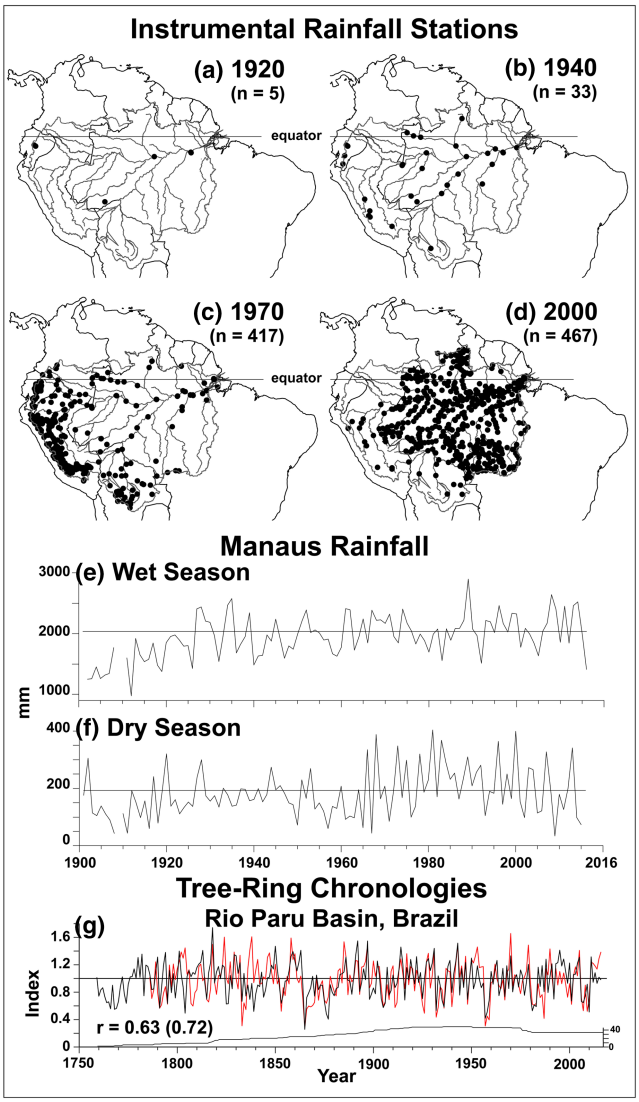

Figure 1. The rainfall recording stations in the Amazon basin operating during each of 4 years are mapped from 1920–2000 (a–d; from ANA, Brazil, and in the Western Amazon from the Climatic Research Unit). Instrumental rainfall totals (mm) for Manaus are plotted for the wet (e; 1902–2016, October–June) and dry season (f; 1901–2015, July–September). These seasonal totals are not homogeneous when compared with Rio Negro maximum and minimum water levels ($p < 0.05$). The two *C. odorata* chronologies from the Rio Paru basin are plotted (g; RPA = red, RPB = black) along with the correlation between the chronologies (for 1786-2016 and 1851-2016) and the sample size each year for RPB.

Decadal episodes without drought or flood extremes are apparent in the Amazon River water level records at Manaus and Obidos from 1903–2015 (Barichivich et al., 2018), and in precipitation and terrestrial water storage indices from 1980–2016 (Chaudhari et al., 2019). Low-frequency variations are nevertheless difficult to document in the short, sparse, and often-interrupted instrumental measurements of precipitation in the Amazon that begin mostly in the mid- to late-20th century (e.g., Marengo, 2004; Garreaud et al., 2009). High-resolution proxy precipitation data could help document multidecadal variability in the preinstrumental period. The first moisture sensitive tree-ring chronologies of *Cedrela odorata* have recently been developed in the Amazon basin (Brienen et al., 2012; Granato-Souza et al., 2018), a significant accomplishment because most tropical tree species do not form consistent annual growth rings suitable for dendroclimatic analysis. The 231-**year** long *Cedrela* chronology from the eastern Amazon was used to reconstruct wet season rainfall from 1786–2016 (Granato-Souza et al., 2018).

