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An Atlantic influence on Amazon rainfall

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Abstract Rainfall variability over the Amazon basin has often been linked to variations in Pacific sea surface temperature (SST), and in particular, to the El Niño/Southern Oscillation (ENSO). However, only a fraction of Amazon rainfall variability can be explained by ENSO. Building upon the recent work of Zeng (Environ Res Lett 3:014002, 2008), here we provide further evidence for an influence on Amazon rainfall from the tropical Atlantic Ocean. The strength of the North Atlantic influence is found to be comparable to the better-known Pacific ENSO connection. The tropical South Atlantic Ocean also shows some influence during the wet-to-dry season transition period. The Atlantic influence is through changes in the north-south divergent circulation and the movement of the ITCZ following warm SST. Therefore, it is strongest in the southern part of the Amazon basin during the Amazon's dry season (July–October). In contrast, the ENSO related teleconnection is through anomalous east-west Walker circulation with largely concentrated in the eastern (lower) Amazon. This ENSO connection is seasonally locked to boreal winter. A complication due to the influence of ENSO on Atlantic SST causes an apparent North Atlantic SST lag of Amazon rainfall. Removing ENSO from North Atlantic SST via linear regression resolves this causality problem in that the residual Atlantic variability correlates well and is in phase with the Amazon rainfall. A strong Atlantic influence during boreal summer and autumn is particularly significant in terms of the impact on the hydro-ecosystem which is most vulnerable during the dry season, as highlighted by the severe 2005 Amazon drought. Such findings have implications for both seasonal-interannual climate prediction and understanding the longer-term changes of the Amazon rainforest.

Keywords Climate variability · Amazon rainfall · Atlantic Ocean variability · Interannual change

1 Introduction

The Amazon is the largest river basin on Earth. The Amazon tropical rainforest accounts for one-third of the planet's tropical forest, and is a crucial player in the global carbon cycle and climate. Interannual variability of rainfall in the Amazon is large, resulting in basin-wide flood or drought events (e.g., Dickinson 1987). The causes of such events have been linked to anomalous warming or cooling of sea surface temperature (SST) over the surrounding ocean basins. SSTs are very important in the tropics because the atmosphere is sensitive to the oceanic and continental surface conditions, which greatly influence the variability of the climate. For example, it was shown that rainfall over the northern part of the Amazon and the Nordeste (northeastern tropical South America) change significantly depending on the phase of El Niño and the Southern Oscillation (ENSO) (Kousky et al. 1984; Ropelewski and Halpert 1987).

Rainfall over tropical South America is maintained by not only local evapotranspiration, but also by convergence of atmospheric water vapor flux (Chen 1985), controlled by

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the tropical atmospheric circulation. Strong upward motion over this region constitutes an important part of the tropical east-west Walker circulation as it plays a role as an atmospheric bridge to the central tropical Pacific Ocean (Kousky et al. 1984; Walker 1928). It is well established that anomalous subsidence (upward motion) over the Central Pacific induced by cooling (warming) over the equatorial central Pacific can alter the east-west Walker circulation, resulting in increased (reduced) rainfall over tropical South America.

Recently it has also been documented that southern and northern Atlantic SST plays a role in the variability of the water budget over tropical South America (Marshall et al. 2001; Ronchail et al. 2002; Uvo et al. 2000), particularly through the north-south migration of rainfall. For example, more (less) rainfall over the basin is associated with anomalously cold (warm) SST in the tropical South Atlantic, coupled with anomalously warm (cold) SST in the tropical North Atlantic. Such a situation is the result of an anomalously northward (southward) location of the Inter-Tropical Convergence Zone (ITCZ) (e.g., Enfield 1996; Moron et al. 1995). This relationship was reported to be regionally confined to northeastern Brazil (north of 5°S and east of 60°W) (Moura and Shukla 1981). Recently, more evidence has emerged that this Atlantic influence could extend into the Amazon basin (e.g., Labat et al. 2004; Ronchail et al. 2002, 2005). For example, inclusion of Atlantic Ocean SST could lead to better forecasts of river discharge over the southern part of the basin (Uvo et al. 2000), and significant correlation was found between river discharge at Obidos and SSTs in the Atlantic (Labat et al. 2004; Ronchail et al. 2005). However, further analysis is needed to understand the mechanism responsible for connecting the Amazon rainfall and Atlantic SST, as well as the relationship of the Amazon-Atlantic linkage with ENSO activity.

The possibility of a tropical Atlantic influence on the Amazon's rainfall was highlighted after the severe drought event in 2005 (Marengo et al. 2008b; Zeng et al. 2008). This drought event was one of the worst in 100 years, and severely affected Amazon tributaries such as the Solimões and the Madeira in the southern Amazon (Marengo et al. 2008b). In contrast, no significant change of rainfall or river levels were observed in northeastern Amazon, where severe droughts occurred in 1926, 1983, and 1998, due to extreme El Niño events. This unusual drought in 2005 motivated us to further investigate the nature of a possible Atlantic SST influence on the Amazon and the relative roles played by the Pacific and the Atlantic Ocean. This linkage has not been well documented, in part due to the scarcity and sometimes uncertain quality of rain gauges in the deep Amazon, and incorporation of these rain gauges into majority of the gridded rainfall analysis (Zeng et al. 2008).

Another difficulty in identifying a clear Atlantic-Amazon connection is to separate the interannual variabilities associated with the Atlantic from those associated with Pacific SSTs because these two basins are correlated either synchronously or with a lag (e.g., Enfield and Mayer 1997; Kushnir et al. 2006; Latif and Grotzner 2000). For example, warming of the tropical Eastern Pacific basin induces warming of the tropical North Atlantic 4–6 months later (Enfield and Mayer 1997; Giannini et al. 2001; Lanzante 1996; Moron et al. 1998). However, some anomalous warm/cold events in the tropical North Atlantic that show no clear connection to Pacific SST variability have also been observed (Handoh et al. 2006a, b; Lanzante 1996). Also, the interannual variability over the tropical South Atlantic Ocean tends to occur in the absence of ENSO, in the southern winter season. In this paper, the relative roles played by the SSTs of the individual oceanic basins are illustrated in terms of the mechanism and their regional and seasonal preference that affect Amazonian rainfall on interannual timescales. At the same time, it will be investigated whether the Atlantic SST affects Amazon rainfall during any specific season and over any concentrated regions in contrast to the Pacific SST which has largest impact on Amazon rainfall during boreal winter and concentrated in the northeastern Amazon (Kousky et al. 1984). Finally, particular attention will be paid to how the Pacific and the Atlantic SSTs play joint or individual roles in influencing Amazonian rainfall on interannual time scales.

This paper is structured as follows. Data and methods are described in the following section. The linkage between the tropical Atlantic Ocean and Amazon rainfall on interannual time scales is established and explained using statistical analysis in Sect. 3. Associated circulation patterns, including divergent circulation anomalies and water vapor flux are also discussed in this section. Seasonal characteristics of this linkage will be discussed in Sect. 4. Further analysis to separate an indirect influence on the Amazon of Pacific SSTs via the North Atlantic will be given in Sect. 5. Finally, discussion and concluding remarks are provided in Sect. 6. As supplemental information to Sect. 3, empirical orthogonal function analysis is also presented in the Appendix 1.

2 Data and methods

Observational data used in this study include different estimates of rainfall, river runoff measured at Obidos, sea surface temperature, atmospheric moisture flux, and upper-level wind. Several kinds of monthly rainfall estimations are used in our analysis. Our primary choice for the rainfall estimate is the outgoing longwave radiation precipitation index (OPI) with spatial resolution of 2.5° × 2.5°, used for real-time monitoring (Xie and Arkin 1996), which has the advantage of temporal continuity and high spatial coverage (Zeng et al. 2008), and runoff data will be used as supporting evidence. We have also made use of gauge-based rainfall estimation such as Precipitation Reconstruction over Land (hereafter PRECL) from NOAA/CPC (Chen et al. 2002) and GPCC, a station-based gridded product from the Global Precipitation Climatology Centre (Rudolf et al. 2005), and satellite-gauge blended products including CMAP (the Climate Mapping and Analysis Project, Xie and Arkin 1996) and GPCP (the Global Precipitation Climatolgy Project, Adler et al. 2003), for comparison. Sea surface temperature obtained from the Hadley Center (http://www.hadobs.org, Rayner et al. 2003) is used in this analysis. All the atmospheric variables are obtained from the NCEP/DOE reanalysis (NCEP-R2; Kanamitsu et al. 2002).

All of the analysis is done for the period from January 1979 to December 2006. Interannual variability of each variable is constructed by removing the climatology based on the period of 1979–2006 for each calendar month. Then, a low-pass filter with an 18-month cutoff using a 2nd order Butterworth filter (Murakami 1979) is applied. All the analysis is performed on these filtered data except the seasonally stratified correlation analysis shown in Sect. 4 and principal component analysis in Appendix 1.

