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**Key Points:**

- A decadal Amazon flow cycle is anticorrelated with solar activity
- The tropical Atlantic may play a role in generating the solar signal
- Solar influences may be modulated by the North Atlantic climate

**Supporting Information:**

- Texts S1–S3 and Figures S1–S4
- Data Set S1

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# Evidence of a decadal solar signal in the Amazon River: 1903 to 2013

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**Abstract** It has been shown that tropical climates can be notably influenced by the decadal solar cycle; however, the relationship between this solar forcing and the tropical Amazon River has been overlooked in previous research. In this study, we reveal evidence of such a link by analyzing a 1903–2013 record of Amazon discharge. We identify a decadal flow cycle that is anticorrelated with the solar activity measured by the decadal sunspot cycle. This relationship persists through time and appears to result from a solar influence on the tropical Atlantic Ocean. The amplitude of the decadal solar signal in flow is apparently modulated by the interdecadal North Atlantic variability. Because Amazonia is an important element of the planetary water cycle, our findings have implications for studies on global change.

## 1. Introduction

Considerable progress has been made during the last 10 years in the understanding of Sun-climate connections [*Gray et al.*, 2010; *Lockwood*, 2012]. In particular, several studies have shown that the decadal solar cycle may have an observable effect on large-scale tropical climate processes [e.g., *Lim et al.*, 2006; *White and Liu*, 2008; *Meehl et al.*, 2009; *Meehl and Arblaster*, 2009]. Because the Amazon River is strongly coupled to the tropical climate system [*Salati and Vose*, 1984], a relationship between this massive tropical river and decadal solar change would thus be expected. However, empirical evidence for a Sun-Amazon River link has remained elusive. From an observational analysis perspective, to some extent, this could be because hydrological records are often generated by nonlinear and nonstationary processes; consequently, classical data analysis methods, which are designed under the hypothesis that data are stationary and/or generated by linear processes, may not be able to detect solar signals and other features in these data. Hence, in this study, we investigate the presence of a decadal solar signal in the Amazon River by applying a nonlinear and nonstationary data analysis method to a 1903–2013 record of Amazon discharge.

## 2. Data and Methods

We considered Amazon flows at Óbidos gaging station, which drains about 80% of the basin. Flow data from this station are available only for 1928–1947 and 1968-near present. To obtain a continuous flow record beginning in 1902, we followed the method reported in previous studies [e.g., *Labat et al.*, 2004; *Dai et al.*, 2009] and reconstructed missing values by linearly regressing monthly flows at Óbidos onto monthly water levels at two nearby stations (supporting information Text S1). Here we used the annual mean Amazon discharges from October to September for 1903–2013; the raw annual mean flow data are shown in Figure 1a. Hereafter, values of every variable considered in this study correspond to annual averages of October–September unless stated otherwise.

The 1900–2014 time series of international sunspot number was used to characterize the decadal cycle of solar activity. Sunspot variability is dominated by a 9–13 year cycle with a mean period of about 11 years.

To analyze surface climate variations, we used longitude-latitude gridded observations of sea surface temperature (SST) [*Smith et al.*, 2008] and surface marine winds [*Woodruff et al.*, 2011], both at 2° × 2°; that for land precipitation was 2.5° × 2.5° [*Schneider et al.*, 2011]. Joint analysis of these data was conducted for 1950–2000, in which the most complete Amazonian network of pluviometers was available [*Marengo*, 2006]. In addition, we used the 1857–2014 record of the Atlantic Multidecadal Oscillations (AMO) index, which is the SST averaged over the North Atlantic between 0° and 70°N [*Enfield et al.*, 2001].

