Causes and Impact of the 2005 Amazon Drought

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Abstract

A rare drought in the Amazon basin that culminated in 2005 drew wide attention to the potential vulnerability of tropical rainforest to natural and anthropogenic perturbations. Using ground and satellite observations, we show that Amazon rainfall in 2005 was indeed below normal but the deficit was not particularly large. Rather, it was the last episode of an unusually long drought started in 2002, leading to the severe depletion of soil moisture and lowering of water levels. The wide-ranging impact of this long-lasting drought can be seen in the lowest river stage in the 25 year data period for the upper Amazon, 16% reduction in the river plume size in the Atlantic Ocean created by Amazon runoff and over 100% more frequent basin-wide fire occurrence compared to the averages of previous 7 years. Atmospheric data analysis and modeling results suggest that the 2005 drought was caused largely by a warm tropical North Atlantic Ocean that generated a seasaw-like modification of the Hadley circulation, corresponding to reduced moisture transport into the Amazon basin. This is in contrast to a conventional wisdom of Pacific Ocean sea surface temperature (SST) control on Amazon rainfall via the El Nino Southern Oscillation (ENSO). Using analysis from 1979 to 2005, we further show that major Atlantic influence on Amazon rainfall is not so rare, and occurs typically when ENSO is weak. The combined effects of tropical Pacific and Atlantic SSTs explain 53% of the Amazon rainfall variability, with comparable contribution from the Pacific and the Atlantic. For the 2002-2005 drought, the El Nino of 2002-03 was mainly responsible for the initial drying, followed by additional contribution from a warm tropical North Atlantic in 2004-05. We also discuss the implications for climate prediction and climate changes in the world's largest rainforest ecosystem.

The 2005 drought in the Amazon was particularly severe in the western and southern parts of the basin (Fig.1) where many rivers and lakes had lowest water level in many decades. 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.

Our analysis of the available station data shows coherent drought conditions over much of the Amazon basin during 2005 (Fig.1). The gauge data are relatively sparse and data quality is not always consistent in this remote region, but the general drying is corroborated by satellite observations which have better spatial coverage, including the CAMS/OPI outgoing longwave and TRMM/TMI microwave precipitation products (*1*). Many other parts of South America including Northeast Brazil and the La Plata basin also experienced drought. Only a small part of the northern Amazon had slightly above normal rainfall.

Changes in rainfall and atmospheric circulation is 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 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 Hadley circulation and a northward shift of the intertropical convergence zone (ITCZ). As a result, reduced rainfall is seen across western and southern Amazon, northeastern Brazil, Equatorial Atlantic ocean and the African Guinea Coast. The atmospheric moisture transport indicates a clear reduction in Atlantic moisture into the Amazon (Fig.1B), which normally flows westward up the Amazon river and turns southward along the Andes.

Two major issues immediately arise. Firstly, precipitation over the Amazon is known to be largely controlled by ENSO via changes in the zonally oriented Walker Circulation, a coupled atmosphere-ocean phenomenon originated from the eastern Pacific Ocean, though ENSO only explains part of the variability (*7–11*). Atlantic SST influence on the ITCZ and rainfall in Northeast Brazil and West Africa Sahel has long been noted (*12–15*), but an Atlantic linkage to the heart of the Amazon basin is not well established (*16, 17*), partly because of the sparse raingauge data in this remote region. Another perplexing issue is the severity of the drought. As shown in Fig.2A, 2005 had relatively small rainfall change, compared to, e.g., the large 1997-98 drought, seemingly contrary to the extremely low river and lake levels seen by people living in the region.

The answer to the second question comes from the observation that the major El Nino events such as 1997-98, 1982-83 that led to large droughts in the Amazon were short lived (about 1 year), often immediately followed by La Nina events that led to anomalously wet conditions so that the land recovers quickly from the drought (Fig.2A). In contrast, although the precipitation anomaly was not particularly large, the 2005 drought was preceded by another drought during 2002-03 (an El Nino year), with little recovery in 2004. Thus precipitation stayed below normal for 4 years from 2002 to the end of 2005. The effect of the long duration can be better seen by the standardized precipitation index (SPI; Fig.2B) which shows the year 2005 to be the driest at least since 1981. Since SPI effectively represents the cumulative effect of rainfall (*18*), and the river and lake levels largely indicates the content of soil moisture and underground water which percolates slowly into the rivers, it is a better indicator of hydrological drought than instantaneous rainfall.