Our analysis strategy is to employ a series of statistical analyses to find out the relationship between Amazon rainfall and the surrounding oceanic SST on interannual time scales. Correlations along with case-by-case analyses were performed. Circulation structures and water vapor flux associated with anomalous SSTs over different basins are constructed using composite analysis. Principal component analysis is also employed to summarize previously identified patterns of interannual variability that is presented in the Appendix 1.

3 Interannual variability of Amazon rainfall and surrounding oceanic SST

To investigate the relationship between surrounding oceanic SST anomalies and the interannual variability of Amazon rainfall, a correlation map of SST with an Amazon-basin rainfall index is presented in Fig. 1. Two regions of high correlation are noted: the tropical Pacific Ocean and the tropical Atlantic Ocean. It has been well documented that the Amazon rainfall changes in accordance to the phase of the Pacific Ocean SST (e.g., Ronchail et al. 2002; Ropelewski and Halpert 1987; Zeng 1999). Yet, relatively little attention has been given a possible Atlantic influence on Amazon rainfall. Some studies (Marengo 1992) also focus on Pacific influence on both the Amazon and the Atlantic, rather than assessing the Atlantic as an independent forcing of rainfall variability. The significant correlation between Amazon rainfall and Atlantic SSTs in Fig. 1 suggests that tropical Atlantic SSTs can play a significant role in determining interannual variability of Amazon rainfall, particularly during Amazon's dry season (Fig. 1c). The tropical Pacific has stronger correlation during the Amazon's wet season (Fig. 1b). Correlation with the tropical South Atlantic Ocean is weaker, but is significant in during the wet to dry transition season as will be discussed later.

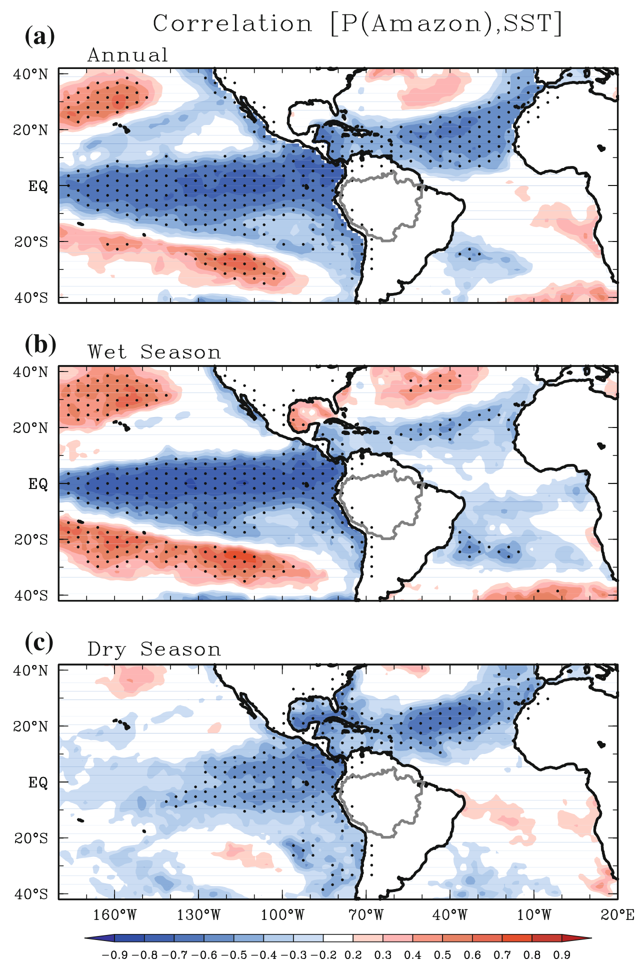

Fig. 1 Correlation patterns of SST with Amazon rainfall index (shown in Fig. 3) using all-season anomalies, wet (December–April), and dry (July–October) seasons in **a**, **b** and **c**, respectively. Two distinct regions of high correlation (tropical Pacific and tropical North Atlantic) are observed. Interestingly, Amazon rainfall has high correlation with Pacific SST during the wet season and Atlantic SST during the dry season. *Dotted areas* are statistically significant at the 95% confidence level, using a sample size of 28 years. The outline of the Amazon drainage basin is shown as a *thick gray line*

3.1 Correlation of SST with basin-averaged rainfall and runoff correlation

Correlation patterns of observed rainfall and SST are constructed with three SST indices: with a typical indicator of the Pacific ENSO, Niño-3.4; an index for the tropical North Atlantic (NATL) following Enfield and Mayer (1997); and an SST index averaged over the tropical South Atlantic (SATL) in Fig. 2. These patterns provide us better insight into how these three SST regions affect Amazon rainfall. Both Niño-3.4 and NATL have significant correlation with Amazon precipitation in general, but their spatial patterns have different characteristics (Fig. 2a, b). The most interesting result is that the North Atlantic correlation is highest over the southern Amazon. Although the ENSO influence is stronger and wide-spread, it has stronger impact toward the river mouth. The correlations with Niño-3.4 and NATL are significant at the 95% confidence level over a large area of the Amazon basin (marked as a dot in Fig. 2). A much clearer picture emerges here, as compared to earlier attempts to diagnose the Atlantic-Amazon connection (Marengo 1992; Ronchail et al. 2002). The NATL influence has a distinct center in the southern part of the Amazon. It is likely that this region of the Amazon was not well studied by scientific research because of reliability/scarcity of data. In recent years, especially after the 1970s, satellite coverage of this region become more regular. This is why our study uses OPI as our primary rainfall dataset. The SATL SST impacts rainfall along the coastal regions of Brazil. Note that Nordeste rainfall (northeastern Brazil) is correlated to both the NATL and SATL indices, and also that the NATL and SATL variabilities are spatially in quadrature, so that the former affects the entire region, while the latter has a north-south pattern. A couple of cautionary notes have to be made here that correlation analysis based on all season anomalies might provide an oversimplistic view about tropical South Atlantic SSTs (Fig. 2c), and secondly that the three basins could be inter-correlated.

Different sub-regions of the Amazon do not always vary in the same way (e.g., Uvo et al. 2000) and as shown in Fig. 2. The Pacific and Atlantic influences have different 'center of action' within the Amazon basin. Nevertheless, the Amazon Basin-averaged rainfall is used here as an index for the Amazon's overall hydroecological variability that can be compared with, e.g., the runoff data.

It is illuminating to see the interplay between the Pacific and Atlantic impacts on Amazon rainfall on an event-by-event basis, based on the Amazon rainfall index versus the three SST indices (Fig. 3). It appears that whenever there is a major ENSO event (warm El Niño events: 1982–83, 1986–87, 1991–92, 1997–98; cold La Niña events: 1988–89, 1999–2000), Amazon rainfall variability is dominated

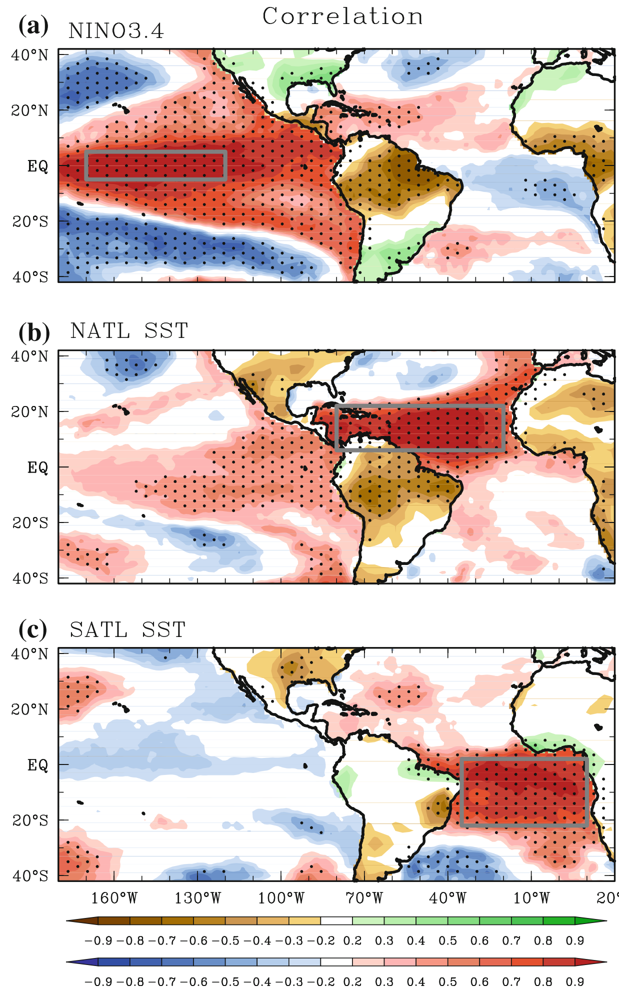

Fig. 2 All-season anomaly correlation of rainfall (land) and SST (ocean) with three SST indices: Niño-3.4 (°C), tropical North Atlantic SST (°C) averaged over the domain of 6–22°N and 80–15°W, and South Atlantic SST averaged over the domain of 25°S–2°N and 35°W–10°E (*boxed areas*) in **a**, **b**, and **c**, respectively. Both Niño-3.4 and NATL indices exhibit strong negative correlation with Amazon rainfall. *Dotted areas* are statistically significant at the 95% confidence level, using a sample size of 28 years