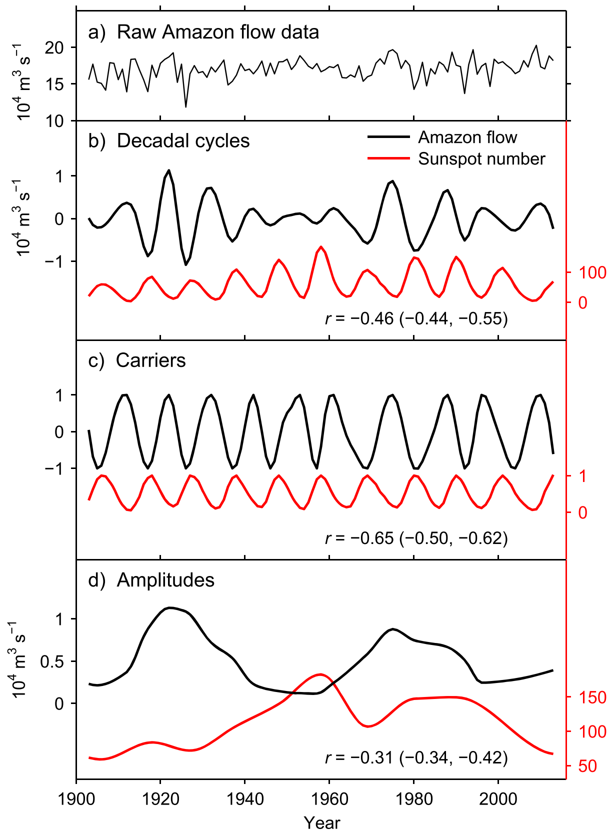


**Figure 1.** (a) Raw data of Amazon flow at Óbidos station. (b) Decadal cycle of Amazon flow and smoothed (3 year moving average) sunspot number; this flow cycle is the third EEMD mode of the time series shown in Figure 1a (Figure S1). (c) Carriers and (d) instantaneous amplitudes of decadal flow and solar cycles. Zero-lag correlation coefficients (*r*) are shown in Figures 1b–1d, along with their 95% and 99% confidence levels in parentheses.

The empirical mode decomposition (EMD) method decomposes time series into oscillatory modes in which the characteristics such as amplitude and frequency are determined by the intrinsic information of data [*Wu and Huang*, 2009]. EMD does not assume that data are linear and/or stationary and can therefore decompose nonlinear and nonstationary time series. Further, EMD provides a temporally local data analysis because it is based on the local characteristics of data. However, EMD has an important limitation known as the mode mixing problem, which arises when a clear spectral separation of modes is not attained. To compensate for this limitation, the ensemble EMD (EEMD) technique has been proposed as an improved version of EMD [*Wu and Huang*, 2009]. In EEMD, the definitive oscillatory mode is defined as the average of the corresponding modes obtained through EMD over an ensemble of many data realizations, generated by adding different white noise realizations to the original data. We applied EEMD to the flow record described above and to other time series considered in this study.

To interpret some cycles, we obtained their instantaneous amplitudes and carriers in the following manner. For a particular oscillation, the instantaneous amplitude was estimated by connecting the local maxima of absolute cycle values with a shape-preserving piecewise cubic interpolation curve. The oscillation carrier was then obtained by dividing the cycle series elements by their corresponding amplitudes.

Significance levels of the Pearson correlation coefficient (*r*) were estimated by combining 1000 Monte Carlo iterations with frequency-domain time series modeling so that autocorrelation is considered [*Macias-Fauria et al.*, 2012].

## 3. Results

The Amazon discharge record was decomposed by EEMD into six oscillatory modes and a residual trend (supporting information Text S2 and Figure S1). The third flow mode accounts for a considerable fraction of total flow variance (23.4%) and is the only one having the same frequencies of the decadal sunspot cycle, at 1/13 to 1/9 cycles per year (supporting information Figure S1). This similarity found in the frequency domain suggests a Sun-Amazon River relationship at decadal time scales. To further investigate this link, in what follows we compare decadal flow and solar cycles in the time domain by separately examining their actual time series, carriers, and instantaneous amplitudes.

The years of minima (maxima) of the decadal Amazon flow oscillation tend to coincide with years of maxima (minima) of the decadal sunspot cycle (Figure 1b). The strongest anticorrelation coefficient between these two cycles, $r = -0.46$, was attained at zero lag when significant at the 95% level (Figure 1b). Moreover, as shown in Figure 1c, the anticorrelation between the carriers of decadal flow and solar cycles is stronger, at $r = -0.65$, and more significant, at the 99% level, providing robust evidence for an antiphase relationship between these cycles.