The impact of the long-lasting 2002-2005 drought can be clearly seen in several other important hydroecological indicators (Fig.2). The Amazon streamflow as measured at Tabatinga (4.25°S, 69.9°W, a station on the Solimões River, main stem of the Amazon) shows the lowest level over the 25 year data period. A novel connection is the Amazon river plume in the Atlantic Ocean generated by the Amazon runoff. Because lower salinity water is largely caused by the fresh water input from the Amazon, the size of the river plume is a measure of Amazon runoff, though other factors such as change in oceanic currents may also play a role. The salinity derived from satellite light attenuation (*19*) shows that in 2005 the plume size is significantly reduced and 'patchier' (Fig.3) than the average of previous 7 years. By the end of 2005, the river plume area was smaller than during the drought year of 1997-98 (Fig.2E). The 2005 average plume size (as measured by the area with salinity smaller than 28 permil) was 16% smaller than the average of 1998-2004.

On average, the Amazon River plume may be responsible for a carbon sequestration by plankton diatom diazotroph associations of up to 1.5 TgC annually (*20, 21*). Thus the change in plume size as a result of changes in precipitation patterns may have had an impact on carbon and nitrogen cycle in the tropical Atlantic ecosystem over 2000 km from the mouth of the river.

The drought also led to enhanced fire in the southern Amazon, several times more than normal in some places as indicated by the satellite observed fire counts (*22*) (Fig.2G). Summed over the whole basin, fire in 2005 was more than twice as frequent as the average of the previous 7 years (1998-2004) (Fig.2F). Typically, fire in the Amazon occurs at the end of dry season around the peripheral of the rainforest in a so-called 'arc of fire' (primarily the colored region in Fig.2G). Although drought was likely the major cause of enhanced fire frequency, it may have been exacerbated by anthropogenic deforestation in some regions. The largest impact region is southwestern Amazon where drought is severe and deforestation is most active (c.f., Fig.1A and Fig.2G), thus the long-lasting drought helped the advancement of the deforestation 'frontier'. Overall, the variety of hydrological and ecological indicators suggest that there was indeed a major drought over the Amazon with wide-ranging hydroecological impact culminating in 2005 as the result of a long-lasting drought.

To further understand the cause of the 2005 drought, climate simulations were conducted using the National Center for Atmospheric Research Community Atmosphere Model version 2. When forced with observed global SST, the model captures the general enhanced rainfall north of the ITCZ and reduced rainfall over southern Amazon and northeastern Brazil, though the exact location of the rainfall anomalies is somewhat shifted compared to the observations (Fig.4). The atmospheric circulation shows a reduced moisture transport into the Amazon and enhanced flux into the subtropical Atlantic, consistent with the observation in Fig.1B. The rainfall averaged over the Amazon basin simulated by the model (Fig.2B) is also in general agreement with the observation, including the major droughts of 1982-83, 1997-98 and 2002-2005, but overestimates the protracted El Nino years of 1991-94. Overall the model results suggest a major influence from SST anomalies for the 2005 drought, as opposed to deforestation or climate change which tend to take place on longer time scales. Although the temporal details of the 2002-2005 drought differ somewhat among the several datasets (including those we have examined but not shown here) and the GCM results (Fig.2A,B), the coherent spatial pattern of a wetter North Atlantic and drier Amazon appears to be robust (Figs.1,4).

To understand the relative contribution from Pacific and Atlantic ocean, model sensitivity experiments were conducted using SST anomalies from tropical Pacific or Atlantic only (Fig.4B,C). The 2005 drought in the southern Amazon appears to be mostly caused by Atlantic SST anomalies. Although there was a mild La Nina condition towards the end of 2005 (Fig.1B) which may be responsible for the drying in Equatorial Pacific (Fig.1A and Fig.4A), it produced little change for the Amazon basin as a whole (Fig.4C). In contrast, tropical Atlantic SST alone (Fig.4B) produced much of the wetting in the subtropical North Atlantic and drying over South America including southern Amazon.

