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Key Points:
- Amazon hydrological changes—increasing seasonal amplitude and increase in severe floods and dry conditions
- Likely caused by warming of tropical North Atlantic
- Effect of dry/hot anomalies in forest plot data visible

Supporting Information:
- Figure S1

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Recent Amazon climate as background for possible ongoing and future changes of Amazon humid forests

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Abstract Recent analyses of Amazon runoff and gridded precipitation data suggest an intensification of the hydrological cycle over the past few decades in the following sense: wet season precipitation and peak river runoff (since ~1980) as well as annual mean precipitation (since ~1990) have increased, while dry season precipitation and minimum runoff have slightly decreased. There has also been an increase in the frequency of anomalously severe floods and droughts. To provide context for the special issue on Amazonia and its forests in a warming climate we expand here on these analyses. The contrasting recent changes in wet and dry season precipitation have continued and are generally consistent with changes in catchment-level peak and minimum river runoff as well as a positive trend of water vapor inflow into the basin. Consistent with the river records, the increased vapor inflow is concentrated to the wet season. Temperature has been rising by 0.7°C since 1980 with more pronounced warming during dry months. Suggestions for the cause of the observed changes of the hydrological cycle come from patterns in tropical sea surface temperatures (SSTs). Tropical and North Atlantic SSTs have increased rapidly and steadily since 1990, while Pacific SSTs have shifted during the 1990s from a positive Pacific Decadal Oscillation (PDO) phase with warm eastern Pacific temperatures to a negative phase with cold eastern Pacific temperatures. These SST conditions have been shown to be associated with an increase in precipitation over most of the Amazon except the south and southwest. If ongoing changes continue, we expect forests to continue to thrive in those regions where there is an increase in precipitation with the exception of floodplain forests. An increase in flood pulse height and duration could lead to increased mortality at higher levels of the floodplain and, over the long term, to a lateral shift of the zonally stratified floodplain forest communities. Negative effects on forests are mainly expected in the southwest and south, which have become slightly drier and hotter, consistent with tree mortality trends observed at the RAINFOR Amazon forest plot network established in the early 1980s consisting of approximately 150 regularly censused 1ha plots in intact forests located across the whole basin.

1. Introduction

The extensive tropical rainforests of Amazonia affect the functioning of the Earth's climate through the exchange of large amounts of water, energy, and carbon with the atmosphere [e.g., *Gash and Nobre*, 1997; *Silva-Dias et al.*, 2002; *Keller et al.*, 2004, 2009]. During the past few decades a large research effort has been devoted to understanding the functioning of Amazonian ecosystems and their responses to deforestation, climate change, and altered fire regimes [e.g., *Gash and Nobre*, 1997; *Silva-Dias et al.*, 2002; *Keller et al.*, 2004, 2009; *Malhi et al.*, 2002; *Malhi-and-Phillips*, 2005; *Huntingford et al.*, 2013; *Phillips-and-Lewis*, 2014]. As the pressure on the forests from Amazon development continues, and as global temperature keeps increasing as a result of fossil fuel burning, the AMAZONICA ("Amazon integrated Carbon Analysis") consortium was formed in 2009 to help continue these research efforts. The consortium included seven Brazilian and seven UK research institutions. AMAZONICA combined for the first time basin-wide regular greenhouse gas observations of the lower troposphere [*Gatti et al.*, 2014] with basin-wide regular forest censuses across a widespread 1 ha plot network [e.g., *Phillips and Lewis*, 2014], comprehensive forest carbon pool measurements at a few selected sites of the network [*Doughty et al.*, 2015], comprehensive remote sensing estimates of land use change, and fires and vegetation modeling over a period of 4 years, starting in late 2009. The outcomes of the AMAZONICA project are summarized in a special issue of which this article is one part. The purpose of this article is to

provide an update of status and recent trends of Amazonian climate as a background for the AMAZONICA studies. We also give a brief outlook on what effects on Amazonian humid forests we may expect in response to observed recent climate patterns and whether there are indeed observed signs of such effects using data from the long-term RAINFOR forest census network [*Peacock et al.* 2007], which have been continued from 2009 to 2014 as part of the AMAZONICA project.

The carbon dynamics of Amazonian rainforests are tightly coupled with variations in the regional hydrological cycle, which is in turn significantly modulated by large-scale climate dynamics like, e.g., El Niño–Southern Oscillation (ENSO). For example, it has been reported that the severe drought in 2005 in the western Amazon has led to an increase in tree mortality in forests affected by the drought [*Phillips et al.*, 2009]. Similarly, during the dry and warm year 2010 there was substantial carbon release to the atmosphere from the Amazon basin, while during the wet and warm year 2011 the carbon balance of the basin was neutral [*Gatti et al.*, 2014].

Previous analyses of Amazon River discharge and precipitation data [*Gloor et al.*, 2013] indicate that the hydrological cycle of the Amazon basin has become more variable during the past three to four decades, with more frequent extreme floods (e.g., 2008/2009, 2011/2012, and 2013/2014) and strong droughts (e.g., 2005, 2007, and 2010) occurring compared to previous decades. This increase in extreme events is consistent with an upward trend in the seasonal amplitude of Amazon River discharge measured at Óbidos (Figure 1a), which drains 77% of the Amazon basin (in a strict sense) [*Callède et al.*, 2004]. Precipitation amount has also increased over the last two to three decades (Figure 1b). There has been an increase in net annual precipitation due to an increase during the wet season in the northwestern, northern, and central parts of the basin, although there has been a small decrease during the dry season [*Gloor et al.*, 2013]. An important exception is the comparably small southwestern part of the basin, which overall has become drier and where dry season length has become slightly longer [*Marengo et al.*, 2011; *Fu et al.*, 2013]. In this paper we use the term "intensification of the hydrological cycle" to summarize these combined phenomena: an overall increase in wet season and annual precipitation, an increasing contrast between wet and dry season precipitation as well as between peak and low flows, and an increase in anomalously severe floods and droughts.