A new 258-**year** long tree-ring chronology of *C. odorata* has been developed in the Rio Paru drainage basin of the eastern Amazon (Rio Paru-Baixo [RPB]). This chronology confirms the exact dating and precipitation response of the first *Cedrela* chronology developed from a separate location on the Rio Paru (i.e., Rio Paru-Alto; Granato-Souza et al., 2018). Positive and especially negative growth extremes in the new RPB *Cedrela* chronology are associated with above and below average precipitation at many instrumental rainfall stations across the Amazon basin. The RPB chronology is used to reconstruct wet season precipitation totals for the eastern equatorial Amazon from 1759–2016. The reconstruction is associated with ENSO extremes and exhibits significant multidecadal variability. Strong low frequency variability in reconstructed wet season precipitation suggests that the recent increase in high and low rainfall extremes may not be entirely unprecedented over the eastern Amazon basin in the context of natural variability.

2. Data and Methods

The new RPB chronology was developed from cross sections of *C. odorata* salvaged at a logging concession in the eastern Amazon (0.997522°S 53.2667°W) located 10 km to the southeast and 80 m lower in elevation than the site at Rio Paru-Alto (RPA; 0.97669°S 53.32586°W). The owners and employees of the logging firm CEMAL and the Environmental and Sustainability Agency in the state of Para facilitated the collection of cores and cross sections from legally harvested trees. All tree-ring specimens have been cataloged and permanently stored in the Tree Ring Laboratory of the Federal University of Lavras where they are available for further scientific research.

All cross sections were dried and highly polished to reveal the cellular anatomy of the annual rings. Well-formed concentric growth rings were found for both of the sites from the Rio Paru, and a new chronology dating from 1759–2016 was developed based on 120 radii from 60 trees at RPB using graphical comparisons of ring width time series and visual dating under the microscope (Douglass, 1941; Stokes & Smiley, 1996). All cross sections from the two sites on the Rio Paru can be dated with dendrochronology, but some specimens were too short or irregular to have value for long chronology development. The chronology from RPB used for these analyses was instead based on the most strongly cross-correlated subset of 50 dated radii from 22 trees. The "Schulman Shift" (Schulman, 1956) was not used in the dating of the ring width series from Rio Paru sites because the wet season typically begins in February in this equatorial area

and both chronologies respond to precipitation during the same calendar year as the wet season (Granato-Souza et al., 2018).

The dendrochronologically dated ring widths were measured with a precision of 0.01 mm on a stage micrometer. The computer program COFECHA (Holmes, 1983) was used to check dating and measurement accuracy. The dated time series were detrended and standardized using data adaptive cubic smoothing splines with a 50% frequency response of 100 years to minimize short-period growth excursions associated with non-climatic stand dynamics in these closed canopy rain forests using the ARSTAN program (Cook & Krusic, 2005). All ring width index series were averaged on a year-by-year basis producing the final robust mean index chronology (Cook & Krusic, 2005).

Correlation and composite analyses with monthly precipitation data were computed in order to define the strength and seasonality of the rainfall signal of this new *Cedrela* chronology. Monthly precipitation data for all Brazilian recording stations in the Amazon basin were obtained from the Agência Nacional de Águas from 1920 to 2016 (ANA, National Water Agency). The RPB chronology was correlated with the gridded monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) V7 0.5° data set (Becker et al., 2013; Schneider et al., 2014) to identify the strongest regional rainfall response. The GPCC data for the wet season (February–July) were then regionally averaged, and that instrumental time series was used for reconstruction.

A reconstruction based on the single new RPB chronology was computed using bivariate regression to calibrate the standardized ring width chronology from the Rio Paru with February–July precipitation data extracted from the 0.5° gridded GPCC data set for 0–1°S and 56–57°W near Santarem and 150 km west of the remote RPB collection site. The tree-ring chronology was calibrated with wet season rainfall totals from 1978 to 2016 when the GPCC precipitation data from the eastern Amazon are based on several reporting stations and appear to be most homogeneous. Validation of the reconstruction prior to the calibration interval is difficult because rainfall stations in the region become increasingly scarce. Nonetheless, the reconstruction was compared with the regional average GPCC wet season rainfall data and with the totals recorded at the Santarem station from 1939–1977. The derived reconstruction was also evaluated 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).