It is important to understand the relative role of Atlantic and the Pacific Ocean on the long-term Amazon climate variability. Figure 5 shows the correlation of 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 (*23*).

The correlation between the SOI index and Amazon average rainfall from the CAMS/OPI satellite data is 0.52 for the period of 1979-2005, explaining 27% (square of 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 and explaining 1.4% of the variance. However, part of the Atlantic influence may actually come from the Pacific because of a lagged Atlantic SST response to ENSO-induced trade wind change (*25, 26*), so that the independent contribution from Atlantic is not necessarily larger than the Pacific. This is also consistent with our lagged-correlation analysis which shows that SOI leads Amazon rainfall by 1 month, while NATL lags rainfall by about 2 months, as can also be seen in Fig.2. A multiple regression analysis with the 3 indices as the predictors for Amazon average rainfall P shows that P is best predicted as

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

where lower case (soi, natl and satl) indicates the quantity 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 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, depends somewhat on the rainfall dataset used, so that we can only conclude that Atlantic SST influence on the Amazon rainfall is comparable to the Pacific. This general conclusion is also supported by similar analysis with runoff data (not shown).

It is illuminating to see the interplay between Pacific and Atlantic in impacting Amazon rainfall event by event. The data from 1979-2005 suggest that whenever there was a major ENSO event (warm El Nino events 1982-83, 1986-87, 1991-92, 1997-98; cold La Nina events 1988-89, 1999-2000), Amazon rainfall was dominated by the Pacific Ocean. When ENSO was weak and the NATL was warm (1979-80, 1984, 1994, 2005), the Atlantic SST had large impact. A prominent example of the latter case is 1984, when a strong warming in South Atlantic and cooling in the North Atlantic during an ENSO transition phase led to a wet Amazon. In 2005, both ENSO and SATL are weak but a warming North Atlantic led to the drought. In general, severe Amazon drought happens when both eastern Equatorial Pacific and North Atlantic are warm (negative SOI plus positive NATL) such as 1983 and 1987. However, some of the spring North Atlantic warming may be partly caused by El Nino which peaks in Boreal winter, and thus exacerbating the direct El Nino drought in the Amazon (*26*). Nonetheless, Atlantic warming is also often not related to El Nino, and severe drought in the Amazon is more likely when they happen either near-simultaneously (such as 1997-98) or sequentially (such as during 2002-2005). This examination of the individual events is consistent with the multiple regression analysis above and the 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 by these. Such potential has been demonstrated by empirical forecast for individual river streamflow (*27*), and the modeling and analysis here provides a basis for basin-wide hydroecological prediction.

It is worth noting that our focus here is on the interannual variability, with climatological seasonal cycles removed from all the data shown. Averaged over the whole basin (dominated by the larger southern Amazon), the wet season is from November to April, dry from June to September in rainfall, while runoff lags by about 3 months (*10*). The seasonal cycle is large in the Amazon so that the drought impact on the ground was felt mostly as a particularly severe dry season when water level was lowest and the forest was more prone to disturbances such as fire. As rainy season came back since December 2005, the signs of drought subsided. The status of the next dry season will depend not only on the upcoming events in the Pacific and Atlantic Ocean, but also the current drought condition.

The recent drought in the Amazon highlights the sensitivity of its hydrology and ecosystem to prolonged drought conditions, but not necessarily large but short-lived ones. The rainforest has adapted to seasonal and short-term drought by strategies such as deep root water uptake (*28*) but may be less resilient to longer term climate change. Instrumental record shows that the Amazon has a relatively stable climate over the last century (*29*), but climate projections for the 21st century suggest perpetual changes in the Pacific Ocean as well as significant changes in the Atlantic overturning circulation and related SST patterns (*30–32*). Such possible climate changes will be likely entangled with natural variability on interannual-interdecadal timescales such as the Pacific Decadal Oscillation (*33, 34*) (PDO) and the Atlantic Multidecadal Oscillation (*24, 35–37*) (AMO). Understanding the causes and impact of Amazon drought will shed light on the future of the world's largest rainforest ecosystem.