by the Pacific Ocean influence. When ENSO is weak and the NATL is warm (1979–80, 1994, 2005), the Atlantic SST has a large impact. In 1984, there was a cold NATL case, with strong warming in the South Atlantic and cooling in the North Atlantic during an ENSO transition phase, leading to a wet Amazon that year. In 2005, both Niño-3.4 and SATL were weak, but a warm North Atlantic led to the drought. However, it is not clear whether such a relation is fundamental or spurious. In general, severe Amazon droughts happen when both the eastern Equatorial Pacific and the North Atlantic are warm (positive Niño-3.4 together with positive NATL), such as in 1983 and 1987. However, some of the North Atlantic warming during the spring may be caused by El Niño, which peaks in Boreal winter, thus exacerbating the direct El Niño drought in the

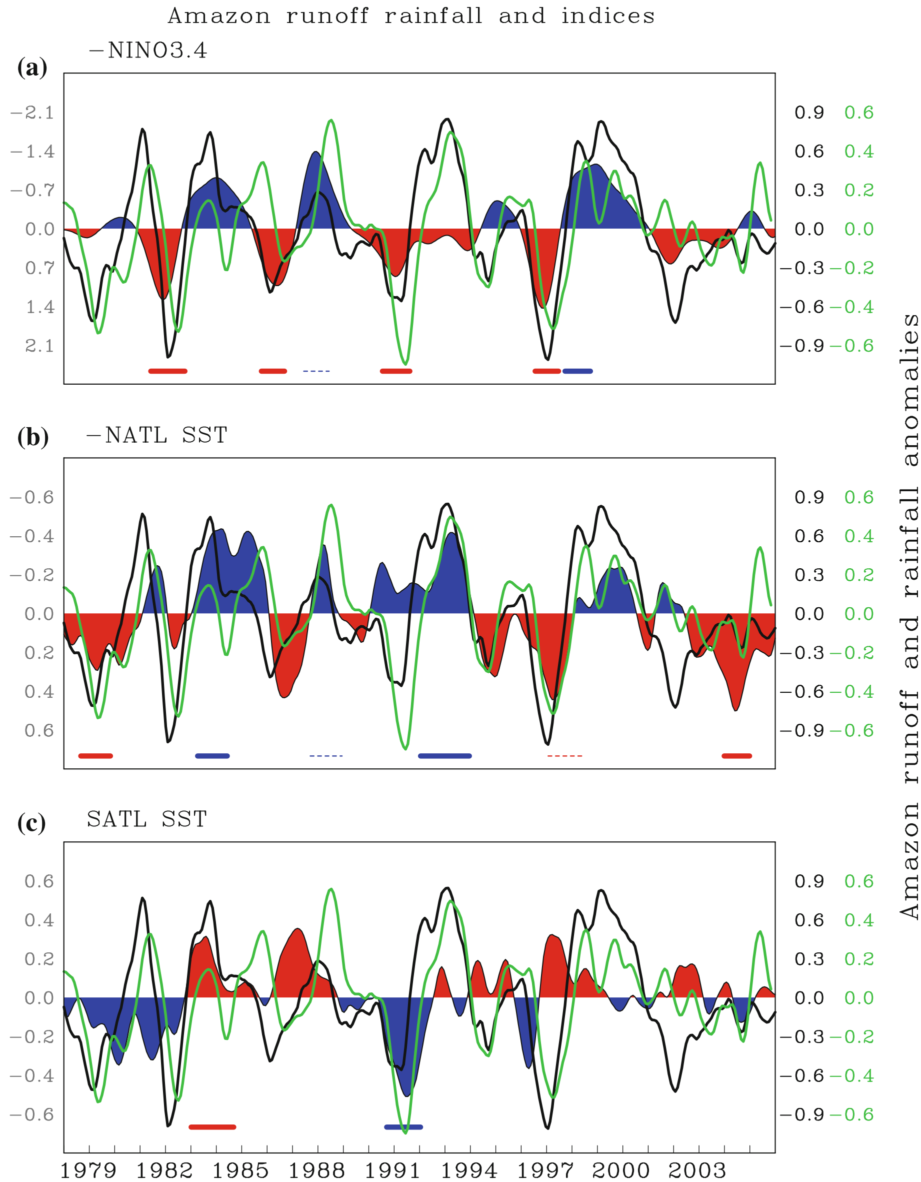

Fig. 3 The Jan1979–Dec2006 time series of the three SST indices (blue and red shaded curves labeled on the left), runoff observed at Obidos (mm day^{-1}; *green line*), and rainfall (mm day^{-1}; *black line*) averaged over the Amazon from OPI. The *short horizontal bars* indicate the events during which the corresponding index had a major influence on Amazon rainfall (following Zeng et al. 2008). Also, some events with a minor influence on Amazon rainfall are identified as short dashed bars. The signs of NINO3.4 and NATL indices are reversed in this figure and the following correlation plots in order to make both Amazon rainfall and SST indices in the same phase. Yet, positive (negative) anomaly of SST is shaded red (*blue*) color that warmer (colder) Pacific or North Atlantic correlates with dry (wet) condition over Amazon

Amazon (Giannini et al. 2001). In addition, events such as the South Atlantic warming in 1984 may be also partially related to the 1982–83 El Niño. Nonetheless, Atlantic warming is often not related to El Niño, and severe drought in the Amazon is more likely to occur when warm spells in the eastern equatorial Pacific and North Atlantic happen either near-simultaneously (such as 1997–98) or sequentially (such as during 2002–2005). Since ENSO influence is typically locked to boreal winter, while the Atlantic impact can be more seasonally variable. Hence, their combined influence may be complex (Giannini et al. 2004). Nevertheless, the examination of the individual events is consistent with the multiple regression analysis shown later, and the results suggest promising prospects for predicting Amazon precipitation and the hydrological cycle on interannual timescales by focusing on the Pacific ENSO signal and Atlantic SST because more than half of the variance can be predicted based on these alone. Such potential has been demonstrated by empirical streamflow forecasts for individual rivers (Uvo et al. 2000), and analysis here provides a basis for basin-wide hydro-ecological prediction.

The linkage between Amazon rainfall and the surrounding oceanic SSTs can be quantitatively measured by coefficients in multiple linear regression analysis with the Amazon basin averaged rainfall and SST indices following Zeng et al. (2008). Correlation between the Niño-3.4 index and Amazon average rainfall from the OPI data is 0.66 (43% of the rainfall variance). The correlation between NATL and Amazon rainfall is 0.50 (25% of the variance), while SATL correlation is 0.12 (1.4% of the variance). These correlation values do not exclude possible influence

Table 1 Multiple linear regression analysis of different rainfall datasets and runoff observed at Obidos with SST averaged over Niño-3.4, tropical North Atlantic, and tropical South Atlantic Ocean basins

	Pacific	North Atlantic	South Atlantic	Variance (R^2) (%)
OPI	−0.50	−0.44	0.01	53.7
PRECL	−0.34	−0.25	0.27	33.9
GPCC	−0.63	−0.20	0.19	55.3
Runoff	−0.51	−0.28	0.15	47.3
GPCP	−0.58	−0.03	0.01	34.8
CMAP	−0.58	−0.02	0.02	33.9

A 5 month lag is applied to the Amazon runoff to maximize variance (R^2) explained by these three indices

from different basin SSTs. Thus, a multiple regression analysis is performed to obtain independent contribution from three SST indices. Amazon rainfall (p) is best predicted as

$$\mathrm{p} = -0.50 \times \mathrm{nino3.4} - 0.44 \times \mathrm{natl} + 0.01 \times \mathrm{satl}, \qquad (1)$$

where lower italic case (p, nino3.4, natl and satl) indicates the variable normalized by its variance. When the three indices are combined as above, the multiple regression coefficient is 0.73, explaining 53% of the Amazon rainfall variance, much higher than for Niño-3.4 alone. This suggests the North Atlantic influence on the Amazon is highly significant over the last 28 years. Yet, the South Atlantic influence is not significant due to cancelation in spatial and seasonal dependency, which will be discussed in later section. A caveat is that these numbers, including the relative importance of Niño-3.4 and NATL, depend somewhat on the rainfall dataset used. For example, the same computations with CMAP (Xie and Arkin 1996) and GPCP (Adler et al. 2003) are dominated by the Pacific influence (Table 1). A couple of encouraging facts are, however, that (1) gauge-based rainfall estimates including PRECL (Chen et al. 2002) and GPCC (Rudolf et al. 2005) support the connection between the Atlantic Ocean and Amazonian rainfall, and that (2) runoff measurements correspond very well with basin-averaged rainfall with some lag (Zeng 1999), also exhibiting strong Atlantic influence. Runoff observed at Obidos (1°54′S, 55°30′W; drainage area 4,640,300 km^2) can be predicted as:

$$\mathrm{runoff}_t = -0.51 \times \mathrm{nino3.4}_{t-5} - 0.28 \times \mathrm{natl}_{t-5} + 0.15 \times \mathrm{satl}_{t-5}. \qquad (2)$$