Semiparametric 90% prediction intervals were computed for each year of the reconstruction to estimate the uncertainty associated with the reconstructions through time (Cook et al., 2013) using the point-by-point regression program of Cook et al. (1999); E.R. Cook, Personal Communication, 2019). These prediction intervals are based on standard least squares theory (Olive, 2007; Seber & Lee, 2003) and the maximum entropy bootstrap method (Vinod, 2006) to randomly rearrange the predictors and predictands. In the generation of the semiparametric prediction intervals, estimates of regression model interpolations and extrapolations were generated from the Hat matrix of predictors and were used to identify extrapolated values likely to be least reliable for interpretation in the reconstruction (Wiesberg, 1985).

Singular spectrum analysis (Ghil et al., 2002; St. George & Ault, 2011) was performed to identify important frequency components in the 258-year reconstruction. The Mann-Kendall test (Kendall, 1975; Mann, 1945) was used assess the presence of significant ($p < 0.05$) monotonic trends in the derived reconstructed time series of wet season precipitation. Spectral and cross spectral coherence analyses were used to compare the two Rio Paru tree-ring chronologies in the frequency domain (Percival & Constantine, 2006), and the 95% confidence level was estimated through 10,000 runs of Monte Carlo simulations.

3. Results and Discussion

Instrumental precipitation measurements have become widespread in the Amazon basin in only the last 70 years (Figure 1). Just 33 stations were operating in the basin in 1940, but 467 were reporting observations in 2000 (Figures 1a– 1d). However, many station observations have not been continuous even in recent decades. The precipitation records at Rio Branco in the southwest and Manaus in the central Amazon are the two longest in the Brazilian Amazon. Both of these important records are subject to significant uncertainties during the earliest years of observation. The wet and dry season totals for Manaus are presented in Figures 1e and 1f, and both are inhomogeneous when cumulatively plotted with the long river level record of the Rio