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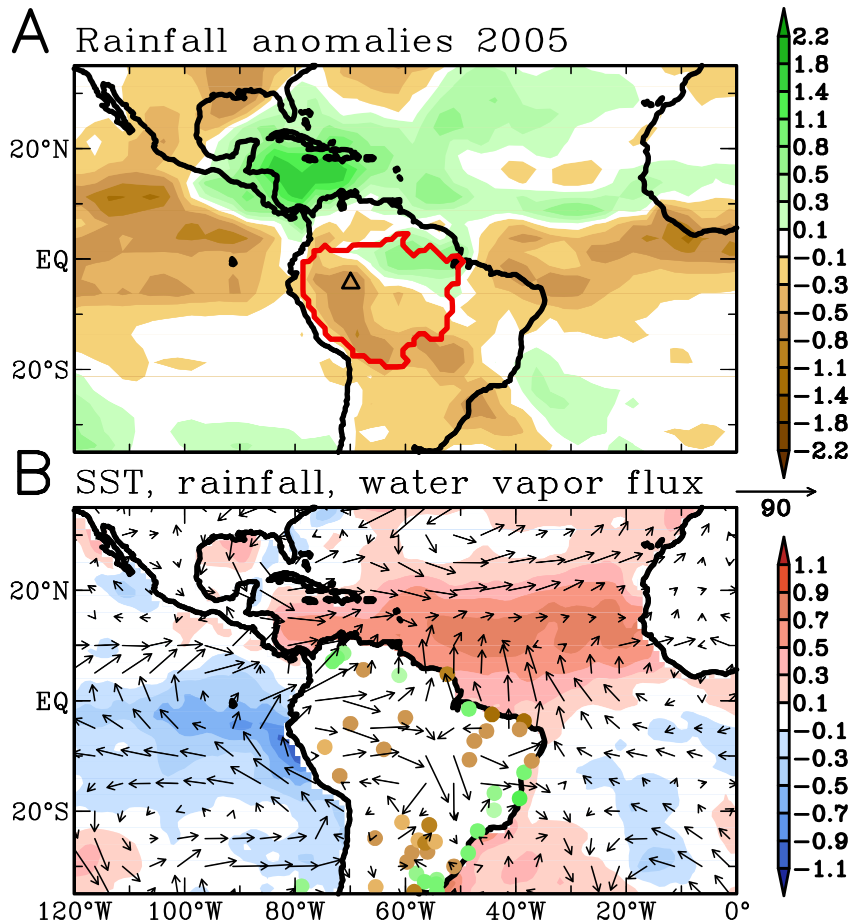

Figure 1: Anomalies for January-December 2005 relative to the means of 1979-2005 of (a) rainfall based on the CAMS/OPI (*2*) (outgoing longwave radiation precipitation index; satellite only version) im mm d^{-1}; (b) station rainfall (color filled circles) over South America from the GHCN network (*4*), SST (degree Celsius) over the ocean (*5*), and vertically integrated moisture transport (arrows) from the NCEP/NCAR reanalysis (*6*) in kg m^{-1} s^{-1}. The outline of the Amazon drainage basin is shown in thick red line.