This runoff observations are from January 1979 to October 2006. A minor portion of the Amazon River (including the River Tapajos, the Xingu River, and the area near the Amazon River mouth) is not accounted for at the Obidos station. However, it covers about 90% of the whole Amazon basin. A 5 month lag is applied to the runoff time series to maximize the variance explained by the three indices. The combination of the three indices above explains 54% of the interannual variability of the runoff observed at Obidos, much higher than for Niño-3.4 alone (21%), suggesting the Atlantic influence on the Amazon is highly significant over the last 28 years. Uncertainty due to difference in results from the various rainfall datasets can be avoided here, because runoff integrates the rainfall over the river basin.

Lagged correlation analyses (Fig. 4) show that precipitation lags Niño-3.4 by 3–4 months, while runoff lags by about 7 months, consistent with Zeng (1999). While runoff lags North Atlantic SST by 1 month, Amazon rainfall leads North Atlantic SST by 4 months. This leads to an apparent puzzle: how could the North Atlantic influence on Amazon rainfall, as suggested by the analysis above, actually lag Amazon rainfall? Also, one can argue that part of the Atlantic influence may originate from the Pacific because of a lagged Atlantic SST response to ENSO-induced trade wind change (Enfield and Mayer 1997; Giannini et al. 2001), so that the independent contribution from the Atlantic may be smaller. The answers to both puzzles lie in the complex interaction between the Pacific and the Atlantic and will be analyzed in Sect. 4. First, however, a physical mechanism behind the Atlantic influence on Amazon rainfall will be examined.

3.2 Circulation structures and mechanism

Rainfall over the Amazon basin is sustained by both evapotranspiration, which is recycled from local sources (Salati and Nobre 1991) and convergence of water vapor flux, which is associated with regional and large-scale circulation structures (Chen 1985). The east-west Walker circulation and the local meridional divergent circulation, which can be called as Atlantic Hadley cell (Wang 2002), are important constituents in seasonal climatology, as well as interannual variability. For example, it has been shown that anomalous Walker circulation is a key mechanism linking the Pacific SST anomaly and wet/dry conditions over the Amazon basin (Kousky et al. 1984; Marengo and Hastenrath 1993; Neelin and Su 2005). Similarly, it has also been hypothesized that anomalous displacement of the Inter-tropical Convergence Zone (ITCZ), associated with the local north-south divergent circulation could be a mechanism linking the Atlantic SST and Amazon rainfall on interannual timescales. Such a mechanism connecting the Atlantic Ocean and tropical South American rainfall has been studied in the past (Moura and Shukla 1981), but the focus was on northeastern Brazil (Nordeste), not the heart of Amazon. This Atlantic influence on the heart of the Amazon was recently examined by Zeng et al. (2008) and Marengo et al. (2008b) with respect to the 2005 Amazon

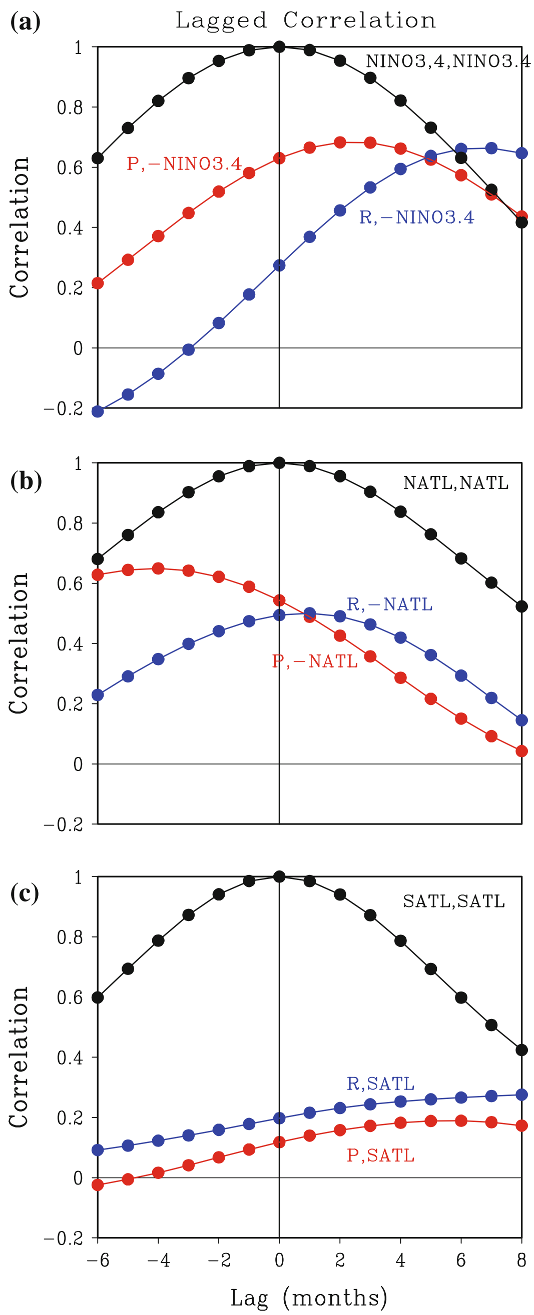

Fig. 4 Lagged correlations of Amazon rainfall (P) and observed runoff at Obidos (R) with the three SST indices: Niño-3.4, SST(NATL), and SST(SATL). Black curve indicates autocorrelation, while blue (red) represents lagged correlation of Amazon rainfall (runoff) with SST indices. *Positive lag* indicates SST index leading Amazon rainfall and runoff. The signs of NINO3.4 and NATL indices are reversed as in Fig. 3

drought. Anomalously warm (cool) SSTs over the tropical North Atlantic Ocean could alter (1) north-south divergent circulation in such a way that the upward (downward) branch is moved to the tropical North Atlantic Ocean (the Amazon basin), eventually (2) reducing (increasing) inland low-level moisture flux. Thus, rainfall over the southern Amazon would vary following enhanced or reduced moisture flux from the tropical Atlantic Ocean. To substantiate our hypothesis, composite analysis was performed using meteorological reanalysis data (Kanamitsu et al. 2002).

Compositing is a useful tool to understand characteristics of the extreme phases of cyclic phenomena, which tracks the anomalously warm or cold tropical North Atlantic Ocean in our case, using a criteria of larger (smaller) than +0.8 (−0.8) standard deviation of the tropical North Atlantic SST index shown in Fig. 3. Rainfall and sea surface temperature are shown in Fig. 5a. It is clear that anomalously dry conditions at the southern Amazon, as well as in the Nordeste region, are observed when the tropical North Atlantic Ocean is warm. During cold NATL periods, opposite patterns are found (not shown). Rainfall and SST patterns are consistent with our previous correlation analysis in Fig. 2.

Moisture flux during warm North Atlantic Ocean (Fig. 5b) events reveals that net divergent moisture flux out of tropical South America is observed, which is an opposite pattern of climatology (Zeng 1999). Also, a suppressed low-level water influx from the Gulf of Mexico toward the Great Plains, and reduced trade winds are interesting characteristics associated with a warm North Atlantic Ocean. These can be explained by parts of the suppressed North Atlantic High in the lower troposphere in the regional or basin-scale circulation. Anomalous warming of the tropical North Atlantic Ocean generates an anomalous circulation pattern in such a way as to suppress the North Atlantic High in the lower troposphere, and was found both in an analytical solution and by numerical model experiments (Moura and Shukla 1981). Although their study was confined to the Nordeste, it is shown here that an anomalous circulation excited and maintained by an anomalously warm North Atlantic Ocean can be extended to the Amazon basin, thus affecting water vapor flux, and finally Amazon rainfall. Further, the influence of Atlantic Ocean SST anomalies on Europe, North America, Africa, and the northeastern region of South America in inter-decadal time scales has been studied (Sutton and Hodson 2005). A positive Northern Hemisphere SST anomaly produces a northward cross-equatorial wind stress anomaly and anticyclonic circulation in the warmer subtropics. The northern counterclockwise wind anomaly acts to weaken the background northeast trade winds, while the southerly wind anomaly strengthens the background southeast trade winds.