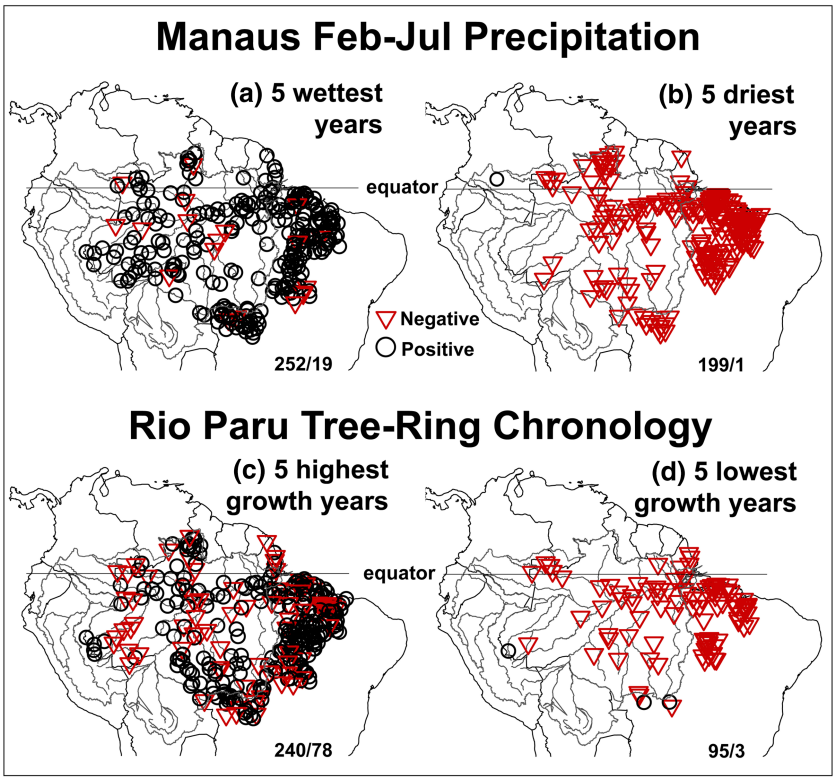

Figure 2. Average anomalies in wet season (February–July) precipitation are plotted for all available instrumental stations in and near the Amazon basin of Brazil for the five wettest (a) and five driest years (b) recorded at Manaus from 1980–2016 (circles = positive, triangles = negative anomalies). February–July precipitation totals are also plotted for all stations during the five highest (c) and five lowest years of tree growth from 1980–2016 (d) in the new Rio Paru-Baixo tree-ring chronology (location = 0.997522°S 53.2667°W). The number of above and below average (below/above) stations is listed below each map.

Negro at Manaus in double mass analyses (Kohler, 1949). The wet season totals appear to be problematic before circa 1920 and the dry season totals before circa 1960 (Figures 1e and 1f). Both seasonal totals exhibit positive trend during the early 20th century that is not strongly present in the maxima, minima, or annual Rio Negro or Amazon River level data (e.g., Gloor et al., 2013; Labat et al., 2004). The early precipitation data at Manaus may be impacted by irregularities in instrumentation or observation that would complicate the detection of low-frequency variability. Moisture sensitive tree-ring chronologies may therefore provide a valuable proxy perspective on decadal to multidecadal variability both during and preceding the instrumental period.

The tree-ring chronology developed at the RPB site is based on highly polished cross sections of *C. odorata* that exhibit obvious and well-defined annual growth rings that are correctly dated to the calendar year of formation. The Rio Paru *Cedrela* is fortunately not subject to the kind of obscure, suppressed, and often locally absent growth rings observed on many tropical tree species. The internal crossdating among the individual trees and radii at RPB is excellent, which is quantified by the fact that the Expressed Population Signal statistic (EPS; Wigley et al., 1984) never falls below the 0.85 threshold from 1759–2016 (ranging from 0.87 to 0.97 for 50-year segments) and the average correlation among all time series (RBAR) ranges from 0.27 to 0.51.

The development of the RPB chronology confirms the exact dating of the original master chronology of *Cedrela* from the nearby RPA site. The two mean index chronologies are correlated over their 230-year common interval at $r = 0.63$ ($p < 0.0001$; 1786–2016) using the autoregressively modeled "white noise" residual versions for both chronologies. This between site correlation increases to $r = 0.72$ ($p < 0.0001$) for the period from 1851–2016 when both chronologies are more fully replicated. The decadal components of both chronologies indicate similar periods of above and below average tree growth over the past 230 years, likely in