In a previous study we had tentatively attributed this intensification, at least partially, to ocean surface warming, specifically rapid warming of the tropical Atlantic over the last few decades (Figure 1d), which we had hypothesized to lead to water vapor increase in air entering the Amazon basin causing an increase in precipitation (Figure 1b). In Figure 1b we have added also estimates from TRMM v7 (Tropical Rainfall Measuring Mission version 7) [*Huffman et al.*, 2007] which cover the past 13 years, as the number of stations included by Climate Research Unit (CRU) has decreased substantially. We have not included Global Precipitation Climatology Project (GPCP) data in Figure 1b [*Huffman et al.*, 2009], because they exhibit a particularly large drop in station numbers in the year 2000 (from 350 to 100).

The proposed mechanism for an increase in annual mean precipitation is broadly consistent with recent simulations of the Climate Model Intercomparison Project 5 analyzed by *Kitoh et al.* [2013], which suggest a future increase of precipitation for the Amazon basin and other tropical monsoonal regions concentrated in the wet season (see, e.g., their Figure 10). Precipitation in these simulations is increasing despite a slight weakening of the atmospheric overturning circulation (Hadley and Walker cells) [*Allen and Ingram*, 2002]. This is because the apparent increase in air water vapor content as a result of sea surface warming causes an increase in water vapor transport from sea to land which overcompensates the decrease of the air uplifting rate. This mechanism is generally consistent with the observed pattern of amplified temperature variability over the land surface compared with sea surface temperature variability during the last few decades [*Dommenget*, 2009]. The latter observation has also been linked to enhanced water vapor import to continents from the oceans with the water vapor enhancing greenhouse warming on land [*Compo and Sardeshmukh*, 2009; *Dommenget*, 2009]. We also note that a recent analysis of terrestrial water storage, estimated with remote sensing of gravity anomalies by *de Linage et al.* [2014], reveals a substantial upward trend in terrestrial water storage in the western and central part of the basin over the past decade. Most recently *Tan et al.* [2015] furthermore stressed a general increase in tropical precipitation over the last decades and used remote sensing data to show that the increase is associated with an increase in the frequency of "mesoscale-organized deep convection" events, while the frequency of less organized convection decreased.

One reason why the results suggesting a recent intensification of the Amazon hydrological cycle are of interest is that they are at odds with a series of well-known studies, which suggested that the Amazon will be drying throughout the 21st century, causing rainforests to be replaced by savannahs and that this forest "dieback"

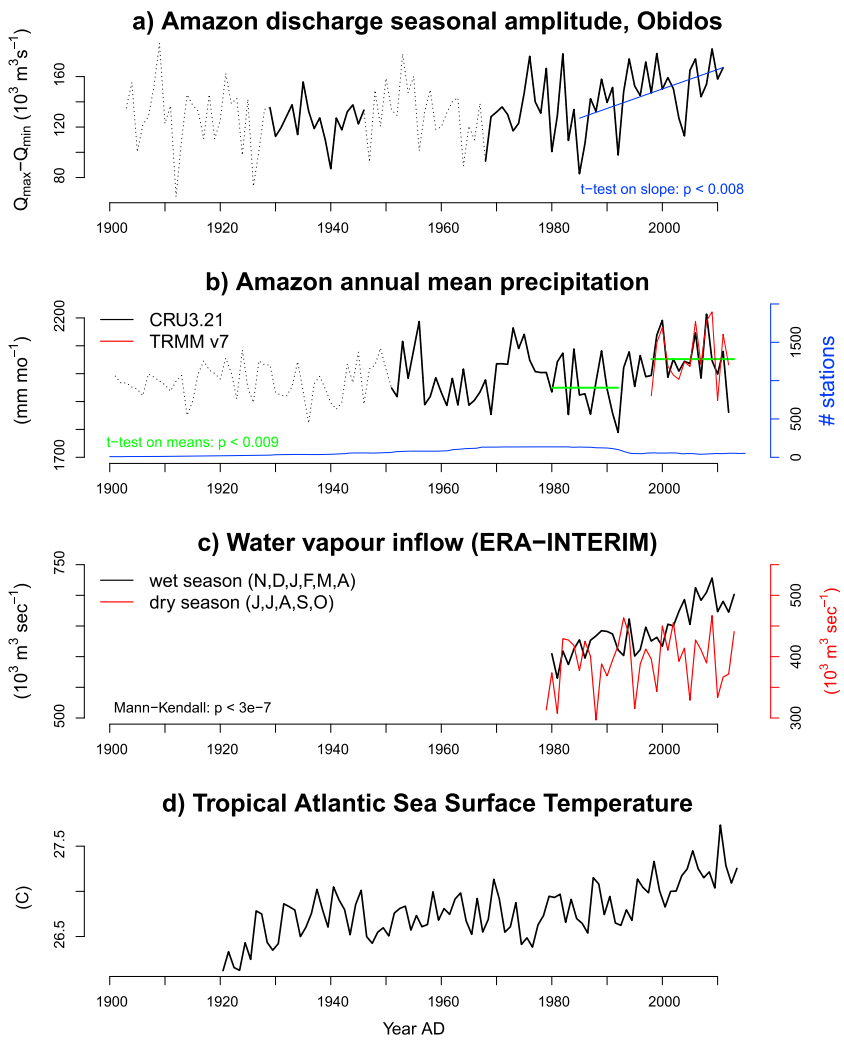

Figure 1. (a) Maximum minus minimum monthly discharge at Óbidos gauge station, draining 77% of the Amazon basin (in a strict sense) [*Callède et al.*, 2004]; dotted lines indicate periods when there are no data available at Óbidos and thus have been estimated by *Callède et al.* [2004] using upstream and downstream hydrographs, (b) annual mean precipitation over Amazon basin and Tocantins catchment combined based on the CRU 3.21 [*Harris et al.*, 2013] climatology and TRMM v7 [*Huffman et al.*, 2007], (c) water vapor inflow into Amazon basin based on ERA-Interim reanalysis [*Dee et al.*, 2011] for wet and dry seasons, and (d) tropical Atlantic sea surface temperatures (5°S to 20°N) calculated from the U.S. National Oceanic and Atmospheric Administration (NOAA) extended reconstructed sea surface temperature (ERSST) record [*Smith et al.*, 2008].

should be ongoing already with drying starting in the east of the basin [*White et al.*, 1999; *Cox et al.*, 2000; *Betts et al.*, 2004; *Cox et al.*, 2008, but see *Huntingford et al.*, 2013]. The results suggesting an intensification of the Amazon hydrological cycle differ also from several other studies, which suggested a drying of the Amazon (*Costa and Foley* [1999]: analyzed period 1977–1996; *Dai et al.* [2009]: 1902–2008; *Marengo et al.* [2011]: 1925–2005; *Trenberth* [2011]; and *Hilker et al.* [2014]), although in 2009 Espinoza et al. reported on a decrease of the low stage runoff in the southern subbasins, but a slight increase of the high stage runoff in the northwestern region for the period 1974 to 2004. Nonetheless together these studies have led to the general perception that the Amazon is drying.

