IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS

Environ. Res. Lett. **3** (2008) 014002 (9pp) doi:10.1088/1748-9326/3/1/014002

Causes and impacts of the 2005 Amazon drought

Ning Zeng[1,2,7], Jin-Ho Yoon[1], Jose A Marengo[3],
Ajit Subramaniam[4], Carlos A Nobre[3], Annarita Mariotti[2,5] and
J David Neelin[6]

[1] Department of Atmospheric and Oceanic Science, University of Maryland, MD 20742, USA
[2] Earth System Science Interdisciplinary Center, University of Maryland, MD 20742, USA
[3] CPTEC, INPE, Cachoeira Paulista, Brazil
[4] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA
[5] ENEA Casaccia, Rome, Italy
[6] Department Atmospheric and Oceanic Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095, USA

E-mail: zeng@atmos.umd.edu

Received 19 November 2007
Accepted for publication 21 January 2008
Published 30 January 2008
Online at stacks.iop.org/ERL/3/014002

Abstract

A rare drought in the Amazon culminated in 2005, leading to near record-low streamflows, small Amazon river plume, and greatly enhanced fire frequency. This episode was caused by the combination of 2002–03 El Niño and a dry spell in 2005 attributable to a warm subtropical North Atlantic Ocean. Analysis for 1979–2005 reveals that the Atlantic influence is comparable to the better-known Pacific linkage. While the Pacific influence is typically locked to the wet season, the 2005 Atlantic impact concentrated in the Amazon dry season when its hydroecosystem is most vulnerable. Such mechanisms may have wide-ranging implications for the future of the Amazon rainforest.

S Supplementary data are available from stacks.iop.org/ERL/3/014002

Keywords: climate, Amazon rainforest

1. Introduction

The 2005 drought in the Amazon was particularly severe in the western and southern parts of the basin (figure 1) where many rivers and lakes had lowest water levels in years. The drought had large impact on transportation, fishery, agriculture, fire and health in the region. In the public media, this drought has been linked to climate change, deforestation, and an anomalously warm North Atlantic Ocean that was thought to also have contributed to an energetic hurricane season [1], but the scope of the drought and the underlying cause has remained unclear. Here we analyze an extensive set of datasets and also use climate model to show the causes and impacts of this unusual drought.

2. Changes in rainfall, SST and atmospheric circulation

The rain gauges in this remote region are relatively sparse and their quality is not always high. We have therefore analyzed 10 datasets including 9 global precipitation datasets based on gauge and satellite and one analysis specifically for South America (see supplementary information for details available at stacks.iop.org/ERL/3/014002). In addition, we conducted our own gauge analysis by applying a highly stringent station selection criterion. We found a spatially coherent rainfall reduction over much of the Amazon basin during 2005 (figure 1(a)). The general dryness as shown in our own gauge analysis (figure 1(b)) is corroborated by satellite observations which have better spatial coverage, including the OPI outgoing longwave [2] (figure 1(a)) and TRMM/TMI + PR microwave precipitation products. Only parts of the lower Amazon

---

[7] Address for correspondence: Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742-2425, USA. http://www.atmos.umd.edu/~zeng.

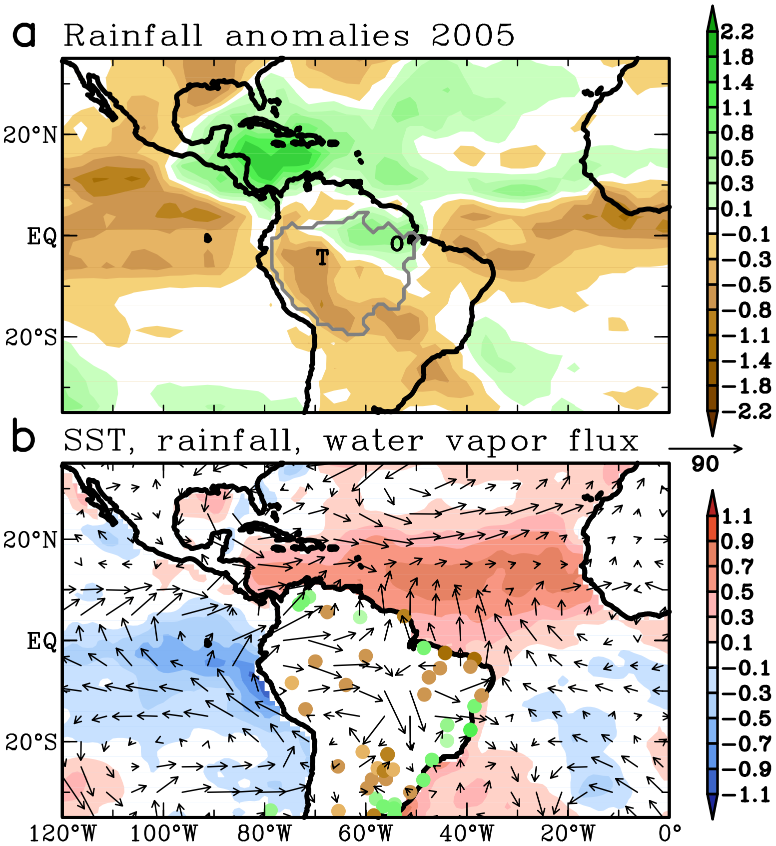

Figure 1. Anomalies for January–December 2005 relative to the means of 1979–2005 of (a) rainfall based on the OPI (outgoing longwave radiation precipitation index) [2] in mm d^{-1}; (b) station rainfall (color filled circles; same color scheme as in (a)) over South America from the GHCN network [3], SST (degree celsius) over the ocean [4], and vertically integrated moisture transport (arrows) from the NCEP/NCAR R2 reanalysis [5] in kg m^{-1} s^{-1}. The outline of the Amazon drainage basin is shown as a gray line.

drainage basin had above-normal rainfall. Such a pattern is consistent with anecdotal evidence on the ground which indicates severe drought in southwestern Amazon in the Brazilian provinces of Acre, Rondonia, Amazonas, and Mato Grosso.