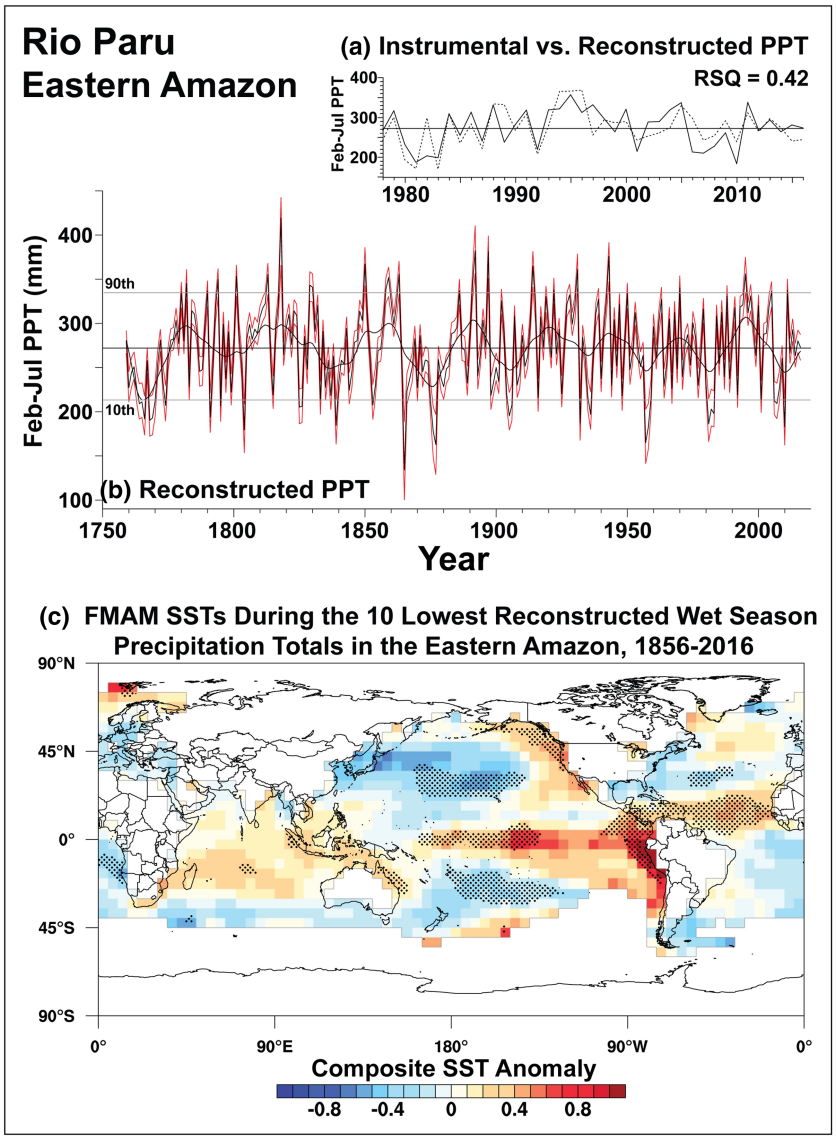

Figure 3. (a) Instrumental GPCC (dashed) and tree-ring reconstructed (solid) wet season precipitation totals (February–July) for the eastern equatorial Amazon are plotted from 1978–2016 (RSQ = R^2adj). (b) The full reconstruction of wet season precipitation for the eastern Amazon is plotted from 1759–2016 (black) along with the 90% prediction intervals (light red). The leading SSA waveform identified in the reconstruction is also plotted (smooth black), highlighting the strong multidecadal variability in the reconstructed wet season precipitation over the eastern Amazon. (c) The 10 driest years in the wet season precipitation reconstruction for the eastern Amazon are used to map SST anomalies for the period from 1856–2016 (SSTs from Kaplan et al., 1998; grid point means significantly different from all remaining years are stippled, $p < 0.05$).

response to multiyear droughts and pluvials. Cross-spectral analysis indicates that the two chronologies are coherent at periods from 2–32 years at $p < 0.05$ and 2–51 years at $p < 0.10$.

The new *C. odorata* chronology from RPB not only confirms the original dating of our first *Cedrela* chronology but also is more strongly coupled with regional rainfall totals and large-scale ocean-atmospheric variability. Station observations of wet season rainfall from ANA, Brasil (2019) were averaged for the five wettest and five driest February–July precipitation totals at the Manaus station from 1980–2016 to illustrate this coherence of precipitation extremes over the Amazon basin, particularly the dry extremes (Figure 2ab; note that all 5 years had to be available for a station to be included in any one of the four maps in Figure 2). When the five highest and five lowest values in the RPB ring width chronology were used to composite the station

precipitation data, a consistent basin-wide pattern of above and below average wet season rainfall was also observed (Figures 2c and 2d), very similar to the precipitation anomalies associated with extremes in the Manaus gage. Similar results were obtained using the February–July precipitation extremes recorded at the Santarem station and in the gridded GPCC monthly precipitation data (also for February–July; not shown). Just 5 years were used in this analysis from 1980–2016, but the association between extremes in the RPB chronology and station rainfall totals is present when compared with the many fewer stations available earlier in the 20th century in the ANA compilation (not shown). Correlation analyses comparing the RPB chronology with February–July precipitation in the gridded GPCC data set identify significant ($p < 0.05$) correlations over the central and eastern Amazon basin for 1978–2016, similar to, though less widespread than, the composite pattern illustrated in Figure 2d.