To put our own analysis in perspective, we first briefly summarize known mechanisms for Amazon climate variation. A well-known large-scale control on interannual variability of the spatial distribution of precipitation in the basin is the El Niño–Southern Oscillation (ENSO). El Niño and La Niña conditions affect mainly the northern and central parts of the basin with positive precipitation anomalies associated with La Niña and negative anomalies with El Niño phases [e.g., *Costa and Foley*, 1999; *Marengo et al.*, 2011]. A second

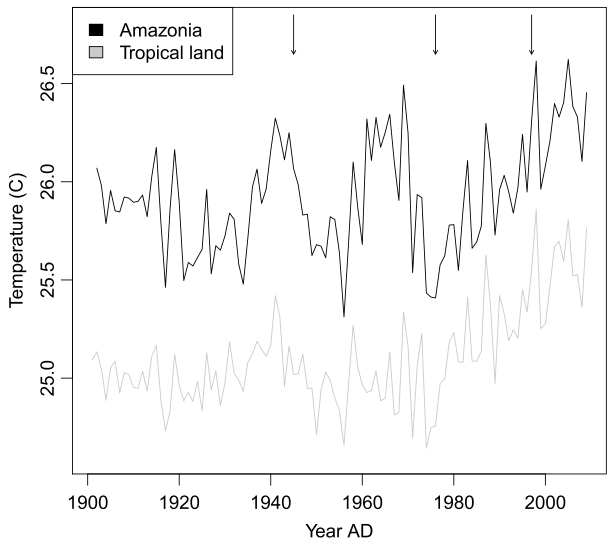

Figure 2. Tropical land temperature 20°S to 20°N and Amazon basin temperature. Arrows indicate when IPO/PDO (Interdecadal Pacific Oscillation/Pacific Decadal Oscillation) index changes sign.

important control on interannual variability of precipitation and runoff over the basin is tropical North Atlantic sea surface temperature (SST) anomalies [*Moura and Shukla*, 1981; *Enfield*, 1996; *Enfield et al.*, 1999; *Marengo et al.*, 2008; *Yoon and Zheng*, 2010]. Basin-wide annual precipitation and total river discharge are anticorrelated with tropical North Atlantic SST anomalies [e.g., *Gloor et al.*, 2013, Figure 1]. The explanation of these authors is that warmer than average tropical North Atlantic SSTs lock in the ITCZ (Intertropical Convergence Zone) more to the north than usual with the shift leading to less overall basin-wide precipitation. *Yoon and Zheng* [2010] furthermore show that the effect of tropical North Atlantic SST anomalies on Amazon precipitation is concentrated to the Amazon dry season (which they define as July to October), while ENSO primarily affects the wet season (December to April). Studies aiming to improve precipitation forecasting in northeastern Brazil, an important region for agricultural production, have similarly pointed out the role of the ITCZ position for precipitation and the relation between North Atlantic sea surface temperature patterns and the ITCZ [e.g., *Uvo and Nobre*, 1989; *Uvo et al.*, 1998].

One particular event with anomalously warm tropical North Atlantic temperatures occurred in 2005. It was paralleled by a strong reduction in precipitation during the end of the wet season in the central westernmost part of the basin [*Espinoza Villar et al.*, 2011]. *Cox et al.* [2008] were able to reproduce Atlantic and Amazon basin temperature and precipitation patterns like the one observed in 2005 in Earth system model simulations and found a strong tendency in their simulations "for the SST conditions associated with the 2005 drought to become more common in the future owing to continuing reductions in reflective aerosol pollution in the Northern Hemisphere." The SST conditions they refer to are elevated temperatures in the Northern Hemisphere tropical Atlantic. The reduction in reflective aerosol pollution in turn is a consequence of stricter emission regulations in the Northern Hemisphere and has been associated with a recent "global brightening" trend at the surface [*Stanhill and Cohen*, 2001; *Wild et al.*, 2005, 2009]. The climate model results thus suggest an increase of such drought-promoting conditions in the future and an important role played by atmospheric aerosol load and spatial distribution.

In this paper, we expand first on earlier climate analyses by looking at recent temperature and precipitation changes. Temperature changes are, amongst others, relevant for vegetation because of their effect on saturation vapor pressure and water vapor deficit, evaporation, and soil moisture status. We then analyze these changes in more detail, spatially resolving discharge trends of subbasins of the Amazon. To support our empirical findings pointing to a recent intensification of the hydrological cycle, we also examine recent trends in water vapor transports into and out of the basin, as well as water vapor content above the Amazon and tropical Atlantic regions. We will further present multidecadal sea surface temperature trends, which give some indications as to what may be behind the observed intensification and thus also of the timescales of the involved phenomena. In the second part of the paper we will discuss what the observed changes may mean for forest vegetation in the nearer future.