As shown in Figure 1d, no relationship was detected between the interdecadal envelopes that modulate the amplitudes of decadal flow and solar cycles; a possible cause for the modulation of flow changes is discussed in the following section. The decadal flow oscillation reached its maximum amplitude around 1920 (Figure 1d), which is in agreement with the decadal cycle reported in previous wavelet analysis of annual mean Amazon flow data [*Labat et al.*, 2004]. It should be noted, however, that *Labat et al.* [2004] did not investigate Sun-Amazon flow links.

## 4. Discussion

The antiphase relationship between flow and sunspot oscillations detected in this study is statistically significant and also persists through 10 consecutive solar cycles (Figures 1b and 1c). Such persistence notably reduces, but does not eliminate, the possibility that decadal flow variations are driven mainly by nonsolar forcings such as internal climate variability, volcanism, and deforestation. Hence, the persistence and statistical significance of the observed anticorrelation strongly support the concept that Amazon flow is influenced by decadal solar variability. That is, our empirical results show that a solar influence hypothesis cannot be simply rejected.

Various mechanisms have been postulated to explain climate responses to the decadal sunspot cycle [*Gray et al.*, 2010; *Lockwood*, 2012]. Most invoke decadal oscillations of total solar irradiance (TSI), which is mainly visible and near-infrared radiation, and solar ultraviolet radiation (UV); these TSI and UV cycles are nearly in-phase with the decadal sunspot cycle. In the top-down mechanisms, stratospheric responses to significant UV changes are propagated downward by the atmospheric circulation. In the bottom-up mechanisms, the effects of small TSI changes on the Earth's surface are amplified and propagated upward by climate processes. Possible top-down and bottom-up processes were identified in the equatorial Pacific and tropical Atlantic oceans, which have been shown to influence Amazon runoff [e.g., *de Souza et al.*, 2000; *Marengo*, 2006].

In the equatorial Pacific Ocean, numerical modeling and observations revealed that top-down and bottom-up mechanisms can induce a surface response to solar forcing with a lag of 1–3 years [*White and Liu*, 2008; *Meehl et al.*, 2009; *Meehl and Arblaster*, 2009]. This delay is not consistent with the zero-lag Amazon response to solar forcing determined in the present study; therefore, this response might not be mediated by the Pacific variability. Nonetheless, the timing and nature of the equatorial Pacific response to decadal solar variability continue to be debated [*Roy and Haigh*, 2009]. Future studies are needed to discard or confirm the role of the Pacific Ocean in generating a solar signal in Amazon flow.

The observational analyses of *Lim et al.* [2006] in the tropical Atlantic Ocean suggested the existence of a bottom-up mechanism where the weak TSI forcing is amplified by variations of air relative humidity. This could explain why, as observed by these and other authors [e.g., *White et al.*, 1997; *Zhou and Tung*, 2010], the decadal cycles of SST and sunspot number are positively (negatively) correlated in the tropical North (South) Atlantic Ocean at zero lag. Owing to this SST response, the cross-equatorial SST difference between the tropical North and South Atlantic oceans ($\Delta T_{EQ}$) has a decadal cycle that is nearly in-phase with the decadal sunspot cycle, as revealed in this study through analysis of the $\Delta T_{EQ}$ record using EEMD (Figures 2a and S2 and supporting information Text S2). We determined that this solar signal in $\Delta T_{EQ}$ is physically consistent with the antiphase relationship detected in this study between flow and solar cycles for the following two reasons. First, as shown in Figures 2b and 2c, positive (negative) $\Delta T_{EQ}$ values associated with solar maxima (minima) are accompanied by weaker (stronger) northeastern trade winds over the North Atlantic, which would reduce