Changes in rainfall and atmospheric circulation are consistent with the notion of an Atlantic origin: above-normal rainfall over the warmer tropical North Atlantic Ocean, a typical atmospheric convection response to warm sea surface temperature (SST). The rising motion in the north generates subsidence in the south over the Amazon and the South Atlantic Ocean, a sea-saw like modification to the South America–Atlantic section of the Hadley circulation and a northward shift of the intertropical convergence zone (ITCZ). As a result, reduced rainfall is seen across western and southern Amazon, equatorial Atlantic Ocean and the African Guinea Coast. The atmospheric moisture transport indicates a clear reduction in Atlantic moisture into the Amazon (figure 1(b)) which normally (climatology) flows westward up the Amazon river and turns southward along the Andes.

Two major issues immediately arise. Firstly, precipitation over the Amazon is thought to be largely controlled by the El Niño Southern Oscillation (ENSO) originating in the equatorial Pacific Ocean [6–8]. However, the equatorial Pacific was largely neutral during 2005. If anything, there were cold SST anomalies in the eastern Pacific toward the end of the year (figure 2) normally associated with a wetter Amazon. The large SST anomalies in the northern tropical Atlantic (figure 1(b)) are the potential influences that we evaluate here. However, while Atlantic SST influences on the ITCZ and rainfall in northeastern Brazil and West Africa Sahel have long been noted [9], an Atlantic linkage to the heart of the Amazon Basin is not well established [10, 11], hampered in part by sparse raingauge data of uncertain quality. Another perplexing issue is the severity of the drought. As shown in figure 3(a), 2005 had relatively small rainfall change, compared to, e.g., the large 1997–98 drought, seemingly inconsistent with the extremely low river and lake levels seen by people living in the region.

Part of the answer to the latter question comes from the observation that the major El Niño events such as 1997–98 and 1982–83 that led to large negative rainfall anomalies in the Amazon were short lived (about 1 year), and often immediately followed by La Niña events that led to anomalously wet conditions which allowed land to recover quickly from the dryness. In contrast, although the 2005 rainfall anomaly was not particularly large, it was preceded by another dry period of 2002–03 (an El Niño year), with little recovery in 2004, which had lingering central Pacific warm conditions. Thus precipitation stayed below normal for 4 years from 2002 to the end of 2005. The effect of the long duration of below-normal rainfall can be better seen by the standardized precipitation index (SPI; figure 3(c)) which shows the year 2005 to be one

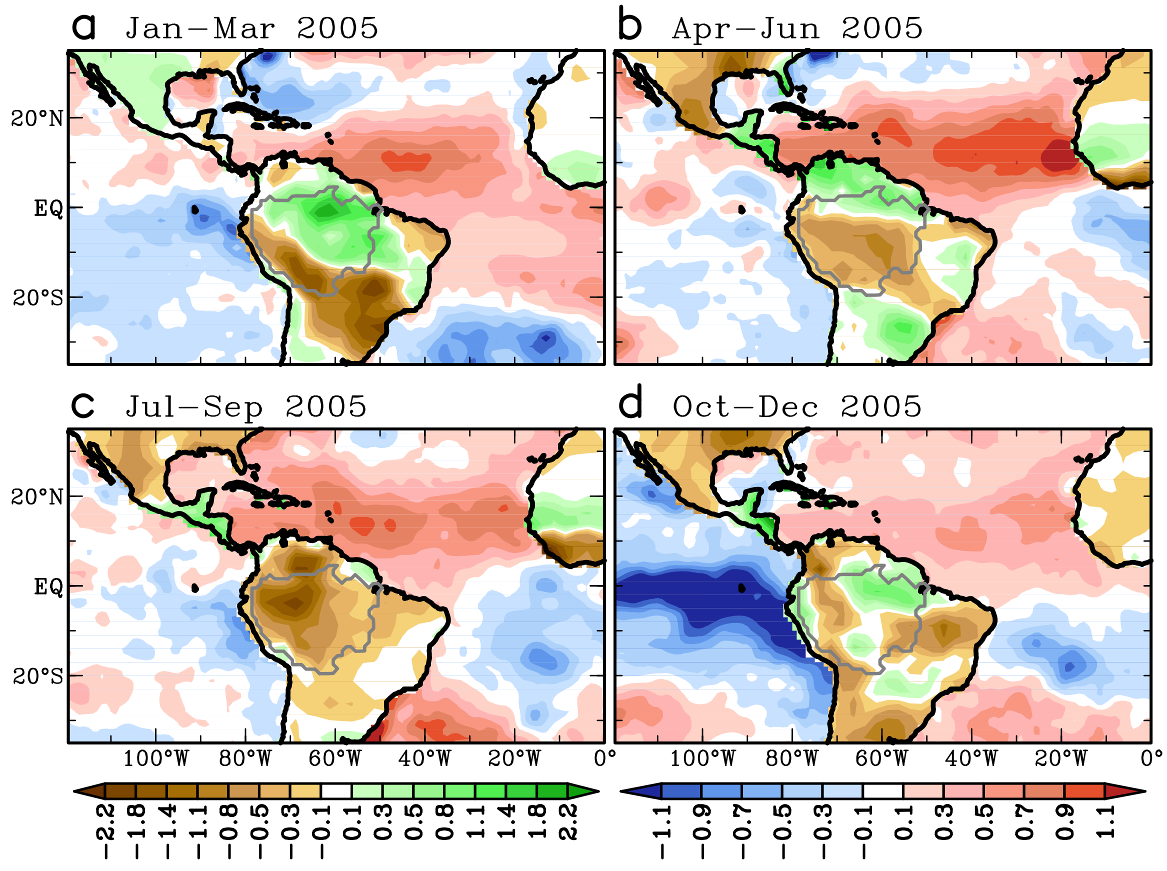

Figure 2. Rainfall (OPI, mm d^{-1}) and SST (degree Celsius) anomalies for the four 3-month periods of 2005, showing the evolution of the Amazon drought. The drought was most severe during the dry season Jul–Sep when everywhere in the Amazon rainfall was reduced. Note the small La Niña cold event during Oct–Dec.