Only divergence or convergence of moisture flux, as opposed to values of the total field, matter in maintaining anomalous rainfall, according to the moisture budget equation (Zeng 1999). Linkage between the divergent component of circulation and anomalous rainfall can be

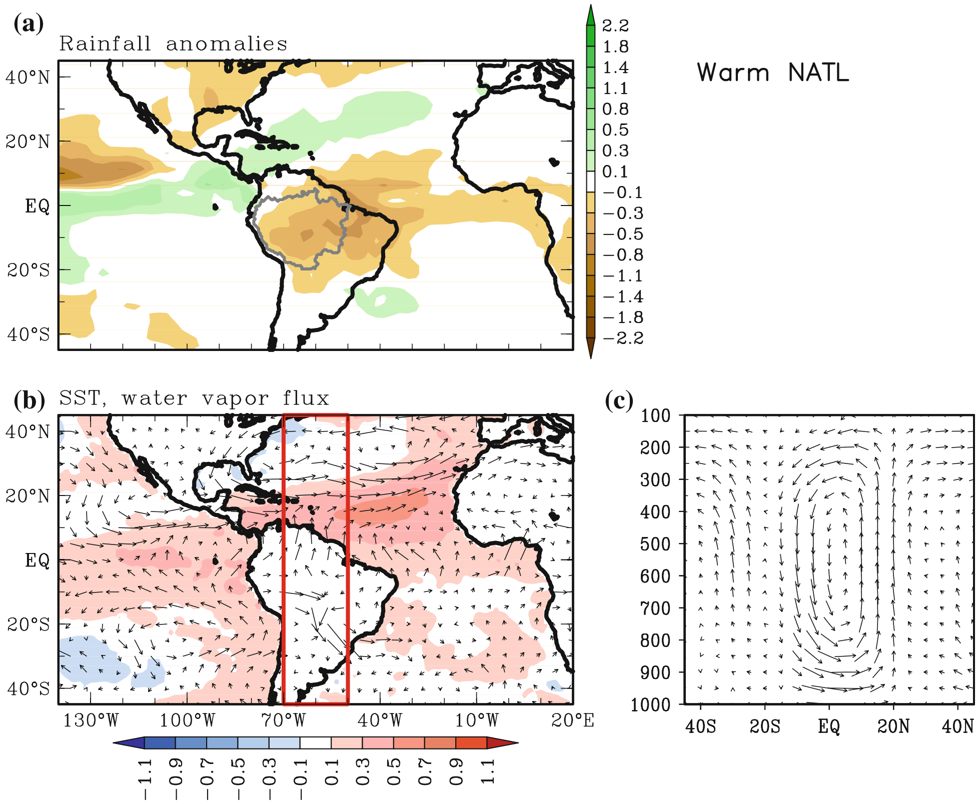

Fig. 5 The composite patterns with the warm North Atlantic SST condition of (**a**) rainfall (**b**) SST and atmospheric water vapor flux, and (**c**) local north-south divergent circulation, or Atlantic Hadley Cell in Wang (2002). SST data is from the Hadley Center and atmospheric wind and water vapor flux are constructed from NCEP-R2 reanalysis. Cross-section of local north-south divergent circulation (v_D, $-\omega$) is averaged over 70–50°W (indicated by the *red box* in **b**)

established by utilizing the meridional circulation composed of divergent meridional wind (v_D) and the negative vertical pressure velocity ($-\omega$), as shown in Fig. 5c. A hypothesized mechanism is that warmer SST (Fig. 5b) over the North Atlantic induces anomalous convergence at the lower level and positive vertical motion. This altered divergent circulation results in anomalous divergence at the lower level and downward motion branch over the Amazon basin (Fig. 5c), which is linked to moisture flux divergence anomaly and reduced rainfall (Fig. 5b). The reverse occurs when the North Atlantic becomes anomalously cold (not shown).

4 Differences in seasonal characteristics between Pacific and Atlantic

The Atlantic and Pacific influence on Amazon rainfall has spatial differences as discussed in previous section. In this section, seasonal characteristics between Pacific and Atlantic influence on Amazon rainfall will be analyzed. In doing so, it will be demonstrated that the Atlantic influence on Amazon rainfall is as important as the Pacific's influence, and that the correlation shown in the previous section is not merely due to Pacific's dominant role in both regions. Some previous studies have also noticed that a correlation between the Atlantic Ocean and Amazon rainfall becomes stronger during boreal autumn (Ronchail et al. 2002), while the ENSO linkage is particularly strong during the rainy season (boreal winter and spring). First, seasonal phase locking of the Atlantic SST variability and seasonally stratified correlation between surrounding SSTs and the Amazon rainfall will be analyzed.

The phase locking of ENSO to the seasonal cycle is well known (Rasmusson and Carpenter 1982). The majority of observed ENSO events over the past 100 years, as measured by the peak time of Niño-3 index, occur during the northern winter season (Tziperman et al. 1998). It is natural to raise the question as to whether the interannual variability of the Atlantic Ocean SST is phase-locked with the seasonal cycle. To answer this question, the standard deviation of three indices (sea surface temperature averaged over Niño-3.4, and the North and South Atlantic regions) are computed for each calendar month. Sea surface temperature over the Niño-3.4 region has maximum variability in December (Fig. 6b) and the SOI has its maximum in February, lagging by 2 months after the observed SST maximum (not shown). This maximum variability of the tropical Pacific SST during the winter season leads the Amazon rainy season (Fig. 6a) by about 2-3 months, which is consistent with the time lag shown in Fig. 4b. In contrast, neither the Northern nor the Southern Atlantic SST index exhibits seasonally dependent variability. Overall, the standard deviation of SST in the tropical Atlantic Ocean is smaller than that in the equatorial Pacific, but nevertheless it is capable of influencing Amazon rainfall.

Rainfall over the Amazon basin shows a profound seasonal cycle, with the rainy season occurring from December to April with maximum rainfall in February, and a dry season from June to October with minimum rainfall in August (Fig. 6a). Hydro-ecological implications of reduced dry season rainfall were examined earlier (e.g., Zeng et al. 2008). If rainfall is less than 100 mm for a month, evergreen rain forests would perish (Sternberg 2001). The role of the dry season rainfall played in the hydro-ecosystem over this region becomes an important issue in terms of climate feedback. Small changes in rainfall amount during the dry season can have large impacts on the Amazon rainforest, which in turn increases surface albedo (Zeng et al. 1996, 2008). Also, it has been found that changes in external oceanic and internal land surface feedbacks resulting from increasing atmospheric CO_2 could lead to a decrease of rainfall and persistent drought over the Amazon. This has the potential to cause "dieback" of the rainforest and further increase atmospheric CO_2 in the 21st century (Cox et al. 2000, 2004, 2008).

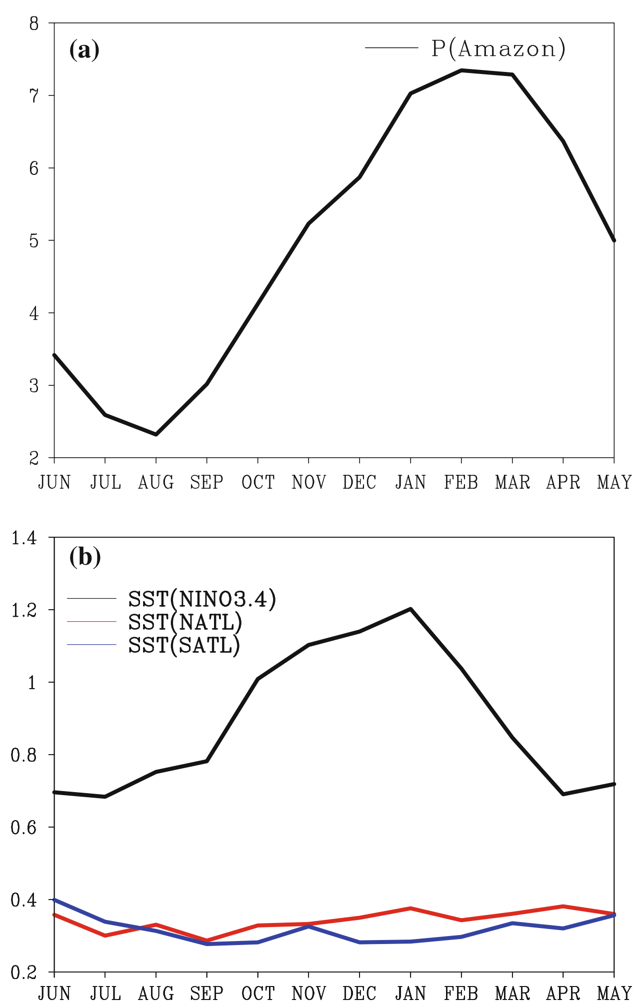

Fig. 6 Seasonal cycle of Amazon rainfall (mm day^{-1}) in **a**, and standard deviation of the three SST indices (°C) over Niño-3.4, NATL, and SATL regions at each calendar month in **b**