2. Recent Amazon Climate Patterns

2.1. Amazon Temperatures

Using gridded temperature data from the CRUTS 3.21 (Climate Research Unit time-series dataset version 3.21 [*Harris et al.*, 2013]), we compare recent annual mean temperatures for the Amazon basin with all tropical land (Figure 2). All our subsequent analyses include the Tocantins River, which drains a catchment at the southwestern end of the Amazon basin, although it is not strictly part of the Amazon basin. A strong temperature increase since the midseventies of the twentieth century is evident for both records, but before

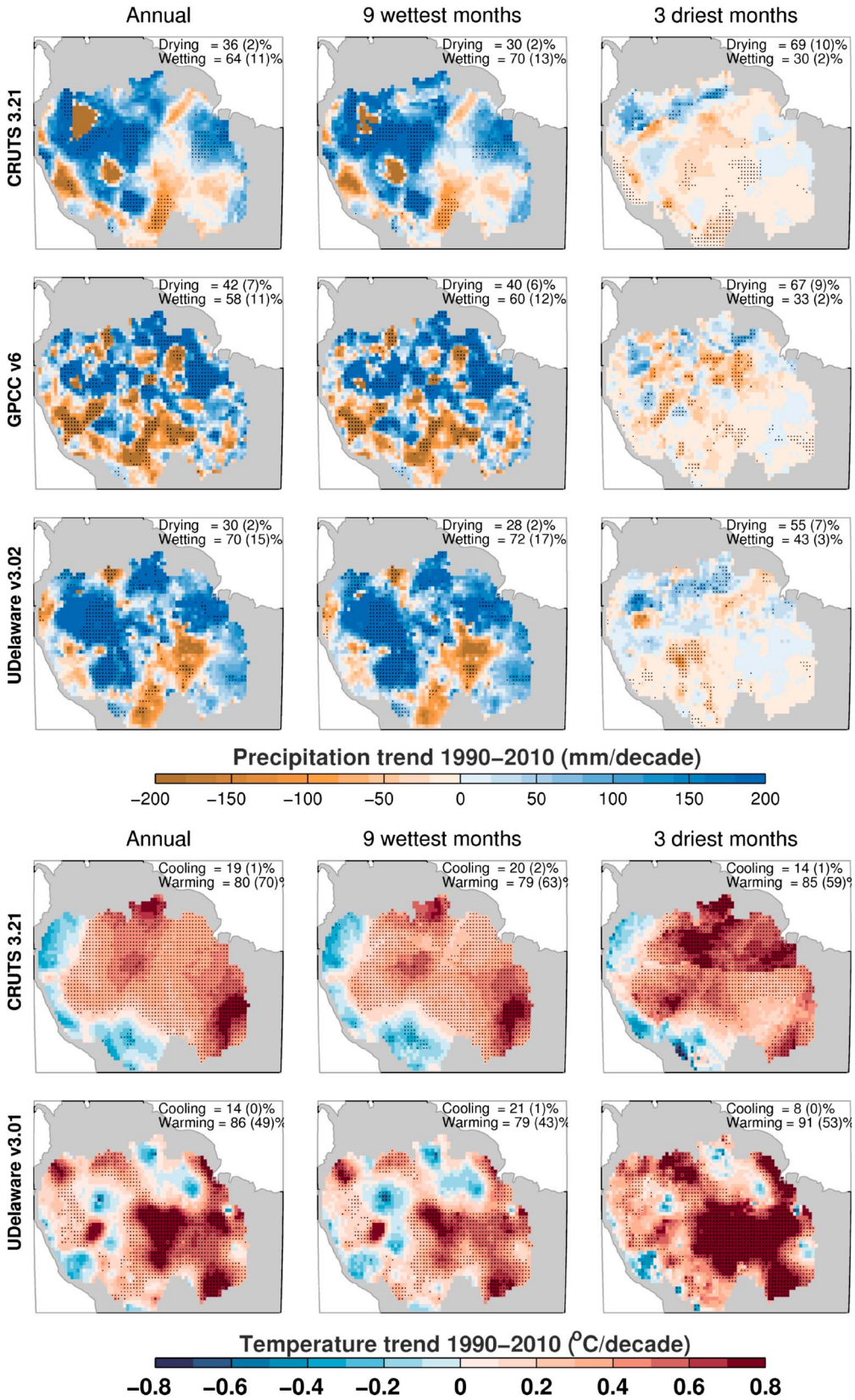

Figure 3. Comparison of precipitation trends for nine wettest months and three driest months of the year for three climatologies (first to third rows) and similar trends for temperature for two climatologies (fourth and fifth rows). The stippling denotes significant trends at the 90% confidence level.

