

## Intensification of the Amazon hydrological cycle over the last two decades

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[1] The Amazon basin hosts half the planet's remaining moist tropical forests, but they may be threatened in a warming world. Nevertheless, climate model predictions vary from rapid drying to modest wetting. Here we report that the catchment of the world's largest river is experiencing a substantial wetting trend since approximately 1990. This intensification of the hydrological cycle is concentrated overwhelmingly in the wet season driving progressively greater differences in Amazon peak and minimum flows. The onset of the trend coincides with the onset of an upward trend in tropical Atlantic sea surface temperatures (SST). This positive longer-term correlation contrasts with the short-term, negative response of basin-wide precipitation to positive anomalies in tropical North Atlantic SST, which are driven by temporary shifts in the intertropical convergence zone position. We propose that the Amazon precipitation changes since 1990 are instead related to increasing atmospheric water vapor import from the warming tropical Atlantic. **Citation:** Gloor, M., R. J. W. Brienen, D. Galbraith, T. R. Feldpausch, J. Schöngart, J.-L. Guyot, J. C. Espinoza, J. Lloyd, and O. L. Phillips (2013), Intensification of the Amazon hydrological cycle over the last two decades, *Geophys. Res. Lett.*, 40, doi:10.1002/grl.50377.

### 1. Introduction

[2] The Amazon basin is an important component of the global climate system, being one of the main locations of deep convection and with a river discharge contributing ~17% of total global freshwater input to the oceans [Callède *et al.* 2010]. It hosts the largest contiguous area of tropical forest (~ 5 mio. km<sup>2</sup>), modulating its own hydrological regime through the recirculation of precipitation and the maintenance of high ambient humidity [e.g., Salati *et al.*, 1979]. The forests and soils of the Amazon basin also store a large amount of organic carbon (on the order of 200 Pg C) [e.g., Malhi *et al.*, 2006], which may potentially be released readily to the atmosphere through forest destruction by forest to pasture conversion or logging or as a consequence of biome

shifts. A large carbon release from Amazon ecosystems could contribute substantially to atmospheric CO<sub>2</sub> and thus to greenhouse warming [e.g., Booth *et al.*, 2012]. This is above and beyond changes expected from deforestation alone.

[3] There are concerns, based primarily on modeling analyses, that in a warming world the Amazon basin may experience a drying trend, which could possibly lead to large losses of rain forest cover and carbon stocks during this century [e.g., Malhi *et al.*, 2009]. Recently two short-term “droughts of the century” in 2005 and 2010 have therefore received attention [e.g., Lewis *et al.*, 2011; Marengo *et al.*, 2008, 2011; Espinoza Villar *et al.*, 2011] and added to the perception that this drying scenario may have begun to be realized.

[4] Because of the importance of the Amazon basin for global (and local) climate, we were interested to examine to what extent changes in the hydrological cycle might be evident in the observational record. Several studies have previously reported on hydrological trends of the Amazon River or its tributaries. Notably Gentry and Lopez-Parodi as long ago as 1980 concluded that upper Amazon River flows were increasing from 1962 to 1978 and attributed this to the effect of deforestation alone. However, that finding was controversial at the time because the increase could also have been due to a precipitation increase [Nordin and Meade 1982]. More recently, Espinoza *et al.* [2009] reported on a diminution of the low stage runoff in the southern subbasins, and a slight increase of the high stage runoff in the northwestern region for the period 1974–2004. Other studies (analyzed period 1977–1996 [Costa and Foley, 1999], period 1925–2005 [Dai *et al.*, 2009], period 1902–2008 [Marengo *et al.*, 2011], period 1925–2005 [Trenberth, 2011]) suggested that there is rather a general decreasing precipitation trend. When analyzing the most up-to-date river discharge and precipitation records, we find that a somewhat different pattern emerges, which we briefly report here.

### 2. Data and Methodology

[5] We use two independent records to investigate trends in the hydrological cycle. The first and primary one is Amazon River discharge at Óbidos. Óbidos is located approximately 800 km inland from the estuary of the Amazon River and drains a basin of ~4.7 × 10<sup>6</sup> km<sup>2</sup>, roughly 77% of the Amazon basin. The Óbidos record is not complete with data existing only after 1928 and with data missing between 1948 and 1967. Callède *et al.* [2002] have devised a method to extend the record backward in time to 1903 and to fill in the 1948 and 1967 gap based on the high correlations with the station records of Rio Negro at Manaus and the Amazon River at Taperinha and Santarém, which we include in Figure 1. The in-filled data

All supporting information may be found in the online version of this article.