Next, we analyze whether there is any seasonal preference of correlation between the tropical North Atlantic oceanic SST and Amazon rainfall. The seasonally-stratified correlation between the Amazon rainfall index and three indices (sea surface temperature averaged over Niño-3.4, the North Atlantic, and the South Atlantic) is computed for every season (Fig. 7) (following Mariotti et al. 2002). ENSO has higher correlation with Amazon rainfall during the Amazon's rainy season (December–February), with maximum correlation over 0.7 (black dot). Meanwhile the tropical North Atlantic Ocean SST has the lowest correlation. Also, the North Atlantic influence on Amazon rainfall is consistent throughout the year at better than 95% significance, except during Amazon's rainy season. Interesting information contained in Fig. 7 is that the South Atlantic influence on Amazon rainfall becomes significant during boreal spring (May and June), consistent with the case-by-case analysis in Fig. 3, whereas the correlation map in Fig. 2 does not show strong correlation between these two. It is likely that tropical South Atlantic SST has strong seasonal preference in influencing rainfall over South America (Kushnir et al. 2006).

Differences in seasonal characteristics between the Pacific and Atlantic become more obvious when the

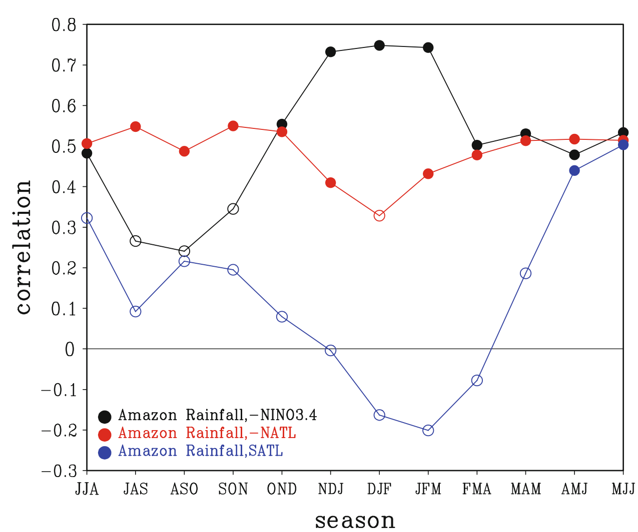

Fig. 7 Seasonally stratified correlation between Amazon rainfall (OPI) and Niño-3.4, SST averaged for the North Atlantic (NATL), and the South Atlantic (SATL). *Closed circles* are used for values which are significant at the 95% confidence level, while *open circles* are for non-significant values. The signs of NINO3.4 and NATL indices are reversed

Amazon's wet and dry seasons are considered. The wet season of the Amazon is from December to April, while its dry season is from June to October (Fig. 6a). The spatial map of correlation between SST indices (NATL, Niño-3.4, and SATL) and SST along with rainfall during these dry and wet seasons (Fig. 8) illuminates whether differences in seasonal characteristics affect patterns in Fig. 2 (where every calendar month is used). Tropical North Atlantic influence on South American rainfall is stronger during the Amazon dry season, but it migrates southward during the wet season, following the location of the ITCZ. This further demonstrates that our hypothesized mechanism (the anomalous local north-south divergent circulation shown in Fig. 5c), plays a role in connecting the Amazon and the Atlantic Ocean. An interesting feature is that during the wet season, Atlantic SST has higher correlation with tropical Pacific SST (Fig. 8b) than during the dry season (Fig. 8a). On the other hand, the Pacific influence on Amazon rainfall during the Amazon wet season is over the entire basin (Fig. 8d). It has very limited influence during the Amazon dry season toward the northern and eastern part of the basin (Fig. 8c). The tropical South Atlantic SST has limited influence over the southern edge of the basin during the dry season (Fig. 8e), consistent with previous studies (Ronchail et al. 2002, 2005). Instead, its influence is more important in the transition season of May–June (Fig. 7). Overall, the Pacific is still the key player, since it exerts influence during the Amazon wet season when most rain events occur. However, the role played by the Atlantic SST is also important. The role of the Atlantic is likely higher in terms of hydroecological impact because of the critical importance of the dry season rainfall to the regional ecosystem. It is worth pointing out that no significant influence from the Pacific is found during the dry season (Fig. 8c).

5 Separation of the Pacific from the Atlantic influence on Amazon rainfall

One of remaining pieces of the puzzle is the examination of whether Atlantic influence on Amazon rainfall is not simply due to indirect Pacific influence. It is known that approximately half of the variance of tropical Atlantic SSTs on interannual timescales is driven by remote forcing (Liu et al. 2004), specifically ENSO and the North Atlantic Oscillation (NAO) (Chang et al. 2003; Czaja et al. 2002; Huang et al. 2002; Saravanan and Chang 2000; Sutton et al.

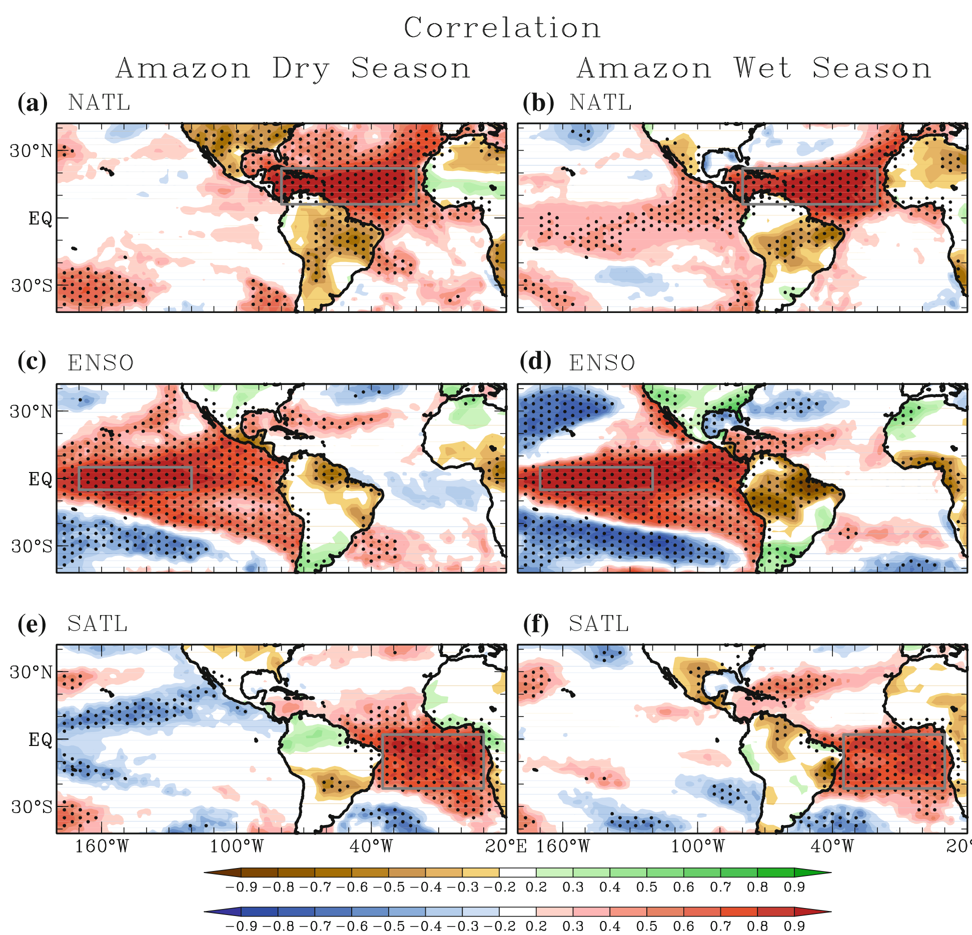

Fig. 8 Correlation map of North Atlantic SST, ENSO, and South Atlantic SST indices with rainfall and SST during the Amazon's dry (June–October) and wet (December–April) seasons like Fig. 2. *Dotted areas* are statistically significant at the 95% confidence level, using a sample size of 28 years

2000). For example, warming of the tropical Atlantic Ocean during 1984 and 1998 was likely triggered by the preceding El Niño events in the Pacific. These events tend to occur during northern spring, 4-5 months after the peak of ENSO, which occurs in northern winter (Enfield and Mayer 1997). However, the tropical Atlantic does appear to exhibit variability that is independent from external forcings (Carton and Huang 1994).