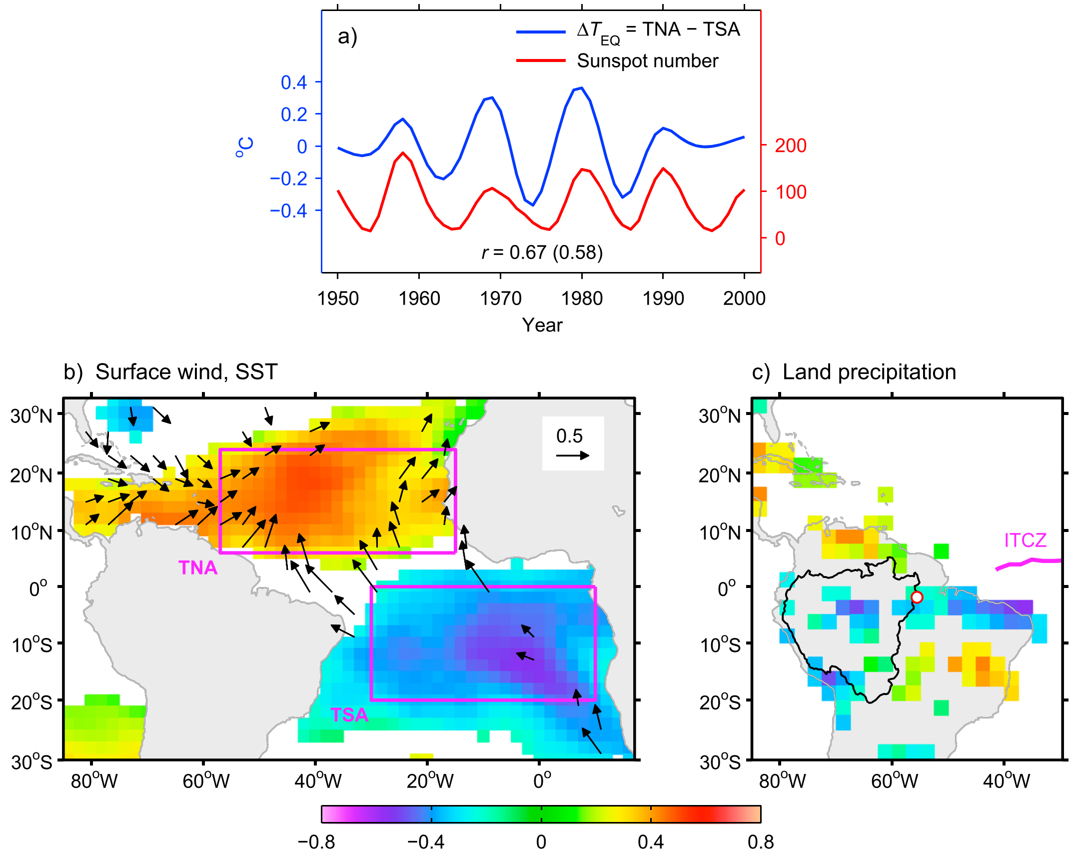


**Figure 2.** (a) Decadal cycle of cross-equatorial SST difference ($\Delta T_{EQ}$) and smoothed (3 year moving average) sunspot number; the zero-lag correlation coefficient (*r*) and its 90% confidence level are indicated with the latter in parentheses. Zero-lag *r* between the decadal $\Delta T_{EQ}$ cycle and raw data (linearly detrended) of (b) SST (colors), surface wind (vectors), and (c) land precipitation. *r* for SST and rainfall is shown only if significant at the 90% level; correlation vectors are shown only where the temporal coverage of wind data is complete and if their magnitude exceeds 0.25. $\Delta T_{EQ}$ is the difference between tropical North Atlantic SST (TNA; SST averaged over 15°W–57°W and 6°N–24°N) and tropical South Atlantic SST (TSA; 10°E–30°W and 0°–20°S); TNA and TSA regions are indicated in Figure 2b. The decadal cycle of $\Delta T_{EQ}$ was obtained by using EEMD (Figure S2). In Figure 2c, the location and watershed of Óbidos station are indicated by the open circle and black curve, respectively. The climatological (1950–2000) annual mean location of the Atlantic ITCZ, where meridional surface winds vanish, is also shown in Figure 2c. Immediately south of this ITCZ position, there is a region of negative correlation that (i) is consistent with meridional ITCZ displacements toward the warmer ocean (Figure S3) and (ii) extends westward into eastern Amazonia.