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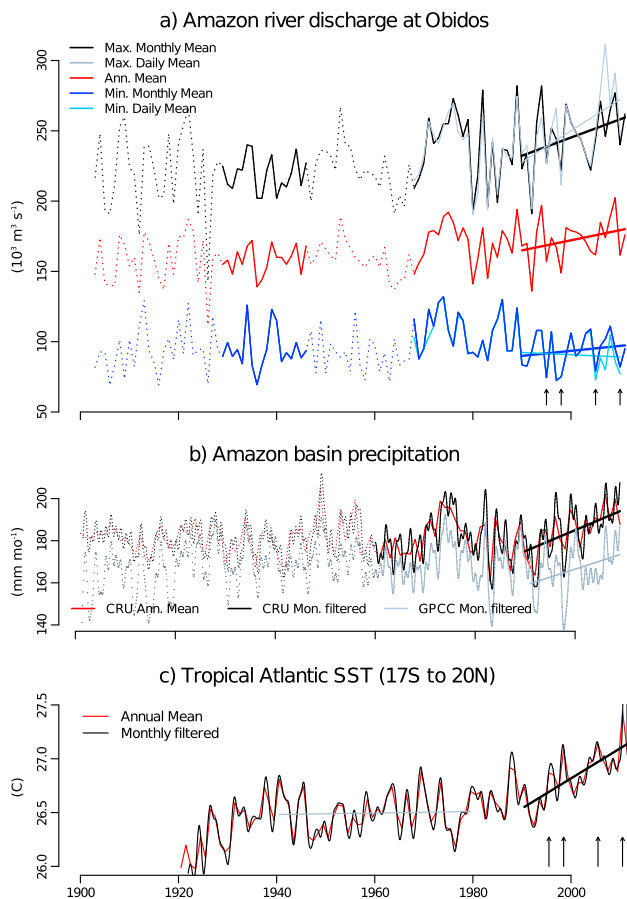
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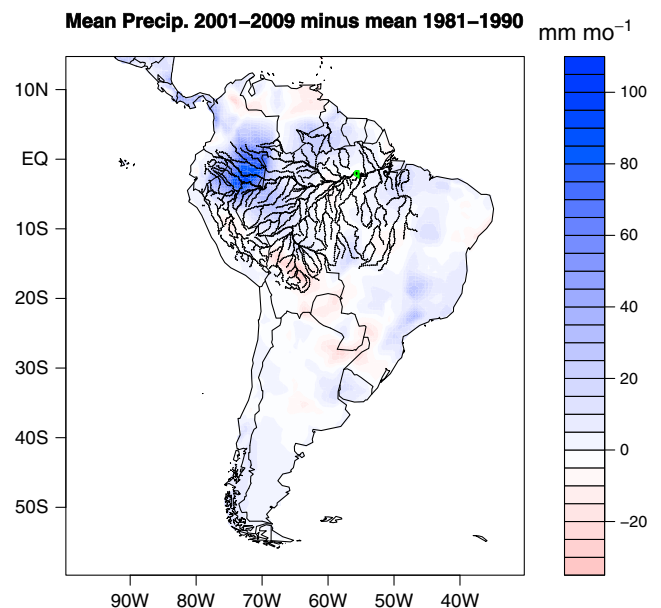
**Figure 1.** (a) Annual mean, maximum and minimum monthly Amazon River discharge at Óbidos, including linear trends for the 1990–2010 period; dotted records are those filled in by *Callède et al.* [2002] using upstream and downstream hydrographs; grey records are maxima and minima of daily maxima and minima within each month respectively. Arrows mark the last four severe drought events in 1995, 1998, 2005, and 2010; (b) Amazon basin-wide annual mean and monthly mean low-pass filtered precipitation from CRU (black and red) and GPCP (gray, offset by  $20 \text{ mm month}^{-1}$ ), including linear trend for 1990–2009 period; dotted lines indicate where data density is very low [see *Costa et al.*, 2009] and the records are thus less reliable; (c) tropical equatorial Atlantic mean sea surface record (latitudinal band from  $20^\circ\text{N}$  to  $17^\circ\text{S}$  and from  $80^\circ\text{W}$  to Africa with exclusion of a coastal strip) calculated from the U.S. National Oceanic and Atmospheric Administration (NOAA) Extended reconstructed sea surface temperature (ERSST) record [*Smith et al.*, 2008]. For all the records linear trends for the 1990–2010 are indicated by a line, and for the sea surface record also for the 1940–1980 period. Arrows mark the last four severe drought events in 1995, 1998, 2005, and 2010.