A question is whether significant correlation between the tropical North Atlantic SST and Amazon rainfall is independent of tropical Pacific variability. To shed light on this issue, the signal associated with ENSO is removed from simple linear regression analysis in the following way:

$$\mathrm{SST(NATL)}_{\mathrm{NoENSO}} = \mathrm{SST(NATL)} - \gamma \times \mathrm{Nino3.4}(t + \mathrm{lag}), \qquad (3)$$

where γ represents the regression coefficient between low-pass filtered tropical North Atlantic SST and Niño-3.4. In our computation, an 8-month lag is introduced based on lead-lag correlation (not shown), consistent with previous studies (Enfield and Mayer 1997). This approach has certain limitations, but has been adopted by previous researchers (e.g., Mariotti et al. 2005). After removing ENSO from Atlantic variability in this way, seasonally-stratified correlation is recomputed (Fig. 9). Compared to the original correlation (red line in Fig. 9 as well as in Fig. 7), the spring and early summer Atlantic-Amazon correlations are reduced below the significance level (green line in Fig. 9), but it remains higher during the Amazon dry season. This supports that Atlantic influence on Amazon during boreal spring season is ultimately caused by the Pacific SST variability. Such a delayed response in the Atlantic to ENSO has long been known (Giannini et al. 2001), but it is interesting to know that the Atlantic acts as an agent to extend Pacific influence through a delayed pathway. In contrast, the Atlantic exerts strong influence on Amazon rainfall during the northern fall season regardless of whether ENSO is removed or not, strongly suggesting that the independent Atlantic influence is concentrated mainly in this season. In the case of South Atlantic SST, no significant change compared to Fig. 7 was observed using the same procedure, apart from overall reduced value (not shown).

Our last puzzle is that of the apparent lag of Atlantic SST behind Amazon rainfall (Fig. 4b, red line), which contradicts the conventional notion that the SST is a cause of rainfall variability over Amazon. It turns out that this paradox can be explained by the strong influence of the Pacific SST on both Amazon rainfall and Atlantic SST. In other words, Amazon rainfall lags ENSO by about 2–3 months. At the same time, ENSO leads the tropical North Atlantic SST by about 4–6 months (Enfield 1996). Therefore, Amazon rainfall appears to be 'leading' the North Atlantic SST. The same procedure as in Eq. (3) was used to remove the Pacific ENSO variability from the SST over the tropical North Atlantic for a low-passed time series. Sea surface temperature over the North Atlantic with ENSO

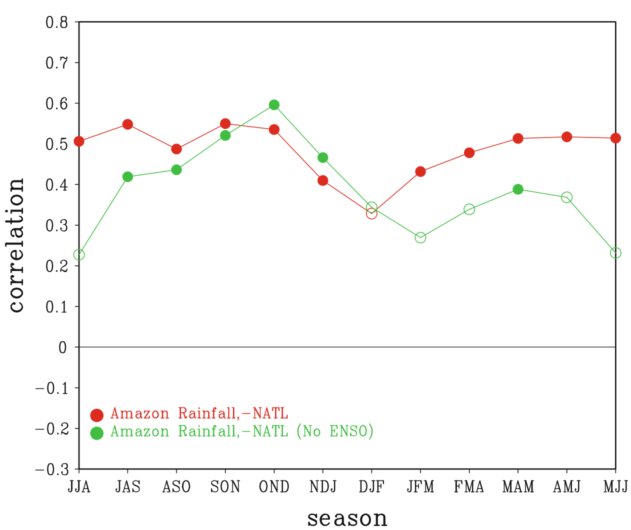

Fig. 9 Seasonally stratified correlation between Amazon rainfall and North Atlantic SST with or without ENSO. Removing ENSO from the North Atlantic SST is achieved by using linear regression as shown in Eq. (3). In the case of South Atlantic SST, an overall decrease of correlation compared to Fig. 7 was observed (not shown). The sign of NATL index is reversed as in Fig. 7

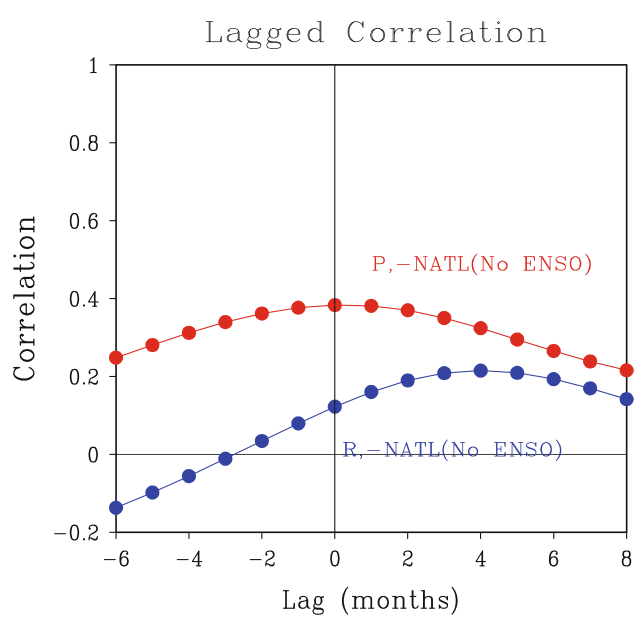

Fig. 10 Lagged correlation of Amazon rainfall using OPI (*red*) and runoff at Obidos (*blue*) with SST averaged over the tropical North Atlantic Ocean with ENSO removed. ENSO has been removed for the period of 1983–2006. The sign of NATL index is reversed as in Fig. 4

removed does not lag, but rather is in phase with Amazon rainfall (Fig. 10). In other words, the apparent lead of Amazon rainfall compared to the SST over the tropical North Atlantic is largely due to the mutual connection to ENSO.

This complex interplay between Pacific and Atlantic Ocean influence on rainfall is not only limited to the Amazon basin. It was shown that over the Caribbean and the southern United States, the tropical North Atlantic SST anomaly has comparable influence on rainfall anomalies to that of the Pacific Ocean. This linkage becomes even stronger during the rainy season (Enfield and Elfaro 1999). More interestingly, the strongest response is observed when the tropical Atlantic is in the configuration of a meridional dipole (antisymmetric across the ITCZ) and the eastern tropical Pacific SST anomaly is of opposite sign to the tropical North Atlantic. Although this part of the Atlantic SST anomalies is forced by ENSO, knowledge of an Atlantic influence is likely to improve seasonal forecasts and assist understanding of climate change.

6 Discussion and conclusion

The Atlantic influence on Amazon rainfall was analyzed using diagnostic approaches with multiple rainfall estimates and atmospheric reanalysis. Correlation and compositing methods were employed to establish an Amazon-Atlantic linkage not only in statistical sense but also in a dynamical perspective using anomalous circulation structures. The tropical North Atlantic SST has an influence comparable to the Pacific SST, while the South Atlantic SST seems to have limited impact. However, seasonally stratified correlation analysis demonstrates that the SATL can have a stronger influence toward the southern edge of the basin during the early dry season. The NATL influence is stronger over the the southern Amazon during the dry season when ENSO has limited activity.

Our main findings are summarized as follows:

- Warming (cooling) of the tropical North Atlantic could induce dry (wet) conditions over the Amazon basin. The influence of North Atlantic SST is stronger on the southern Amazon and during the dry season. In contrast, ENSO's influence is stronger over the entire basin (with its maximum influence toward the river mouth) especially during the wet season. A mechanism responsible for the Amazon and Atlantic linkage is anomalous north-south divergent circulation. Warming (cooling) of the tropical North Atlantic Ocean induces downward (upward) motion over the Amazon basin, resulting in reduced (increased) moisture flux convergence and below (above) normal rainfall. Because of seasonal migration of rainfall and this local north-south divergent circulation, this NATL influence exhibits meridional migration so that during the wet season its influence moves southward.
- Because of the influence of ENSO on both the Atlantic SST and Amazonian rainfall variability, the linkage between the tropical North Atlantic SST and Amazon rainfall is somewhat complex. Stronger correlation between these two during boreal spring and the apparent lead of Amazon rainfall over the North Atlantic SST is a result their mutual connection with ENSO. The Atlantic linkage becomes stronger during the dry season in Amazonia, when ENSO has limited activity.
- Using multiple-linear regression, it was found that a combination of Niño-3.4 and North Atlantic SST explains 53% of Amazon rainfall variability (with 25% from Niño-3.4, 20% from North Atlantic). Although sub-basin variability for the northern and southern sub-basins correlates with different SSTs during different seasons (Figs. 7, 8), the area-averaged rainfall index over the 6,000,000 km^2 basin can provide us insight into how these three SSTs influence Amazon rainfall as a whole.