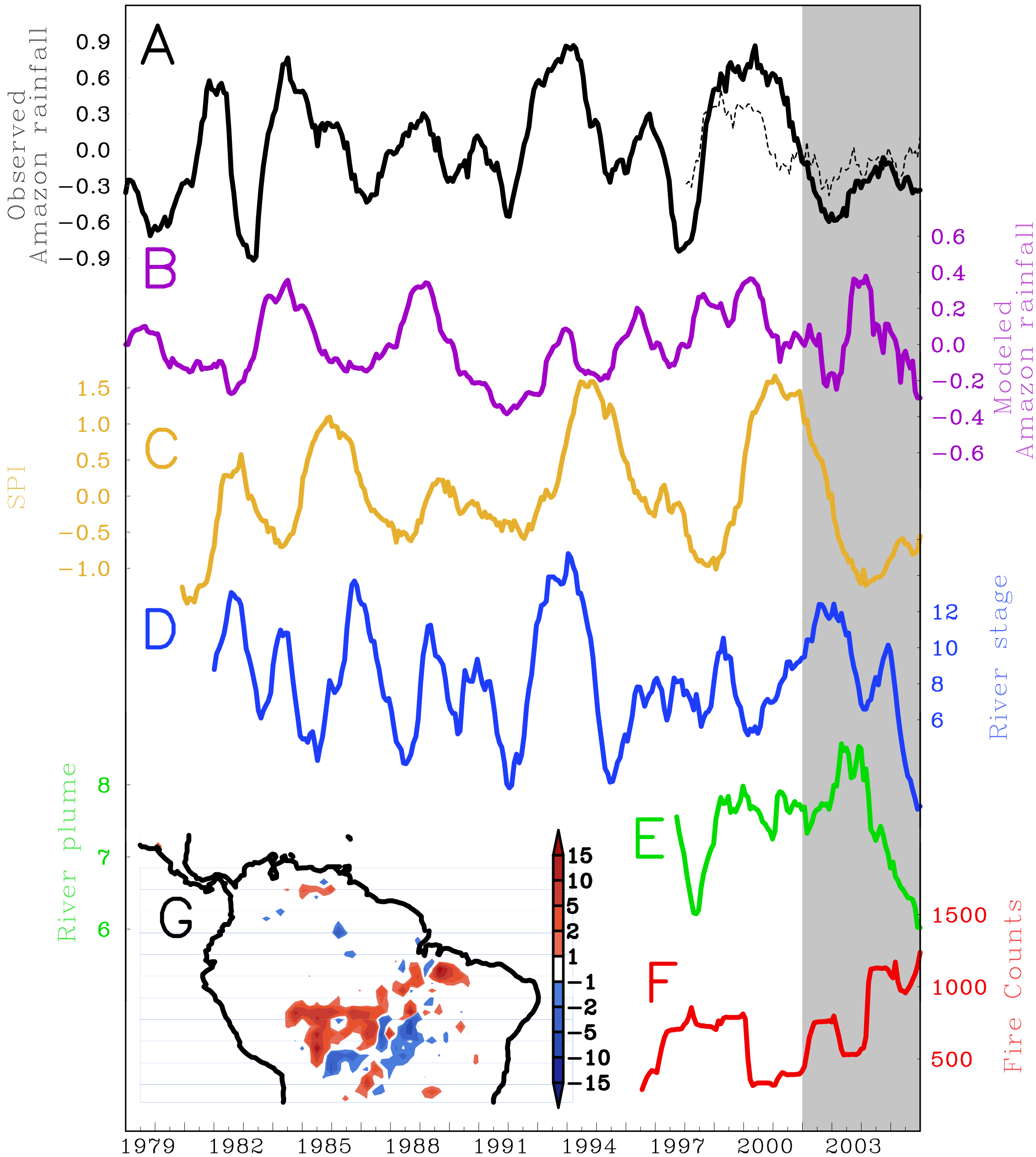

Figure 2: Interannual variations of rainfall and related variables from Jan1979 to Dec2005 for the Amazon drainage basin: (a) rainfall (mm d^{-1}) from CAMS/OPI (solid black line) and from the TRMM/TMI (dashed black line); (b) Amazon rainfall simulated by the NCAR atmospheric model; (c) the standardized precipitation index (SPI) derived from CAMS/OPI precipitation, showing the cumulative effect of rainfall by using a timescale of 24 months (*18*); (d) river stage (meters) at Tabatinga (marked by open triangle in Fig.1A); (e) size of the river plume (100,000 km^2) generated by the Amazon runoff into the Atlantic ocean based on satellite derived salinity; (f) satellite fire counts (number of fires per month) summed over the whole Amazon basin; (g) the spatial pattern of 2005 fire counts anomalies (per month per $1^{\circ}\times1^{\circ}$ box) relative to the average of 1998-2004, showing much higher fire frequency in the southern Amazon (by several folds in some area). A 12 month running mean filter was applied to all the data to remove higher frequency variability, and the 2002-2005 drought period is shaded in grey.