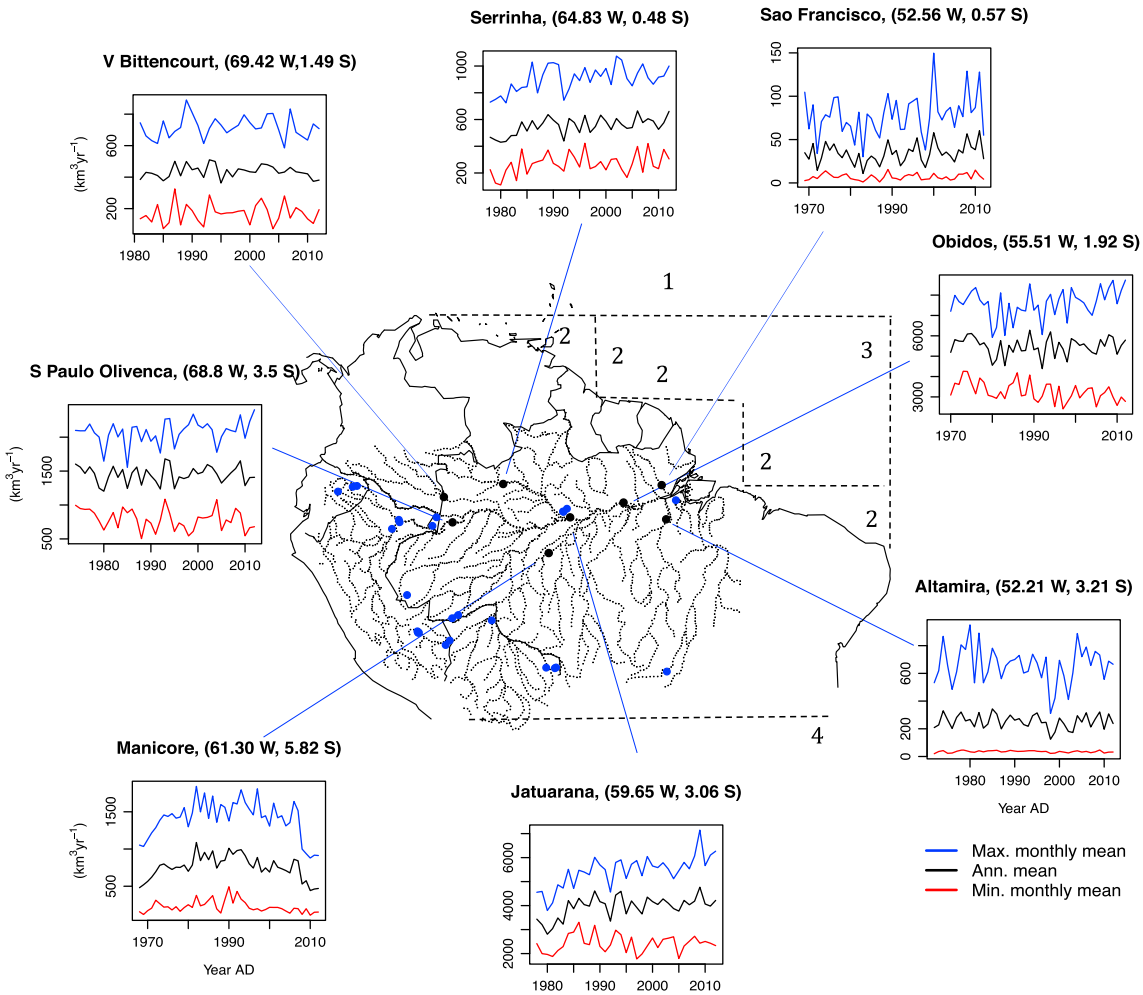

Figure 4. Maximum monthly (blue), annual mean (black), and minimum monthly (red) river discharge of catchments upstream of the gauge stations indicated on the Amazon basin map. Stippled lines indicate boundaries across which we calculated water vapor transports using ERA-Interim reanalysis data [*Dee et al.* 2011] shown in Figure 1c and Figure 5. Black dots indicate the location of the river height gauge stations; blue dots indicate forest plot census sites of the RAINFOR network.

approximately the 1970s the Amazon seems to have experienced approximately 25 year long swings of warming and subsequent cooling with an amplitude of ~ 0.5°C which are absent in the pantropical land record. Similar temperature trends have previously been reported also by *Victoria et al.* [1998], *Malhi and Wright* [2004], and *Collins et al.* [2009] although their analyses end earlier in time.

Spatial maps of temporal trends for CRUTS 3.21 and UDelawarev3.02 (University of Delaware Climate data set version 3.02) climatologies [*Willmott and Matsuura*, 2013] (Terrestrial air temperature: 1900–2010 gridded monthly time series, provided by the NOAA/Oceanic and Atmospheric Research (OAR)/Earth System Research Laboratory (ESRL) Physical Sciences Division (PSD), Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/) in Figure 3, fourth and fifth rows, furthermore suggest that the warming in the Amazon since the midseventies is slightly stronger during the dry season than the wet season. As a result of the strong multidecadal-scale variability the Amazon temperature increase over the last 100 years has been slightly less than for the rest of tropical land in agreement with an earlier temperature trend analysis by *Malhi and Wright* [2004].

2.2. Spatiotemporal Patterns in Precipitation and River Discharge

The peak minus trough values of the Amazon river record measured at Óbidos shown in Figure 1a reveal an increase in the contrast between wet and dry season precipitation. Spatial patterns of wet season versus dry season precipitation trends (here the three wettest quarters versus the driest quarter of the year) of the CRUTS 3.21 UDelawarev3.02 and Global Precipitation Climatology Center version 6 (operated by the German

Table 1. River Gauge Stations

Gauge Station Name	Coordinates	Part of Amazon Basin Drained	River Catchment
		Northern Tributaries	
Villa Bittencourt	(69.42°W,1.49°S)	NE	Japura
Serrinha	(64.83°W, 0.48°S)	N	Negro
Sao Francisco	(52.56°W, 0.57°S)	NW	Jari
		Amazon Main Stem	
Sao Paulo de Olivenca	(68.8°W, 3.5°S)	W	Solimoés
Jatuarana	(59.65°W, 3.06°S)	W, NW, and SW	Solimoés, Negro, and Japura
Óbidos	(55.51°W, 1.92°S)	Rio Amazonas (77%)	Amazonas
		Southern Tributaries	
Manicore	(61.30°W, 5.82°S)	SW	Madeira
Altamira	(52.21°W, 3.21°S)	SE	Xingu

Meteorological Service) [*Schneider et al.*, 2011] confirm this general pattern despite there being considerable spread among the climatologies (Figure 3). The spread is clearly illustrated by the varying ranges of grid cells with positive versus negative trends depending on the climatologies. It is also apparent that the south and southwest of the basin tend to get rather drier all year round, independent of the climatology used. The reason for the spread across different climatologies is differences in data availability, data selection criteria, and spatial interpolation methodology. The magnitude of the differences reflects the comparably coarse data density and gives a sense of the uncertainty of these fields.

Instead of using precipitation data to determine spatiotemporal precipitation variability, we may inquire what in situ riverine records tell us about recent regional precipitation patterns and whether they support earlier conclusions based on gridded precipitation data derived from a quite sparse station network and the Óbidos Amazon River discharge record alone. The Brazilian government maintains a network of river gauge stations across the Amazon basin with records freely available from http://hidroweb.ana.gov.br/. From the available records, we have identified a set of stations, which cover at least the last 30 years. The selected records measure the drainage of the main subbasins of the Amazon and thus give a sense of the spatial distribution of precipitation (Figure 4). The selected sites and the basins they drain are listed in Table 1. This analysis updates the earlier work of *Espinoza Villar et al.* [2009].