need thus to be interpreted with some caution. The second record is Amazon basin catchment integrated precipitation based here primarily on the  $0.5 \times 0.5$  longitude by latitude Climate Research Unit (CRU) climatology [*Mitchell and Jones* 2005]. Our preference for river stage data is based on the observation that longer-term precipitation records in the Amazon are sparse, noisy, often not continuously measured, and probably only sufficiently dense for whole basin trend analysis from 1980 onward [e.g., *Haylock et al.*, 2006; *Costa*

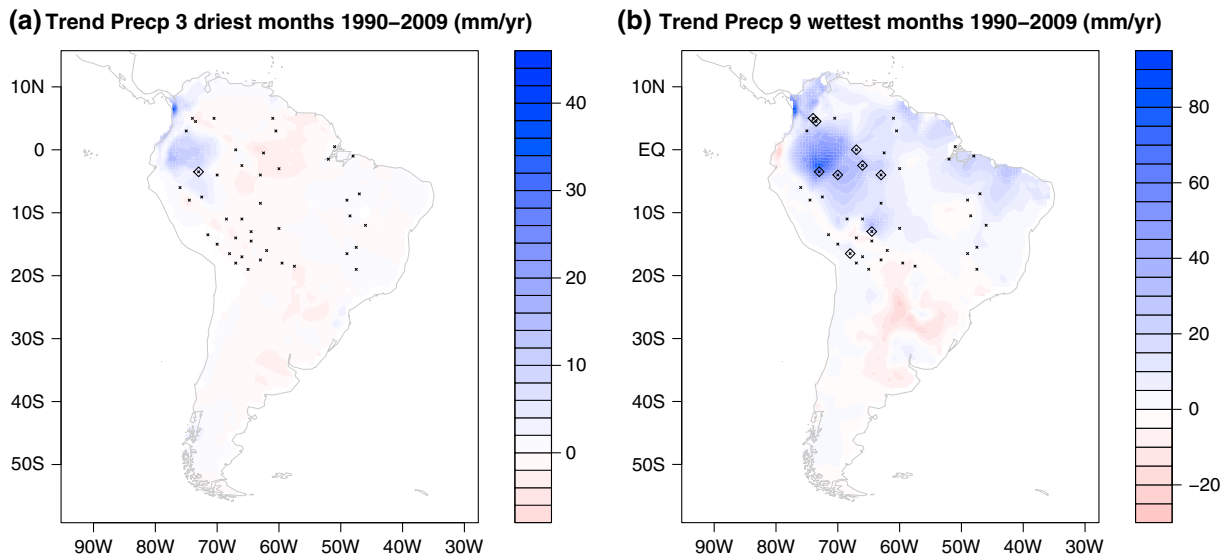
*et al.*, 2009]. Specifically, *Costa et al.* [2009] demonstrate a strong increase in rainfall stations during 1960–1980 from nearly no stations and thereafter stagnation or even decrease in numbers (their Figure 2). In contrast river stage measurements are simple to make and, because of their integrative nature, act like a low-pass filter, thus providing a less noisy and more robust record compared to precipitation data. The Óbidos discharge data are available online from the Agência Nacional de Águas (ANA) in Brazil (<http://hidroweb.ana.gov.br>; monthly mean, daily minimum, mean and maximum discharge). A disadvantage of the river stage records is that annual totals are “blind” to (i.e., cannot discern) changes in the ratio of runoff previously recirculated via evapotranspiration to nonrecirculated runoff. Thus, the relationship between river discharge and basin-wide precipitation is not simply one to one, and this is the main reason we use the CRU climatology for calculating basin-wide precipitation here as well. We chose this specific climatology because it is more closely based on observational data than other ones obtained using methods of data assimilation into general circulation models. Nonetheless for additional verification, we also make limited use of the GPCP (Global Precipitation Climatology Center) [*Beck et al.*, 2005] version 6 precipitation data set. To calculate basin-wide precipitation, we multiplied the precipitation fields with an Amazon catchment area mask and then integrated spatially. We also use the extended reconstructed sea surface temperature (ERSST) record [*Smith et al.* 2008] from the U.S. National Oceanic and Atmospheric Administration (NOAA) to probe potential causes of trends in the hydrological cycle.