The tropical South Atlantic SST plays a role in determining interannual variability of Amazon rainfall during boreal spring and summer seasons (Fig. 7), with spatial extent over the Atlantic coasts of tropical South America and the southern edge of the Amazon basin. The mechanism responsible for the SATL influence is an anomalous local Hadley circulation over this region (Xie and Carton 2004). Although its impact on Amazon rainfall seems small in an all-season correlation, its influence becomes significant over the southern edge of the basin during the early dry season (Huang and Shukla 2005; Kushnir et al. 2006; Ronchail et al. 2005). Note that further analysis with station data may be able to better detect localized influence from the tropical South Atlantic Ocean.

We have identified a clear linkage between rainfall variability in the heart of the Amazon basin and the Atlantic that is pronounced during the southern Amazon's dry season. Such an influence may be particularly important from an impact point of view, as the hydro-ecosystem would be most vulnerable at the end of the dry season, as shown in the 2005 Amazon drought (Marengo et al. 2008a, b; Zeng et al. 2008). There may be an important implication for possible future climate change, as a longer dry season is projected in most of the coupled climate models (Li et al. 2006).

Our study is mainly based on diagnostic analysis using observational datasets. Although a case study by Zeng et al. (2008) used NCAR CAM to demonstrate the possible

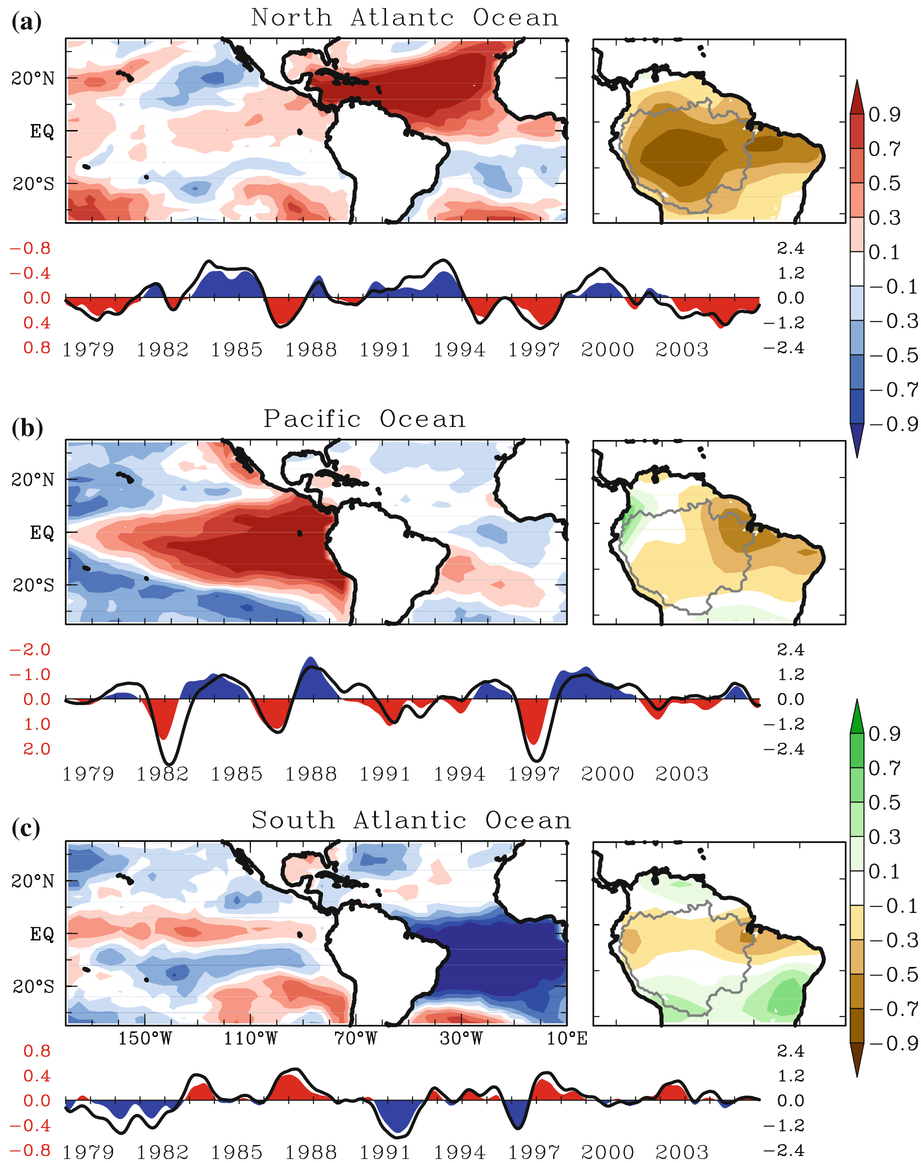

Fig. 11 Rotated Multivariate EOF (RMEOF) of rainfall (Xie and Arkin 1996) over tropical South America (north of 22°S) and SSTs (Rayner et al. 2003) over the tropical Pacific and Atlantic Oceans. The contour interval is 0.2 (°C and day^{-1}). The variance of precipitation over the Amazon explained by these three modes is 57.9% for North Atlantic SST, 30.4% for tropical Pacific SST, and 7.8% for South Atlantic SST

impact of Atlantic SST on the 2005 Amazon drought, further research in this direction using both atmospheric general circulation models forced by observed SST for long-term simulation, or coupled climate model simulations would confirm the Amazon-Atlantic linkage, as well as its interplay with Pacific SST (e.g., Good et al. 2008; Pezzi and Cavalcanti 2001). Also, any interaction with the underlying land-surface condition could be understood in a more mechanistic way (e.g., Fu and Li 2004). It is interesting to note that the southern edge of the Amazon basin has been deforested (D'Almeida et al. 2007). So how tropical SSTs and human interference affect the ecosystem over this region is an important issue. Better understanding of these influences can provide valuable information for projecting the future of the Amazon rainforest (Cox et al. 2008).

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Appendix 1: Emperical orthogonal function (EOF) analysis

Principal component analysis has been used to identify coherent interannual variability patterns over the Atlantic Ocean (e.g., Ruiz-Barradas et al. 2000). Here, rotated multivariate (rainfall and SST) EOF is adapted to summarize our findings. Conventional approaches are taken, such as normalization by individual variables' standard deviation, and the first five eigenmodes meeting a criterion of explaining >5% of the variance each (together they explain more than 68%) were then rotated, while preserving the orthogonality in time, but relaxing it in space. In particular, the total number of grid points for both variables have been adjusted using interpolation, to reduce the possibility that one variable dominates the other. By relaxing the spatial orthogonality constraint, the spatial patterns of the rotated eigenvectors should be more directly related to the natural patterns of variability in the physical system (Richman 1986), and becomes more useful in identifying localized variability in Atlantic Ocean (Dommenget and Latif 2002). A number of algorithm choices are possible for rotation. Here the varimax method is used following Kaiser's (1958) approach.

To emphasize the relative roles of different oceanic SSTs on Amazon rainfall, we rank our eigenmodes in decreasing order of local variance over the Amazon basin rather than following a conventional decreasing order of global variance of each mode. To achieve this, each reconstructed eigenmode [Z(x,y,t)] is obtained by multiplying its eigencoefficient [C(t)] and eigenvector [E(x,y)], in other words projecting these modes back to the time-space domain. The standard deviation of Amazon basin averaged rainfall of each eigenmode is computed. The first three modes, using this local variance ranking, are displayed in Fig. 11.

One of the advantages of the RMEOF is isolation of the temporally orthogonal variability. It is well known that both tropical Atlantic oceanic SSTs and Amazon rainfall are affected by the interannual variability of the tropical Pacific Ocean (e.g., Enfield 1996; Zeng 1999). By employing this RMEOF, we can present three different patterns of interannual variability, connecting Amazon rainfall and the surrounding oceanic SST's. Tropical North Atlantic and Pacific influence on Amazon rainfall variability in interannual timescales are actually separated in RMEOF analysis. These patterns are arranged in the decreasing order of its influence on Amazon rainfall variability. The largest pattern is associated with the North Atlantic Ocean (58%). The second and third ones are related to the tropical Pacific Ocean (30%), and the South Atlantic Ocean (8%), respectively. These magnitudes of variance are slightly different from those obtained from multiple linear regression. This could be due to numerical relaxation of orthogonality for the spatial pattern. For example, the western side of the tropical Atlantic Ocean is more closely correlated with tropical ENSO (Enfield and Mayer 1997). Yet, this analysis separates the western Atlantic variability from the Pacific variability, so that some portion of variance in the first pattern (Fig. 11) might not be pure Atlantic influence on Amazon rainfall. Consistent patterns of interannual variability with previously identified ones are found in Fig. 11. Also, this is consistent with observations and model results which show that the SST over the tropical Atlantic affects the interannual variability of climate over the Nordeste and the eastern Amazon (Hastenrath and Heller 1977; Marengo 1992; Moura and Shukla 1981; Ronchail et al. 2002). The influence of Pacific SSTs on the interannual variation of South American rainfall is concentrated over the northern part of the Amazon and northeastern Brazil (Nordeste).

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