of the driest since 1979. Since SPI effectively represents the cumulative effect of rainfall [13], and the river and lake levels partly indicate the amount of soil moisture and underground water which percolate slowly into the rivers, it is a better indicator of hydrological drought than rainfall (meteorological drought)[8].

The other half of the answer to the severity question lies in the seasonal evolution of 2005 drought, in particular its behavior during the dry season. Averaged over the whole basin (dominated by the larger southern Amazon), the Amazon wet season is from November to April, and dry season from June to September, with runoff lagging by about 3 months [8]. As seen in figure 2, Amazon rainfall reductions were most extensive from April to September 2005 when subtropical North Atlantic SST was warmest. The dry spell somewhat led but mostly coincided with the climatological dry season, thus contributing to the extremely low water levels. This dry season Atlantic impact is in contrast to the typical ENSO influence which is locked to the boreal winter, i.e., the Amazon wet season.

3. Impact on the hydrology and ecosystem

The impact and the severity of the long-lasting 2002–2005 drought can be clearly seen in several other important hydroecological indicators (figures 3–6). The Amazon streamflow measured at Obidos (captures rainfall from about 90% of the total Amazon drainage basin) shows an unusually long and slow decrease since 2000, culminating in late 2005, a trend consistent with the precipitation anomaly. Since the 2005 rainfall deficit was mostly in the southwestern Amazon (figure 1(a)), we also show river stage (height of river level) at Tabatinga (a station on the Solimões River, the main stem of the Amazon), which captures the rainfall from the upper Amazon basin with source water mostly from the eastern Andes. The Tabatinga river stage shows a rapid drop in 2005, but it lacks the several years of slow decrease seen in the Obidos streamflow. This is because the 2002–03 El Niño impact was mostly in the lower Amazon basin (below). The Tabatinga river stage was one of the lowest in the 24 year period analyzed.

The seasonal cycle in the Amazon is large so that the drought impact on the ground was felt mostly as a particularly severe dry season when water level is at its lowest. To capture the seasonal aspects, the 9 years with

---

[8] Meteorological drought typically refers to below-normal rainfall with sufficient duration, while hydrological drought describes prolonged depletion of water on land as seen in river and lake level, soil moisture, ground water, etc. See, e.g., the 'Glossary of Meteorology' at http://amsglossary.allenpress.com/glossary. A timescale needs to be chosen for SPI by the user to characterize the duration of the drought. In figure 3(c) we used a timescale of 18 months. When 24 months was used (not shown), the drought in 2005 had the lowest SPI since 1981, as a result of the long duration of the 2002–05 drought. This 'arbitrariness' in the choice of timescale is unavoidable using only precipitation as a drought indicator.