(increase) the moisture transport from this ocean to Amazonia and thus may explain the observed reductions (increments) of Amazonian precipitation and runoff. Second, positive (negative) $\Delta T_{EQ}$ differences cause northward (southward) shifts of the Atlantic Intertropical Convergence Zone (ITCZ), as revealed in supporting information Figure S3, and therefore would contribute to the reduced (increased) rainfall in eastern Amazonia during the solar maxima (minima), as evidenced in Figure 2c. It is important to note that the wind and precipitation changes shown in Figures 2b and 2c agree with the results of previous studies on the relationship between $\Delta T_{EQ}$ and surface climate [e.g., *Enfield*, 1996; *Nobre and Shukla*, 1996; *de Souza et al.*, 2000; *Chiang and Vimont*, 2004]. Considering all of these factors, we propose that the tropical Atlantic variability, described here by $\Delta T_{EQ}$, plays an important role in imprinting a decadal solar signal in the Amazon River.

As noted in the previous section and shown in Figure 1d, the amplitude modulation of the decadal Amazon flow cycle does not follow the envelope of solar activity. The phenomenon underlying this modulation might be associated with the AMO because, as shown in previous studies [e.g., *Enfield et al.*, 2001; *Knight et al.*, 2006], this slow North Atlantic oscillation can modulate interannual climate variability in the tropical Atlantic Ocean, which is a source of Amazonian moisture [*Marengo*, 2006], and also in the Americas. In fact, as revealed in Figure 3, the amplitude of the decadal Amazon flow cycle tends to be large (small) when the AMO is in its cold (warm) state, suggesting that the AMO might modulate the Amazon River response to decadal

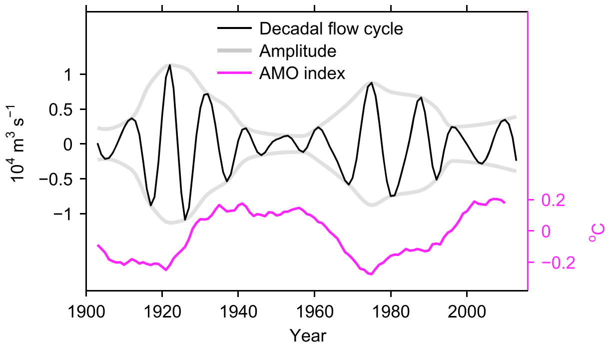


**Figure 3.** Decadal cycle of Amazon flow, its instantaneous amplitude and the smoothed (9 year moving average) index of the Atlantic Multidecadal Oscillation (AMO).

solar variability. Interestingly, this AMO modulation could reflect a long-term solar influence on Amazonia because recent modeling experiments have suggested that interdecadal North Atlantic changes may result from solar forcing [*Menary and Scaife*, 2014]. Nevertheless, it should be stressed that the AMO modulation detected here may be an accidental result because it was observed for less than two AMO cycles (Figure 3). Future research would be valuable to more effectively investigate this possible modulation.

Given that several solar influences on climate occur mainly in boreal winter [e.g., *Meehl et al.*, 2009; *Roy and Haigh*, 2009; *Gray et al.*, 2013], it is worth investigating whether a solar signal appears in boreal winter Amazon runoff. Hence, a record of this runoff was decomposed by using EEMD, which revealed a decadal solar signal similar to that found in the annual mean Amazon flow (supporting information Text S3 and Figure S4). This finding provides additional support for the Sun-climate link in boreal winter.

Regarding paleoclimate inferences, a recent analysis of an Andean lake record for the last 2300 years revealed that centuries of enhanced (diminished) solar activity are characterized by low (high) Amazonian rainfall and by northward (southward) shifts of the Atlantic ITCZ [*Bird et al.*, 2011], which is in agreement with our results and interpretations. This agreement lends further support for an anticorrelation between solar activity and Amazon runoff.

Finally, it is highlighted that the Amazon basin is an important element of the global water cycle. The Amazonia is one of the main regions of tropical atmospheric convection, contains the world's largest tropical forest and accounts for 15–20% of the total global runoff into the oceans [*Dai et al.*, 2009; *Salati and Vose*, 1984]. Consequently, the Sun-Amazon flow link identified in this study provides valuable insights for future studies on the responses of global climate to solar forcing.

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