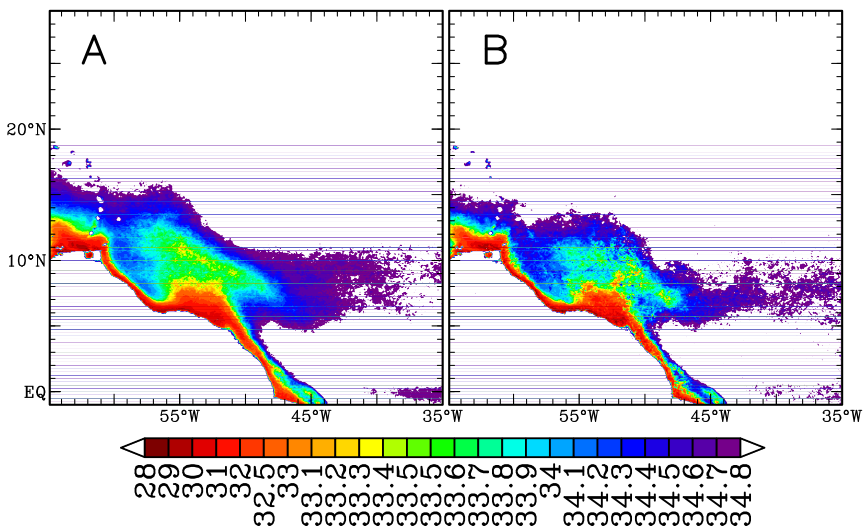

Figure 3: Amazon river plume in the Atlantic Ocean as indicated by satellite observed salinity (permil) based on light attenuation (*19*): (a) average for 1998-2004; (b) year 2005. Lower salinity is mostly due to fresher water input from the Amazon river. The 2005 plume area is 16% lower than the 1998-2004 average.

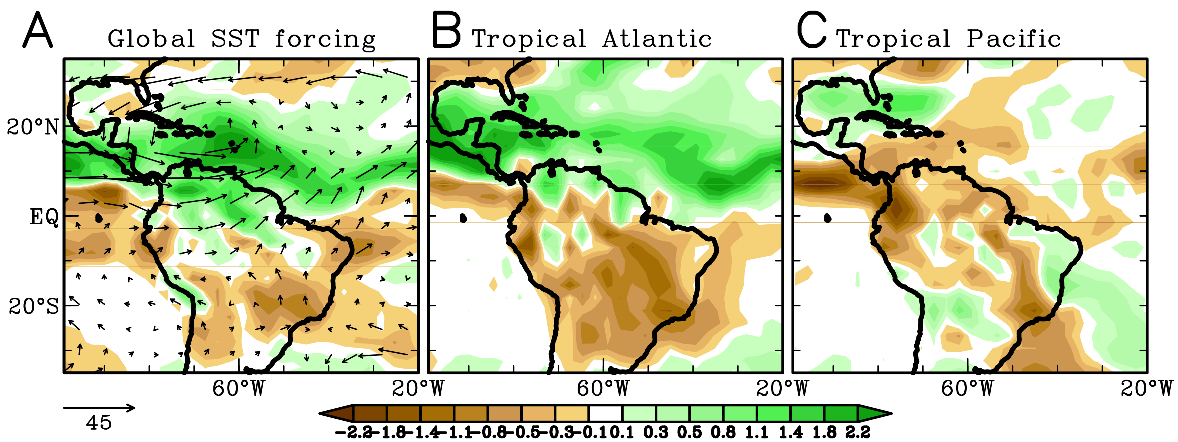

Figure 4: Rainfall (mm d^{-1}) and atmospheric moisture transport (kg m^{-1} s^{-1}) anomalies for 2005 simulated by the NCAR atmospheric model forced by observed (a) global SST; (b) tropical (between 20°S and 20°N) Atlantic SST only; (c) tropical Pacific SST only. Most of the 2005 drying over the Amazon and the wetting of the subtropical North Atlantic was caused by the warming in the North Atlantic.