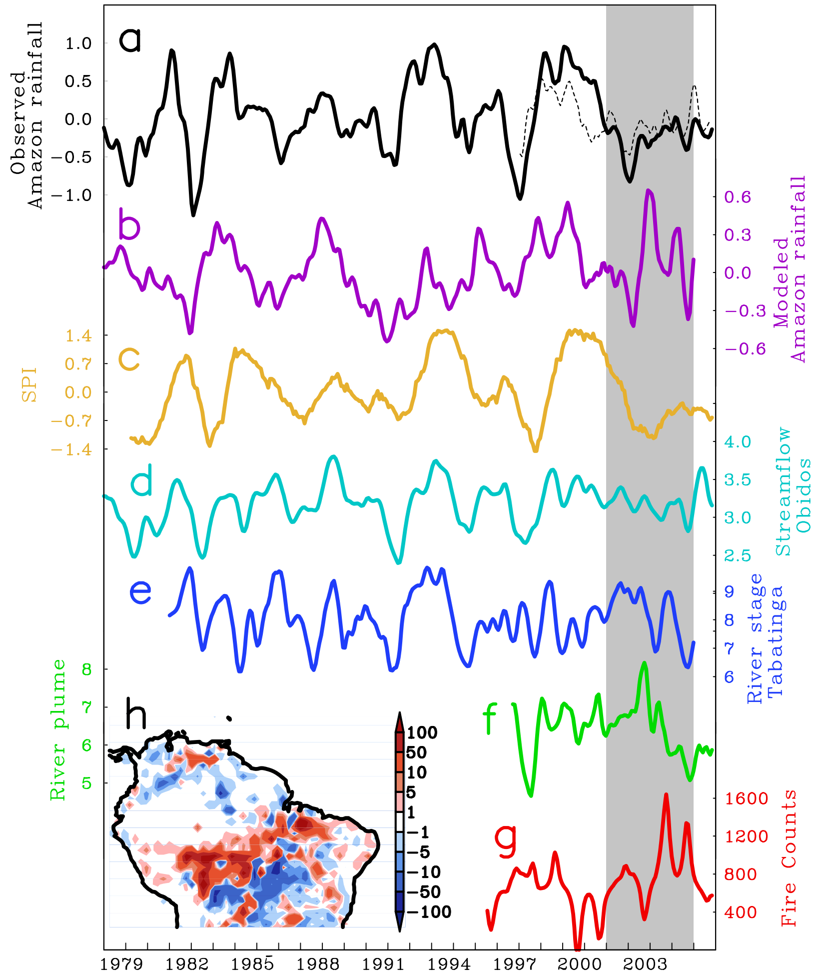

Figure 3. Interannual variations of rainfall and related variables from January 1979 to December 2006 for the Amazon drainage basin: (a) rainfall (mm d^{-1}) from OPI (solid black line) and from the TRMM/TMI/PR (dashed black line); (b) Amazon rainfall simulated by the NCAR/CAM2 atmospheric model; (c) the standardized precipitation index (SPI) derived from OPI precipitation, showing the cumulative effect of rainfall by using a timescale of 18 months [13]; (d) streamflow (10^5 m^{3}s^{-1}) at Obidos (marked by letter O in figure 1(a)); (e) river stage (metres) at Tabatinga (marked by letter T in figure 1(a)); (f) size of the river plume (100 000 km^2) generated by the Amazon freshwater runoff into the Atlantic ocean based on satellite-derived salinity; (g) satellite fire counts (number of fires per month) summed over the whole Amazon basin; (h) the spatial pattern of 2005 fire counts anomalies (per year per 1° × 1° box; for instance, a value of 10 means that there were 10 fire counts more in the year of 2005 in that box) relative to the average of 1998–2004, showing much higher fire frequency in the southern Amazon (by several folds in some area); note that nearly all fires take place during the dry season as can be seen in the sharp peaks in figure 3(g) and figure S3g (available at stacks.iop.org/ERL/3/014002). A low-pass filter based on a first-order Butterworth function [12] with half-amplitude at 12 month was applied to all the timeseries to remove higher frequency variability, and the 2002–2005 drought period is shaded in gray.

lowest streamflow for Obidos and river stage for Tabatinga are shown in figure 4. These are ranked in the legend by the lowest monthly value in any given year regardless of which month the minimum occurred (the original monthly timeseries are shown in supplementary figure S3 available at stacks.iop.org/ERL/3/014002). By this criterion, 2005 (in October) was the second driest after 1997 (in November) for Obidos, while it was the second driest (September) after 1988 (September) for Tabatinga. Thus, for both stations, 2005 was the second on record for the respective analysis period. This of course does not exclude some Amazon tributaries from breaking record in 2005, especially in the most drought-prone regions, as suggested in the news. At the height of the drought, Obidos streamflow was 32% lower than long-term climatology, while Tabatinga river stage was lowered by 2.4 m compared to climatology, 29% of the seasonal amplitude. The rainfall averaged over the corresponding catchment basins for April–October 2005 was the lowest (figure 5), thus breaking record in the data period analyzed. The importance of lowest water level at the end of the dry season cannot be over-emphasized because this is when the hydrological cycle, ecosystem and human activities that depend on them are most vulnerable.

A dramatic indicator of the 2002–05 drought was enhanced fire occurrence over the southern Amazon, as indicated by the satellite observed fire counts [14] (figures 3(g) and (h)). Summed over the whole basin, fire in 2005 was more than twice as frequent as the average of the previous 7 years. Typically, fire in the Amazon occurs at the end of the dry season around the periphery of the rainforest in a so-called ‘arc of fire’ (primarily the deep-colored regions in figure 3(h)). In