### 3. Evolution of the Hydrological Cycle

[6] The first main feature of the hydrological records is that there is an upward trend in Amazon River discharge at Óbidos, as well as Amazon basin integrated precipitation, i.e., an intensification of the hydrological cycle, over roughly the last two



**Figure 2.** Difference between 2001 to 2009 minus 1981 to 1990 mean precipitation according to the CRU climatology [*Mitchell and Jones* 2005]. Green circle marks the position of the Óbidos River stage measurements.



**Figure 3.** (a) Precipitation trend from 1990 to 2009 for the three driest months in the year calculated individually for each data grid box using the CRU climatology. The locations of the stations on which the data are based and for which the records include at least 50% data coverage and data at both the beginning and the end of the period are indicated by black crosses. Diamonds indicate where trends are significant at the 95% significance level. (b) Precipitation trend from 1990 to 2009 for the nine wettest months in the year calculated individually for each data grid box using the CRU climatology. The locations of the stations on which the data are based and for which the records include at least 50% data coverage and data at both the beginning and the end of the period are indicated by black crosses. Diamonds indicate where trends are significant at the 95% significance level.

decades (Figure 1). The upward trend is clearly evident in the monthly records and is even more pronounced in daily records indicating also a shift toward more severe events. The annual mean discharge record indicates changes from the middle of the last century onward. There was a temporary fast intensification around 1970 which had dissipated by 1980, with a second intensification starting around 1990 and continuing until today ( $\sim 8\%$  from 1990 to 2010,  $p=0.26$  for annual means,  $p=0.08$  for monthly maxima). This increase over the last two decades is also evident in the Amazon catchment integrated precipitation, which has increased at a similar relative rate ( $\sim 10\%$  over the same period,  $p=0.24$ ; for another more stringent measure of significance, see Figure 3) with results similar when using the GPCP precipitation climatology. The decadal-scale event in the 1970s is well known and is generally associated with the Pacific Decadal Oscillation and a shift to more intense ENSO variability around 1970 [Miller, 1994]. The general upward trend in river discharge over the last century had already been reported by Callède *et al.* [2004].

[7] Where in the basin has precipitation increased the most? We find no consistent trend across the basin but northwestern Amazonia shows the strongest increase in precipitation (up to  $80 \text{ mm month}^{-1}$  when comparing the 2000–2009 mean with the 1981–1990 mean; Figure 2). This is also the region, which is already the wettest part of the basin. Southwestern Amazonia and the Gran Chaco region toward the southern periphery of the basin show some drying (up to  $-20 \text{ mm month}^{-1}$ ). Possible reasons for this trend are changes in the land surface cover due to deforestation, and thus, water recirculation to the atmosphere shifts in the intertropical convergence zone (ITCZ) due to changes in albedo caused by deforestation [Doughty *et al.* 2012] or changes in water vapor export out of the basin to the southeast [Espinoza *et al.* 2009]. The southern drying trend

may also be due to decadal scale variation as it disappears when choosing a different reference period (e.g., 1961–1980). We also note that the results of Chou *et al.* [2013] based on the GPCP (Global Precipitation Climatology Project) reveal a picture quite similar to Figure 2 of our study.

[8] To avoid the risk of pattern overinterpretation, we indicate in Figures 3a and 3b the locations of the station records on which the maps are based as well as time trend significance levels calculated from CRU monthly mean station records (available at <http://www.metoffice.gov.uk/hadobs/crutem4/data/download.html>). We also verified that the stronger trend in the Western basin is not an interpolation or “site switching” artifact by estimating the station time series mean time trend directly from the monthly mean observational records (Figures S2a and S2b).

[9] The increasing trend in annual precipitation over the last two decades occurs overwhelmingly during the wet season (the wettest 9 months; Figure 3b), again with the exceptions of the southwestern and Gran Chaco regions which show slight decreases. One consequence is a strong increasing trend in the difference in annual monthly maxima minus annual monthly minima in river discharge (Figure 1a and Figure S1) exhibiting a change of approximately  $10\%$  over the period from 1990 to 2009 ( $p=0.18$  for period 1990–2010,  $p=0.004$  for 1980–2010). Although not included in our analysis, the year 2012 is in line with the general wetting trend during the wet season with Amazon stage measurements in Manaus being the highest recorded in time since 1903.