The single RPB chronology was calibrated with the regional GPCC February–July precipitation data (0–1°S and 56–57°W) using bivariate regression and explains 42% of wet season precipitation variability from 1978–2016 (R^2adj = 0.42, adjusted for the loss of degrees of freedom; Figures 3a and b). The February–July interval is the wet season for the Rio Paru region of the northeast Amazon. The region of GPCC data used for calibration with the RPB chronology was selected because it is well correlated with the RPB chronology from 1978–2016 (including the GPCC data from the remote Rio Paru basin in this regional average did not improve the calibration). The cross-validation reduction of error statistic indicates little loss of explained variance when tested against withheld instrumental observations during the calibration period (CVRE = 0.39). However, the reconstruction is not significantly correlated with the extracted GPCC data from 1939–1977 ($r = 0.21$). This lack of correlation during the precalibration period may be due in part to deficiencies in the gridded instrumental data. The mean and variance of the regional GPCC precipitation data become increasingly impacted by the lack of stations observations before 1978, limiting the time interval available for cross-validation of the reconstruction. The reconstruction is modestly correlated from 1939–1977 with February–July precipitation recorded at Santarem 250 km west of the collection site ($r = 0.38$, $p < 0.05$, $r = 0.46$ omitting 1943). The reconstruction is also significantly correlated from 1939–1977 with a four-station instrumental average of February-November precipitation for the central and eastern Amazon (Granato-Souza et al., 2018) at $r = 0.41$ ($p < 0.01$). The association between reconstructed drought years in the eastern Amazon with warm sea surface temperature (SST) anomalies in the tropical Pacific and Atlantic from 1870–2016 (Figure 3c) provides some additional validation of the reconstruction.

The reconstruction is plotted from 1759–2016 in Figure 3b along with the 90% regression prediction intervals calculated from a suite of pseudoreconstructions (Cook et al., 2013). The reconstruction exhibits strong interannual and low-frequency variability, including decadal to multidecadal episodes of drought and wetness. The mid-19th century drought is especially notable because it extended with little relief from 1864–1882 (Figure 3b) and was also reconstructed by Granato-Souza et al. (2018). The two reconstructions now available from the Rio Paru sector therefore indicate that severe and sustained drought has been a feature of natural climate variability over the eastern equatorial Amazon, including decadal moisture regimes that exceeded any recorded during the relatively short instrumental period (Figure 3).

Spectral analysis identifies concentrations of reconstructed precipitation variance at periods of approximately 4.0, 6.0, and 11.0, and especially at 35 years ($p < 0.05$, using the Blackman-Tukey method). Singular spectrum analysis indicates that multidecadal variability represents approximately 20% of the variance in reconstructed wet season precipitation totals over the eastern Amazon, highlighted by the leading 35.4-year waveform in Figure 3b (bandwidth = 20). Similar and significant multidecadal power peaking at 33.4 years ($p < 0.01$) is detected in the instrumental observations of February–July rainfall totals at Manaus from 1901–2016, the longest instrumental precipitation record from the central and eastern Amazon. The homogeneity of the Manaus precipitation measurements during the early 20th century is doubtful, but significant multidecadal power is nevertheless present in February–July rainfall when the analyses are restricted to the period from 1920–2016 ($p < 0.01$). The Rio Negro maximum annual stream level record at Manaus also has significant multidecadal spectral power from 1920–2013 ($p < 0.05$), but not for the full period of observation from 1903–2016 (e.g., Labat et al., 2004).

The multidecadal variability of reconstructed wet season precipitation in the eastern Amazon could have practical implications for interpretation of trends in the short instrumental precipitation data from the region. The reconstruction was tested for significant monotonic trends using the Mann-Kendal test applied to 30-year

segments and a 1-year time step proceeding through the time series. Significant ($p < 0.05$) positive and negative trends of 30-year duration were both detected in the reconstruction during the instrumental and pre-instrumental period. If multidecadal swings are an important component of natural wet season variability, then significant linear trends of 30-year duration are likely to also be present. The extended perspective provided by this reconstruction suggests that the recent decade scale changes in hydroclimate over the Amazon may not be unprecedented over the past 258 years. The wet season precipitation estimates provide analogs of both extreme individual years (such as 1818 and 1865) and low-frequency changes in the mean.