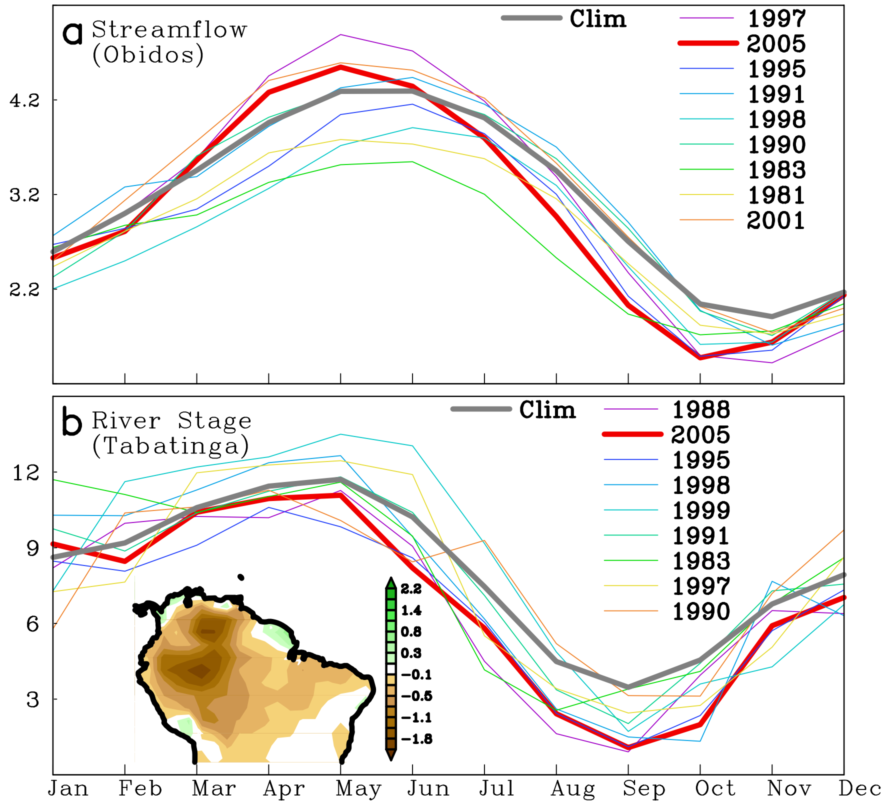

Figure 4. The 'driest' years for (a) the whole Amazon basin as indicated by the streamflow measured at Obidos (1.9°S, 55.5°W; marked by 'O' in figure 1(a); in 10^5 m^3s^{-1}) and (b) the upper Amazon basin (Solimões River) as river stage measured at Tabatinga (4.25°S, 69.9°W; marked by 'T' in figure 1(a); in metres). Year 2005 is in thick red, long-term climatology (1979–2005 for Obidos, 1982–2005 for Tabatinga) is in thick gray. Other dry years are thin lines in different colors. These 'driest' years were chosen and ranked in the legend according to the lowest water level in that year (which could be either in September or October), and they often but not always correspond to the lowest precipitation years, e.g., year 2005, as streamflow depends on cumulative precipitation, evapotranspiration and soil water storage. The inset in (b) is Jul–Sep 2005 rainfall anomaly in mm d^{-1} as in figure 2.

2005, nearly the whole southern Amazon basin along this 'arc' had more fire. Major increases were found in the provinces of Rondonia and Mato Grosso, with several times more than normal in some places. Although fire in this region is mostly ignited by humans, drought makes the forest more prone to burning. The relative roles of their effects are difficult to delineate at present.

A novel connection is the Amazon river plume in the Atlantic Ocean generated by the Amazon freshwater runoff. Here absorption of light due to colored dissolved organic matter (CDOM) dominates total absorption and there is a high correlation between salinity and CDOM absorption [15]. Thus satellite-derived light attenuation can be converted to salinity and used to estimate plume size and location (figure 6). The climatological monthly plume size is highly correlated with the river discharge at Obidos with correlation 0.98 while the interannual anomaly correlation is 0.58. Thus satellite-derived plume size can be considered a measure of the integrated Amazon runoff although other factors such as surface winds and currents also influence plume size. The 2005 plume size (area within the 34.7 salinity contour) was 15% smaller than the mean annual plume size and the size in December 2005 was the smallest over the 9 years of measurements (supplementary figure S3 available at stacks.iop.org/ERL/3/014002). Biological drawdown by diatom diazotroph associations found in the Amazon plume may sequester between 14 and 20 TgC annually [16]. Thus, changes in the plume size, as a consequence of changes in precipitation patterns, may have an impact on the carbon and nitrogen cycles in the tropical Atlantic.

In summary, the variety of hydrological and ecological indicators suggest that there was indeed a major drought over the Amazon, culminating in 2005, and with wide-ranging hydroecological impact. This was the result of a 'one-two-punch' combination from the 2002–03 El Nino and 2005 Atlantic warming with large dry season rainfall reduction.

4. Role of the Atlantic versus Pacific Ocean

An Atlantic influence is also supported by climate model experiments using the National Center for Atmospheric Research Community Atmosphere Model (NCAR/CAM2)[9]. When forced with observed SST, the model does a reasonable

---

[9] A newer version of the model (CAM3) is also available, but CAM2 does a better job in simulating the main features of Amazon climatology as well as variability, we therefore used CAM2. In general, tropical land convective rainfall is challenging for current models to simulate and the degree of agreement between figures 3(a) and (b), or figures 7(a) and (b), is less than satisfactory but is state-of-the-art.

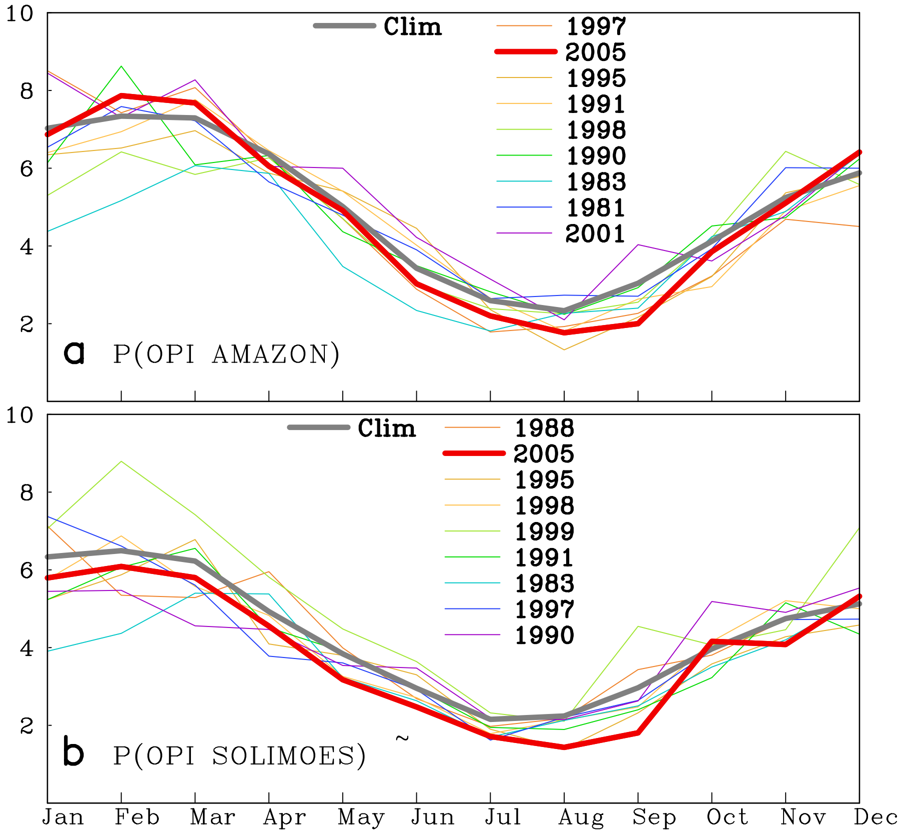

Figure 5. Similar to figure 4, but for rainfall over (a) the Obidos catchment (most of the Amazon) (b) the Tabatinga catchment (the upper Amazon). These 'driest' years were chosen and ranked according to the corresponding streamflow/river stage data as shown in figure 4, not rainfall itself. Calculation shows that the average June–September rainfall in 2005 was the lowest in the 27 year period, although the corresponding streamflow/river stage was the second lowest due to higher rainfall in earlier seasons.