#### 4. Discussion of Possible Causes

[10] Finally, we attempt attribution by comparing the Amazon River discharge and basin integrated precipitation

records with tropical Atlantic sea surface temperature (Figure 1). There are two notable features. First, interannual variability in the hydrology record tends to be anticorrelated with interannual variability of sea surface temperature, i.e., negative precipitation anomalies tend to be associated with positive sea surface temperature anomalies. This anticorrelation has been attributed to variations in the location of the ITCZ, which is steered northward by the positive equatorial north Atlantic SST anomalies [e.g., Yoon and Zeng 2010; Marengo et al. 2008]. Examples for this anticorrelation are the most recent four severe drought events in 1995, 1998, 2005, 2010 (Figures 1a and 1c), which were particularly intense over western Amazonia [Espinoza Villar et al., 2011] and the decade long positive Amazon precipitation anomaly in the 1970s. Atlantic tropical sea surface temperature anomalies are, however, not the only influence on Amazon precipitation patterns as El Niño Southern Oscillation (ENSO) events exert the most dominant control on interannual variability. El Niño phases are associated with negative precipitation anomalies in the north of the basin leading to lower than usual Amazon River discharge. Likewise La Niña phases are associated with positive precipitation anomalies and higher river discharge [e.g., Costa and Foley, 1999; Marengo et al., 2011; Espinoza et al., 2012].

[11] The second notable feature is that the Tropical Atlantic SST record (17°S–20°N) exhibits a strong upward trend ( $p=0.002$ , Figure 1c). This is similar to the hydrology record and commences at a similar time, thus suggesting that the two phenomena might be linked. The positive correlation between the upward trends in hydrological records and Tropical Atlantic SSTs over the last two decades also suggests a different mechanism from the ITCZ shifts that is associated with a negative correlation between the two variables.

[12] One possible cause for the changes of the hydrological cycle over the last two decades is an intensification of the monsoonal circulation during austral summer and an associated increase in the sea-land temperature contrast. However, this explanation is not supported by sea surface and land temperature data. The coincidence of the onset of the trends suggests that the intensification of the hydrological cycle might simply be due to the increase of water vapor input by the airstream entering the basin from the tropical Atlantic and “feeding” the Amazon hydrological cycle [Stohl and James, 2005].

[13] An increase in sea surface temperature of  $\sim 0.7^{\circ}\text{C}$  as observed for the 1990–2010 period would be expected to cause an increase in the saturation water vapor pressure of approximately 5% (Clausius-Clapeyron equation) [e.g., Held and Soden, 2006], an expectation confirmed by remote sensing estimates of tropical Atlantic air column vapor content [Santer et al. 2007]. All else being equal then, the increased water vapor input can explain around half of the observed Amazon River discharge increase. An additional possibly linked mechanism is therefore likely to be involved, like changes in water vapor outflow or changes in atmospheric stability and cloud convection. A more detailed analysis of the causes behind the observed trends of the hydrological records will likely only be possible with the help of Earth system model simulations.

[14] We note that a link between positive (southern) tropical Atlantic sea surface temperatures and increased precipitation particularly in the northwestern region of the Amazon during the wet season is consistent with the analyses of Yoon and Zeng [2010, Figures 8e and 8f] and Marengo et al. [2011], who analyzed the causes of the exceptional 2009 flood

(their Figure 1f). Furthermore, trends in sea surface salinity also reveal an intensifying trend of the hydrological cycle globally and particularly in the tropics [Durack et al., 2012]. We finally would like to stress that, while the link to a warming tropical Atlantic sea surface might suggest a link to global warming and thus may indicate a longer-term regime shift of the Amazon hydrological regime, the changes from 1990 to present may of course instead be due to multidecadal natural variability.

## 5. Summary

[15] There is thus good evidence that the catchment of the world’s largest river has become substantially wetter since the late twentieth century starting approximately in 1990 with a simultaneous strong trend toward an increase in the annual amplitude of river discharge and an increase of the severity of events. Together, these observations do not support the recent perception of a general imminent drying of the Amazon basin, although there are indications of some drying of the drier southern margins of the basin. The onset of the increasing trend coincides with the onset of a similar increasing trend in tropical Atlantic sea surface temperatures, which suggests that the two phenomena might be related, possibly through an increase in water vapor import from the tropical Atlantic Ocean. It is not immediately clear how an intensification of the hydrological cycle affects forest productivity and the Amazon carbon balance. It may however not be entirely coincidental that the onset of the intensification starts at approximately the same time as an increase of the global land carbon sink [Sarmiento et al. 2010]. The observed progressively greater differences between annual peak to trough flows may have large implications for both the functioning of the natural ecosystems and the people living along the Amazon floodplain and depending upon them for their livelihood.

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