The wet season reconstruction is only weakly correlated with SSTs in the tropical Pacific (not shown), but composite mapping of the 10 driest years in the reconstruction over the period from 1856–2016 indicates a strong negative response to El Niño conditions in the tropical Pacific and a weaker but still significant negative response to SSTs in the tropical North Atlantic (Figure 3c). This pattern of response is similar to the SST forcing of instrumental precipitation variability over the Amazon basin (Enfield, 1996; Dettinger et al., 2001; Yoon & Zeng, 2010; Fernandes et al., 2011; Yeh et al., 2018). Unlike the instrumental precipitation data, the tree-ring estimates are not significantly associated with cold SSTs in the tropical Pacific or Atlantic during reconstructed wet extremes (not shown). Figure 3c also indicates a basin-wide pattern of Pacific SST anomalies that could be consistent with the Pacific Decadal Oscillation (Mantua et al., 1997) or more broadly the Inter-Decadal Pacific Oscillation (IPO; Dong and Dai, 2014). The quasi-oscillatory IPO has full period of 40–60 years, with phase reversals every 20–30 years (Dong & Dai, 2015) and may have influenced the low-frequency variability of reconstructed precipitation in the eastern Amazon over the past 258 years. The reconstruction is only marginally correlated with the Atlantic Multi-Decadal Oscillation ($r = 0.159$; $p < 0.05$; June and July average, 1856–2016).

Multidecadal variability has important implications for forest ecosystem dynamics and biogeochemical cycling in Amazonia. The recently observed decline in the long-term carbon sink of Amazon rainforests (Brienen et al., 2015) has been attributed to increasing climate variability, including the severe droughts of 2005 and 2010 (Aragao et al., 2018; Lewis et al., 2011). However, the influence of multidecadal variability on rain forest dynamics in the Amazon is difficult to investigate because direct forest monitoring data rarely exceed 30 years of record.

4. Conclusions

The new tree-ring chronology from RPB provides important validation of the master dating chronology for *C. odorata* in the eastern Amazon and confirms the climate response first identified by Granato-Souza et al. (2018). Tree-ring chronology development and climate reconstruction in the Amazon basin are both predicted on the consistent formation of annual growth rings and their exact calendar year dating with dendrochronology. The evidence for the exact dating of *C. odorata* ring width data from the Rio Paru now includes the significant correlation between the two chronologies from the Rio Paru, the similar and significant response of both chronologies to instrumental precipitation totals, and the link between reconstructed drought extremes and SST anomalies in the tropical Pacific where ENSO conditions have a strong impact on instrumental precipitation over the eastern Amazon.

The new Cedrela chronology has been used to reconstruct wet season rainfall totals over the eastern equatorial Amazon from 1759–2016. This reconstruction confirms the severe sustained drought in the mid-19th century first estimated with the RPA chronology by Granato-Souza et al. (2018). This mid-19th century drought is registered by both *Cedrela* chronologies from the Rio Paru basin and in both cases is estimated to have been more extreme than any reconstructed during the relatively short instrumental data for the eastern Amazon. Another intense and prolonged drought is reconstructed during the late-18th century (Figure 3b), which if confirmed with additional tree-ring data would suggest that decadal droughts may be underestimated in the available instrumental precipitation observations for the region.

Tree-ring reconstructed wet season precipitation totals in the eastern Amazon have been subject multidecadal regimes over the past 258 years. This multidecadal variability of reconstructed February–July rainfall has impacted the frequency of drought extremes in the eastern Amazon. Several decadal to multidecadal regimes without droughts in the lowest 10th percentile are reconstructed from 1759–2016 (Figure 3b). Similar decadal episodes without drought or flood extremes have been noted in other instrumental precipitation and river level data from the Amazon basin. If quasiperiodic low-frequency variability is truly an

important component of natural precipitation that can impact the occurrence of drought and wetness extremes, then it needs to be validated because it might help explain some of the recent increase in floods and drought witnessed in the Amazon and would likely interact with predicted anthropogenic forcing of future precipitation extremes.

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