job in reproducing the observed interannual rainfall variability including the drought in 2005 (figure 3(b)). The spatial pattern of enhanced rainfall north of the ITCZ and reduced rainfall over southern Amazon is well represented, though the location of the rainfall anomalies is somewhat shifted compared to the observations (figure 7). A model sensitivity experiment was conducted using SST anomalies from the tropical Atlantic only, with climatological values in the rest of the world ocean. The results show that tropical Atlantic SST alone can produce much of the precipitation increase in the subtropical North Atlantic and drying over South America including the southern Amazon (figure 7).

To further identify the relative roles of the Atlantic and the Pacific Ocean on the long-term Amazon climate variability, figure 8 shows the correlation of observed rainfall with the Southern Oscillation Index (SOI), an atmospheric indicator of ENSO, and with the SST averaged over tropical North Atlantic (NATL) and SST averaged over the tropical South Atlantic (SATL). Both SOI and NATL have significant correlation with Amazon precipitation, but the spatial patterns differ. The ENSO correlation has highest values around the Amazon river mouth but significantly weaker in the southern Amazon. The North Atlantic correlation is highest over northeastern Brazil and a large expanse of southern Amazon. Since southern Amazon has the largest area and highest climatological rainfall rate among its subregions, the importance of the Atlantic Ocean is thus elevated for the Amazon basin as a whole. South Atlantic SST also shows a large-scale correlation pattern, but the signal is much weaker over the Amazon basin[10]. The correlations with SOI and NATL are significant at 95% level over large area of the Amazon basin. Compared to earlier studies on Atlantic–Amazon connection [10, 11], a much clearer picture emerges here, largely due to the judicious use of satellite based data after a careful analysis of the multiple precipitation datasets and streamflow data.

The correlation between the SOI index and Amazon average rainfall from the OPI data is 0.52 for the period of 1979–2005, explaining 27% (the square of the correlation) of the rainfall variance. The correlation between NATL and Amazon rainfall is 0.57, explaining 33% of the variance, while SATL correlation is 0.12, explaining 1.4% of the variance. A multiple regression analysis with these 3 indices as the predictors for Amazon average rainfall P shows that P is best predicted as

$$p = 0.42\text{soi} - 0.52\,\text{natl} + 0.07\,\text{satl}$$

---

[10] We have also examined an SST gradient index (tropical North Atlantic minus South Atlantic) because their effects tend to have opposite sign [9] (figure 8), though they are only weakly correlated on interannual timescale. The results indicate that treating NATL and SATL separately lead to higher correlation achieved at weighting factors significantly different from (1:-1) (see the multiple regression analysis in text).

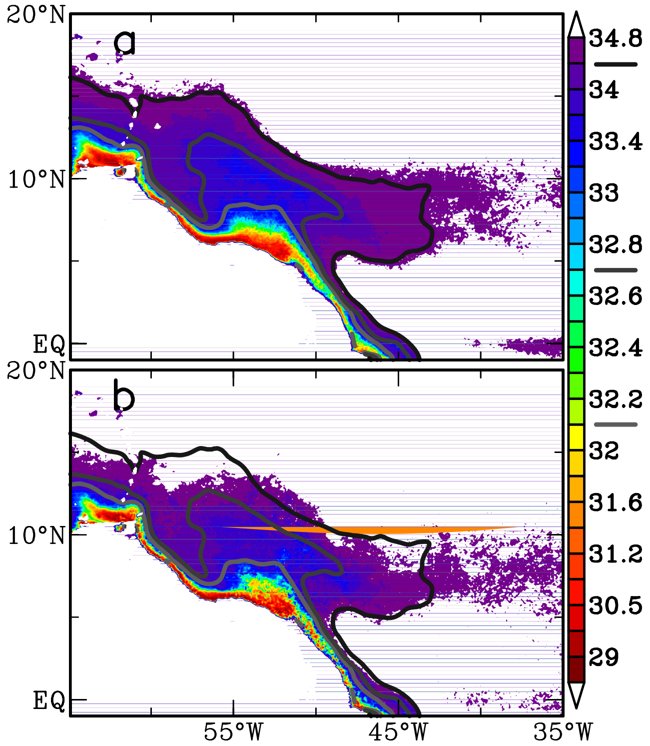

Figure 6. Amazon river plume in the Atlantic Ocean as indicated by satellite observed salinity (psu) based on light attenuation [15]: (a) average for 1998–2004; (b) year 2005. Lower salinity is mostly due to fresher water input from the Amazon river. Three contours corresponding to 34.7, 33.9, 33.4 in (a) are also overlaid on (b) so the 'shrinking' of the plume area in 2005 can be better visualized.

where lower case (p, soi, natl and satl) indicates the variable normalized by its own 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 SOI alone, suggesting the Atlantic influence on the Amazon is highly significant over the last 27 years, not just 2005. A caveat is that these numbers, including the relative importance of SOI and NATL, depend somewhat on the rainfall dataset used, so that we can only conclude that Atlantic SST influence on the Amazon rainfall may be comparable to the Pacific.