Trends in river stage levels can be caused not only by changes in precipitation amounts upstream of the gauge station but also by changes in the timing of precipitation maxima and minima in upstream subcatchments. If there are changes in timings, then at confluence the discharge from upstream may "interfere" positively or negatively, giving a false impression of net change. Thus, to avoid misinterpretation of observed trends of the Óbidos record, we have evaluated whether there are temporal shifts of maximum and minimum discharge in subcatchments upstream. There is indication of greater variation of months of maximum and minimum discharge over the last decade for the Solimões (central western part of Amazon basin), the Tocantins (southeast), and Japura catchments (northwest), but there are no clear trends (Figure A1). Trends in river discharge at the Óbidos gauge station, which drains a large part of the basin, are thus not due to changes in seasonal phasing of precipitation maxima and minima upstream.

We inquired then to what extent the spatiotemporal patterns suggested by precipitation (Figure 3) are consistent with subbasin river discharge records (Figure 4). Records from northern and central parts of the basin reveal indeed tendencies toward increased discharge, particularly during the wet season, in contrast to the southwest (Madeira catchment) which shows a decline to the comparably low 1970 values over the past few years. Overall, the subbasin river discharge records are thus quite consistent with the trends seen in gridded precipitation data and the more integrative Óbidos discharge record alone, which shows an increasing contrast between wet and dry season precipitation with a net annual increase in precipitation (Figures 1a and 1b).

2.3. Recent Changes of Water Vapor Transports and Amazon Atmosphere Water Vapor Content

A strong indication for an increase in wet season precipitation would be an increase in water vapor transport into the basin and an upward trend in water vapor in the atmosphere above the basin. The ERA-Interim reanalysis climate fields from the European Centre for Medium-Range Weather Forecasts [*Dee et al.*, 2011]

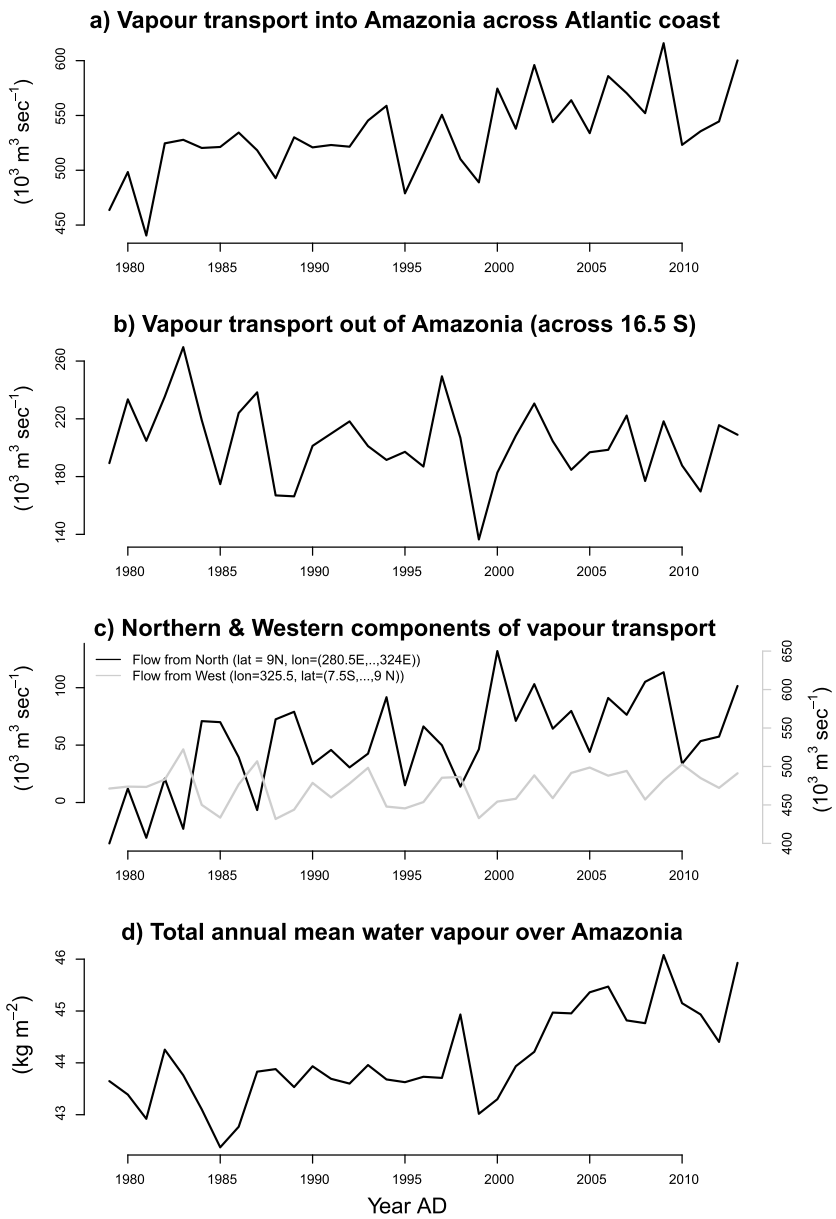

Figure 5. (a) Water vapor transport into Amazon basin (across line 2 in Figure 4), (b) water vapor outflow (across line 4 in Figure 4), (c) water vapor transports across lines 1 and 3 in Figure 4, and (d) water vapor content over the Amazon basin, all based on ERA-Interim reanalysis [*Dee et al.*, 2011].

reveal indeed an upward trend in annual mean water vapor transport into the basin (Figures 1c and 5, transport across line annotated with 2 in Figure 4), and a decrease in transport out of the basin (Figure 5d, transport across line 4 in Figure 4). In order to identify in more detail where the additional vapor is coming from, we have also calculated transports across a fixed azimuth (9°N) and a fixed meridian (325.5°E) (Figure 5c). These lines are annotated 1 and 3, respectively, in Figure 4. We find that the increasing water vapor inflow trend is due to transport from the north, i.e., the transport across the 9°N azimuth. The increase in net water vapor transport into the basin is concentrated in the wet season (Figure 1c), consistent with the observed increase in wet season precipitation (Figures 1a and 3) and also consistent with a net increase in precipitation since approximately 1995 (Figure 1b). Test scores for basin mean changes and trends are included in Figure 1 and are highly significant. It is those basin-wide numbers which are the basis of our assertion of an intensification of the Amazon hydrological cycle, while the spatial patterns (Figure 3) serve to show where the increases happened. We also find a positive trend of water vapor content above the basin (Figure 5d) which has most recently been reported also by *Bordi et al.* [2014], as well as over the northern tropical Atlantic (not shown, region examined:

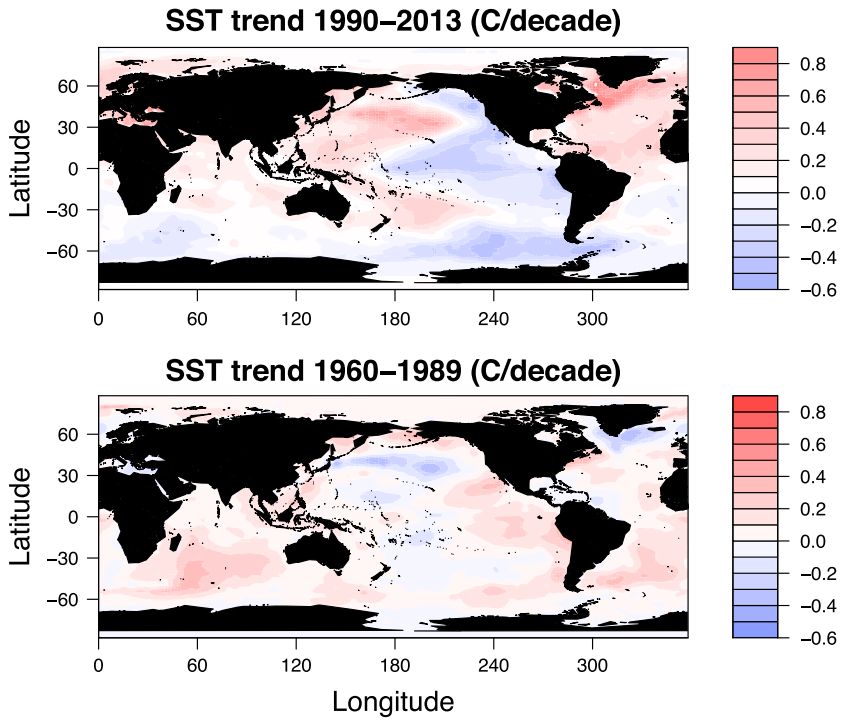

Figure 6. (top) Sea surface temperature trends 1990–2013 based on ERSST [*Smith et al.*, 2008]; (bottom) same as Figure 6 (top) but for 1960–1989.

latitude range: 1.5°N, …, 31.5°N and longitude range: 298.5°E, …, 328.5°E). This latter trend is also seen in stand-alone remote sensing data [*Santer et al.*, 2007] and is consistent with expectations given recent tropical Atlantic surface warming (Figure 1d).

Sea surface warming trends over recent decades have been particularly large in the tropical and Northern Hemisphere Atlantic (Figures 6 (top) and 6 (bottom)) [*Harrison and Carson*, 2007] which feed the airstream entering the Amazon basin. This particularly strong warming has been attributed to global warming and variation of the northward transport rates [*Robson et al.*, 2011], which are generally directed northward in the Atlantic and thus tend to warm the Northern Hemisphere Atlantic [e.g., *Gloor et al.*, 2001].

Sea surface temperatures (SSTs) influence not only water vapor content of the troposphere but also atmospheric circulation at large scale. Spatial maps of SST time trends (Figure 6) reveal a distinct PDO pattern (Pacific Decadal Oscillation/Interdecadal Pacific Oscillation) [*Zhang et al.*, 1997; *Folland et al.*, 2002] in the Pacific Ocean. During the late 1990s the PDO has switched from a positive phase with warm tropical eastern Pacific temperatures to a negative phase with cold tropical eastern Pacific temperatures. SST warming/cooling trends associated with the PDO have changed around 1990 (Figure 6). Negative phases of the PDO are associated with an increase in precipitation in the central and northern parts of the basin and a decrease in the southern parts [*Marengo*, 2004]. The switch of the PDO to a negative phase in the late 1990s is thus likely a second reason for the current intensification of the hydrological cycle. The combination of a strong warming of the Atlantic and the switch to a cool state of the tropical eastern Pacific has recently also been highlighted by *McGregor et al.* [2014] who used data and climate model simulations to demonstrate that the combined effect is an intensification of the Walker circulation characterized by an increase in air upwelling and in precipitation over the Amazon basin. As shown by *Yoon and Zheng* [2010], warmer than usual tropical North Atlantic temperatures tend to cause a northward shift of the ITCZ location during the dry season and thus lead to a slight decrease in dry season precipitation in the south of the basin. We have therefore also examined whether there are trends in the ITCZ location during the dry season over the last decades using ERA-Interim near-surface winds. We found a significant although weak northward trend (not shown).

The strong warming of the North Atlantic over the past few decades is difficult to explain independently from anthropogenic greenhouse warming; thus, it is unlikely just a temperature anomaly due to a climate fluctuation which causes the recent intensification of the hydrological cycle, but rather that global warming

must play a role. Furthermore, since the timescales associated with the PDO and global warming are decadal or longer, they imply decadal or longer timescales for the expected future duration of the intensification.

Besides large-scale changes in the climate system, deforestation may also play some role for observed changes in precipitation, particularly the reduction of precipitation in the south. Removal and replacement of forest vegetation reduces evapotranspiration, the flux of water vapor back from the soils to the atmosphere via forest canopies, and thus causes a decrease in precipitation downwind of the deforested area. This has been examined and the magnitude of the effect estimated by several modeling studies [*Salati et al.*, 1979; *Martinelli et al.*, 1996; *Silva Dias et al.*, 2002; *Werth and Avissar*, 2002; *van der Ent et al.*, 2010] and more recently also quantitatively assessed with observations by combining surface land cover data measured from space with air-mass trajectories [*Spracklen et al.*, 2012]. There have also been suggestions, although controversial, that forests change atmospheric dynamics at large scale (*Makarieva and Gorshkov* [2007], but see *Angelini et al.* [2011]). Furthermore, deforestation in the Amazon is usually associated with biomass burning which occurs mostly during the dry season. Biomass burning changes precipitation because substantial amounts of aerosols are released which act as condensation nuclei and cause a droplet distribution characterized by comparably small droplets. Small droplets coalesce and precipitate more slowly than larger droplets [*Andreae et al.*, 2004].