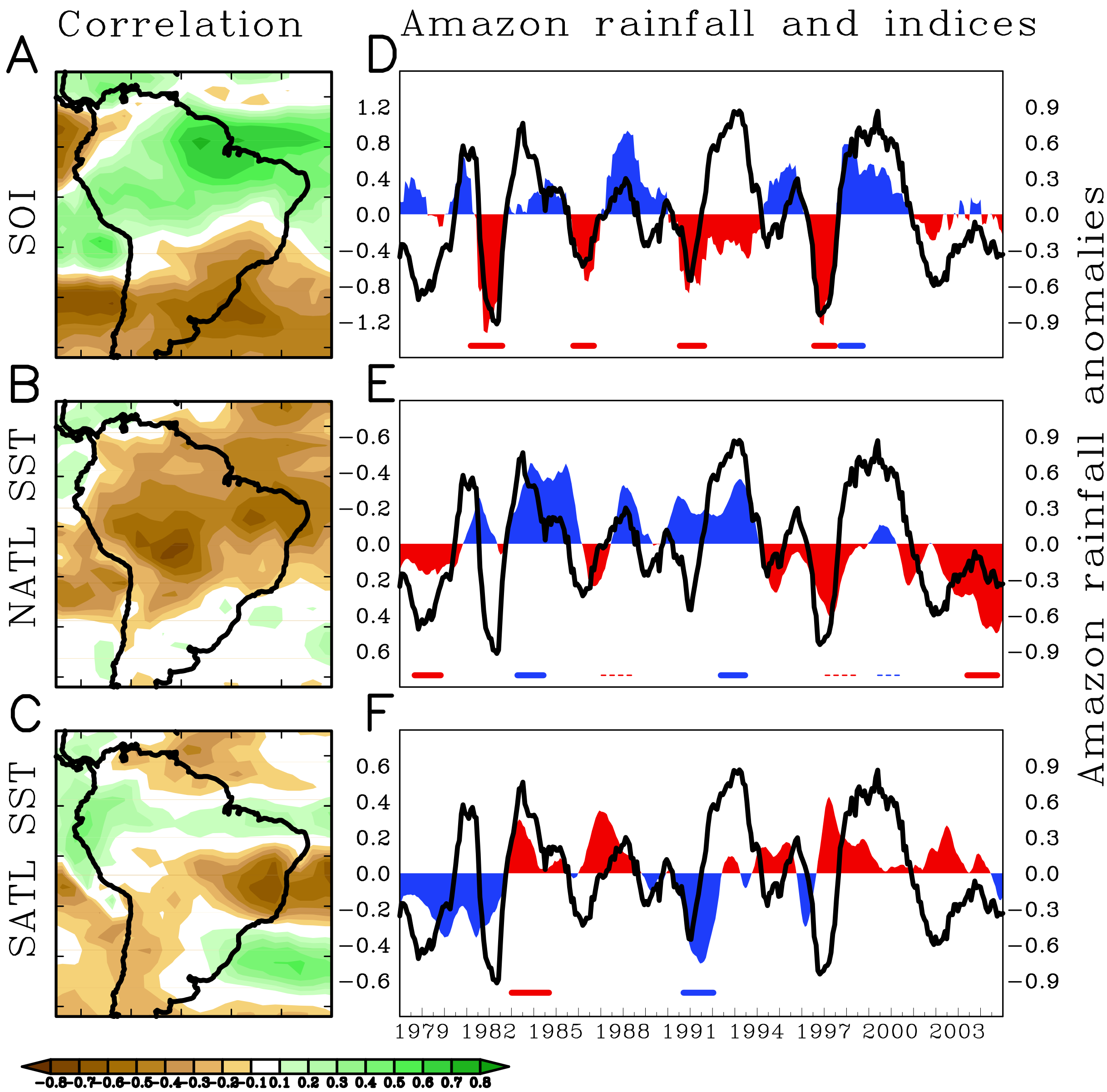

Figure 5: Correlation pattern of rainfall (left 3 panels) with 3 indices: SOI (mb), subtropical North Atlantic SST (degree Celsius) averaged over the domain of 6°N-22°N and 80°W-15°W, and South Atlantic SST averaged over the domain of 25°S-2°N and 35°W-10°E. The right panels are the Jan1997-Dec2005 timeseries of the 3 indices (blue and red shaded curves labeled on the left) and rainfall (mm d^{-1}) averaged over Amazon from CAMS/OPI satellite. The short horizontal bars in the right panels indicate the events during which the corresponding index had major influence on Amazon rainfall.