Since ENSO typically peaks during boreal winter with rainfall change mostly over the lower Amazon, while the Atlantic connection is not seasonally locked with the largest impact in southwestern Amazon, their combined influence is complex and varies from event to event. This is further complicated by a partial influence of ENSO on North Atlantic SST [17, 18]. Regardless of these challenging questions that need to be elucidated by further research, our results suggest promising prospect for predicting Amazon precipitation and 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 SST-based empirical streamflow forecasts [19], and the modeling and analysis here provide a basis for basin-wide hydroecological prediction.

5. Conclusion

The recent drought in the Amazon highlights the sensitivity of its hydrology and ecosystem to prolonged drought conditions, as opposed to large short-lived ones. The rainforest has adapted to seasonal and short-term drought by strategies such as water uptake by deep roots [20], but may be less resilient to longer term change. The recent IPCC AR4 climate model simulations predict rainfall reduction in the Amazon [23], possibly due to a combination of changes in the Pacific and Atlantic SSTs as well as overall warming-induced changes [21]. Although the causes of 2005 drought and future scenarios may differ, similar impact mechanisms likely underly the risk of possible alteration to the Amazon ecosystem and carbon cycle [22, 23]. Because the dry season behavior is central to water level, fire stress and other factors that are of paramount importance to the hydroecosystem and human activities, and the dry season is also when these land processes may have strong feedback to

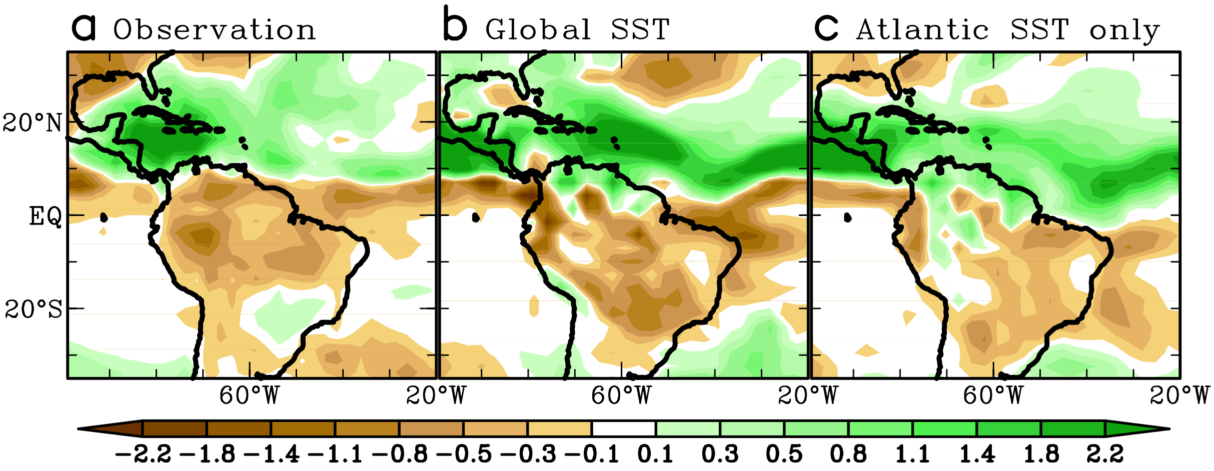

Figure 7. Rainfall anomalies (mm d^{-1}) for June–November 2005 (dry season) (a) from OPI observation; and simulated by the NCAR/CAM2 atmospheric model forced by observed (b) global SST; (c) tropical (between 20°S and 20°N) Atlantic SST only; most of the 2005 drying over the Amazon and the wetting of the subtropical North Atlantic was caused by the warming in the North Atlantic.

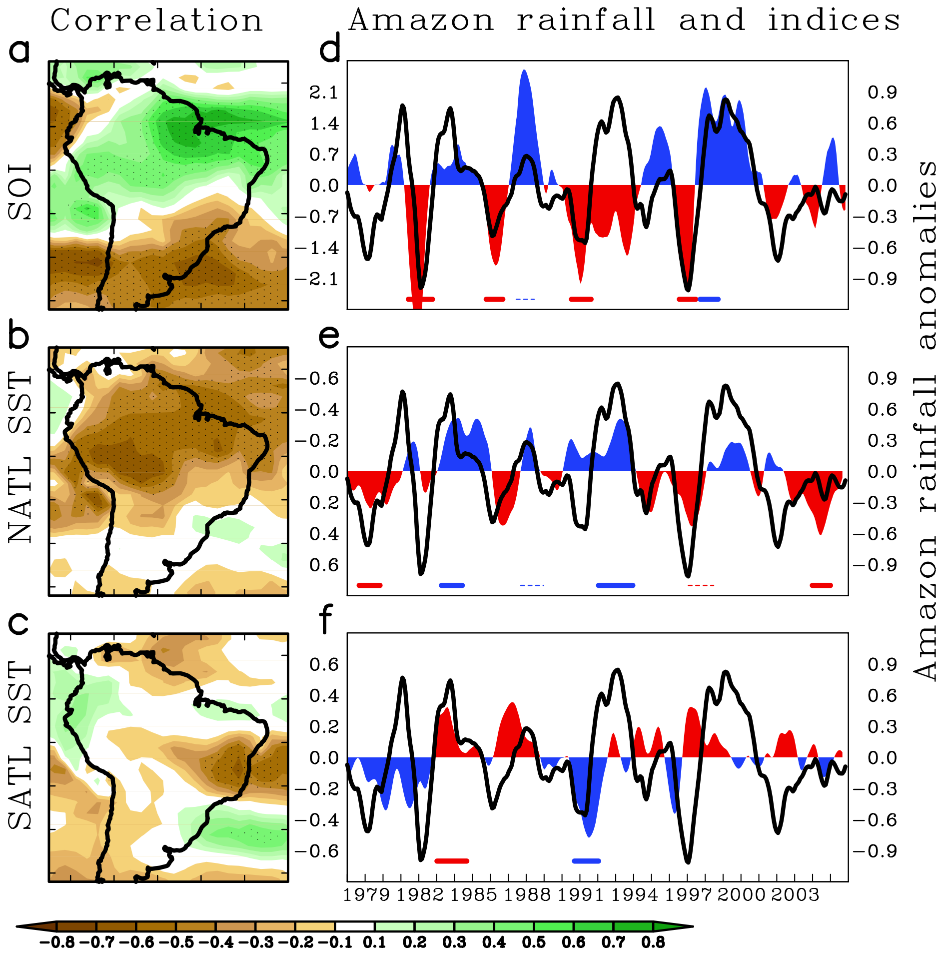

Figure 8. Correlation pattern of rainfall (left 3 panels) with 3 indices: SOI (mb), subtropical North Atlantic SST (degree Celsius) averaged over the domain of 6°N–22°N and 80°W–15°W, and South Atlantic SST averaged over the domain of 25°S–2°N and 35°W–10°E. Dotted areas in the left panels are statistically significant at 95% level using a sample size of 27 (years). The right panels are the Jan1979–Dec2006 timeseries of the 3 indices (blue and red shaded curves labeled on the left) and rainfall (mm d^{-1}; black line) averaged over Amazon from OPI satellite. The short horizontal bars in the right panels indicate the events during which the corresponding index had major influence on Amazon rainfall.

the climate, the critical role of the dry season climate may be the main lesson driven home by the 2005 Amazon drought.

Acknowledgments

We thank the following organizations for data and model: Brazilian National Water Agency (ANA), NCAR/SCD, LLNL, and individuals for discussion or analysis: D Nepstad, C Birkett, P Arkin, J Janowiak, D Vila, R Persaud, M Munnich, J E Meyerson, and support from NOAA, NSF and NASA.

References

[1] Hopkin M 2005 Amazon hit by worst drought for 40 years *Nature News* (Nature online 11 October 2005) doi:10.1038/news051010-8

[2] Janowiak J E and Xie P 1999 CAMS-OPI: a global satellite-rain gauge merged product for real-time precipitation monitoring applications *J. Clim.* **12** 3335–42

[3] Peterson T C and Vose R S 1997 An overview of the Global Historical Climatology Network temperature data base *Bull. Am. Meteorol. Soc.* **78** 2837–49

[4] Rayner N A, Parker D E, Horton E B, Folland C K, Alexander L V, Rowell D P, Kent E C and Kaplan A 2002 Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century *J. Geophys. Res.* **108** 4407

[5] Kanamitsu M *et al* 2002 NCEP-DOE AMIP-II reanalysis (R-2) *Bull. Am. Meteorol. Soc.* **83** 1631–43

[6] Moron V, Bigot S and Roucou P 1995 Rainfall variability in subequatorial America and Africa and relationships with the main sea-surface temperature modes (1951–1990) *Int. J. Climatol.* **15** 1297–322

[7] Nobre P and Shukla J 1996 Variations of sea surface temperature, wind stress and rainfall over the tropical Atlantic and South America *J. Clim.* **9** 2464–79

[8] Zeng N 1999 Seasonal cycle and interannual variability in the Amazon hydrologic cycle *J. Geophys. Res.* **104** 9097–106

[9] Enfield D B 1996 Relationships of inter-American rainfall to tropical Atlantic and Pacific SST variability *Geophys. Res. Lett.* **23** 3305–8

[10] Marengo J A 1992 Interannual variability of surface climate in the Amazon basin *Int. J. Climatol.* **12** 853–63

[11] Ronchail J *et al* 2002 Interannual rainfall variability in the Amazon basin and sea-surface temperatures in the equatorial Pacific and the tropical Atlantic Oceans *Int. J. Climatol.* **22** 1663–86

[12] Murakami M 1979 Large-scale aspects of deep convective activity over the GATE area *Mon. Weather Rev.* **107** 994–1014

[13] McKee T B, Doesken N J and Kliest J 1993 The relationship of drought frequency and duration to timescales *Proc. 8th Conf. of Applied Climatology (January, Anaheim, CA)* (Boston, MA: American Meteorological Society) pp 179–84

[14] ATSR World Fire Atlas, European Space Agency-ESA/ESRIN, Frascati, Italy. Data available at http://dup.esrin.esa.it/ionia/wfa/index.asp

[15] Del Vecchio R and Subramaniam A 2004 Influence of the Amazon river on the surface optical properties of the Western Tropical North Atlantic Ocean *J. Geophys. Res.* **106** C11

[16] Cooley S R and Yager P L 2006 Physical and biological contributions to the western tropical North Atlantic Ocean carbon sink formed by the Amazon river plume *J. Geophys. Res.* **111** C08018

[17] Enfield D B and Mayer D A 1997 Tropical Atlantic sea surface temperature variability and its relation to El Niño-Southern Oscillation *J. Geophys. Res.* **102** 929–45

[18] Giannini A *et al* 2001 The ENSO teleconnection to the tropical Atlantic Ocean: contributions of the remote and local SSTs to rainfall variability in the tropical Americas *J. Clim.* **14** 4530–44

[19] Uvo C B, Tolle U and Berndtsson R 2000 Forecasting discharge in Amazonia using artificial neural networks *Int. J. Climatol.* **20** 1495–507

[20] Nepstad D C *et al* 1994 The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures *Nature* **372** 666–9

[21] Neelin J D *et al* 2006 Tropical drying trends in global warming models and observations *Proc. Natl Acad. Sci.* **103** 6110–5

[22] Cox P M *et al* 2000 Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model *Nature* **408** 184–7

[23] Scholze M *et al* 2006 A climate-change risk analysis for world ecosystems *Proc. Natl Acad. Sci.* **103** 13116–20