Deforestation has been particularly intense in the southwestern and western regions of the basin [e.g., *Fearnside*, 2005]. The catchment of the Madeira River in particular has experienced strong deforestation, mostly in the Brazilian part of the catchment [*Trancoso et al.*, 2010] but also in the Bolivian part close to the Andes [*Mueller et al.*, 2012]. The riverine record for the Madeira catchment (measured at Manicore, Figure 4 bottom left panel) exhibits a clear downward trend since approximately 1990. Altogether it is thus conceivable that this trend is related to deforestation via either one or both of these mechanisms, although it is probably not possible to "prove" this conclusively with existing data.

3. Possible Implications for Amazon Humid Forests

What may this mean for tropical forest functioning and well-being in the coming decades? in the following we distinguish terra firme forests, which cover most of the basin from seasonally flooded forests located along the river main stems. Unfortunately, existing data, which would permit firm conclusions, are sparse, and clearly, more studies are needed. Here we attempt to bring together what we can learn from the limited existing results.

Suggestions for terra firme forest response are provided by results on main controls and limiting factors on growth, and limited observations of recent effects of unusually dry and warm episodes in parts of the basin. Field studies measuring carbon and water fluxes as well as incoming photosynthetically active radiation suggest that in the eastern and central parts close to the equator (approximately 5°S to 5°N) forests are mostly light limited [*Costa et al.*, 2009; *Restrepo-Coupe et al.*, 2013]. An important reason are deep roots (reaching up to 10 m depth and more [*Nepstad et al.*, 1994]) permitting access to a large "Plant Available Water" pool. Our knowledge about rooting depth throughout the basin is limited. Nonetheless, recent soil surveys of *Quesada et al.* [2011] reveal that deep roots occur mainly in the region just mentioned where soils are deep, well-developed oxisols (ferralsols) (soil map in Figure 4 and rooting/soil depth in Figure 22 of *Quesada et al.* [2011]). This survey also reveals that northwestern, western, and southwestern soils are comparably shallow and so is rooting depth [*Quesada et al.*, 2011, Figures 4 and 22].

Experimental data on drought response exist just for two forest sites in the eastern tropical Amazon, at Caxiuanã National Forest and Tapajós National forest [*da Costa et al.*, 2010; *Nepstad et al.*, 2007]. At these sites soils and rooting depth are deep. Continued imposed forest drought experiments at these sites had, not so surprisingly, only substantial effects after 3 to 4 years [*Nepstad et al.*, 2002, *da Costa et al.*, 2010] with several years of artificial drought affecting primarily the tallest trees.

In the west/northwest of the basin there are no published data on controls from ecosystem flux studies. It is the region where annual mean precipitation is particularly high, but, on the other hand, rooting depth is shallower compared with the east with soils being generally less physically developed [*Quesada et al.*, 2011, Figures 4 and 22]. Probably, most helpful at this stage for understanding how changes in climate may affect these forests would thus be detailed ecosystem flux measurements, similar to the studies summarized in *Restrepo-Coupe et al.* [2013]. Finally, available data on ecosystem functioning for southern Amazon (10°S) and Cerrado (20°S) terra firme forests reveal "modest to sharp declines" in dry season productivity — revealing that water limitation is an important control on these systems [*Restrepo-Coupe et al.*, 2013; *Costa et al.*, 2009].

Based on the controls on terra firme ecosystem functioning just discussed and recent observed climate patterns, we would thus expect most negative effects of observed climate patterns in regions which experience some drying trend and which have comparably shallow soils. The candidate regions for such negative effects are thus primarily southwestern and southern parts of the basin. By negative effects we mean effects which may lead to substantial changes in forest functioning and shifts in species composition.

Recent observational (as opposed to experimental) studies of terra firme forest response to the recent strong climate variations in the basin have revealed the following. In 2005 the westernmost part of the Brazilian Amazon received substantially less rain than usual during the wet season (~25% reduction at the end of the wet season) causing a severe water deficit in the southern part of this region during the dry season [*Espinoza Villar et al.*, 2011; *Phillips et al.*, 2009]. Forest census plot remeasurements before and after the event suggest this has caused an increase in tree mortality [*Phillips et al.*, 2009] but no substantial change in forest growth rates. An analysis of backscatter data from the SeaWinds Scatterometer (operating in the microwave, 13.4 GHz) on the QuickSCAT satellite, interpreted as measuring changes in forest canopies/biomass, suggest changes in canopy biomass, probably by loss of branches (D. Schimel, personal communication, 2014), and that these changes are noticeable until 2010, suggesting quite substantial changes of tree canopies as a consequence of the 2005 drought [*Saatchi et al.* 2013]. The year 2010 was another rather dry year and with elevated temperatures by up to 1.5°C compared to the 1981–2010 mean, while 2011 was a wet year with similarly elevated temperatures. Atmospheric greenhouse gas balances for 2010 and 2011 suggest a strong decrease in carbon fixation at the end of the dry season in parts of the basin with also elevated losses due to fires compared to 2011 [*Gatti et al.*, 2014]. These large-scale integrating results are consistent with comprehensive on-ground biometric carbon pool measurements at 14 sites, suggesting similar down regulation of carbon fixation during unusually hot and dry months in parts of the basin which experienced unusually dry conditions [*Gatti et al.*, 2014; *Doughty et al.*, 2015].

To examine whether our expectations of terra firme forest response to recent large-scale climate patterns is supported by observations, we analyzed data of biomass dynamics from the RAINFOR inventory plot network [*Peacock et al.*, 2007] in the Amazon basin with sites shown in Figure 4 (blue dots). As already mentioned this network consists of permanent inventory plots established in forests that lack signs of anthropogenic disturbance. These plots cover a range of climates—in particular, several of the sites are in regions where we expect negative effects on the forests. Within the plots (usually 1 ha in size), all trees with stem diameter greater than 100 mm were identified and measured repeatedly to record changes in biomass dynamics over time until they die. For each plot, we calculated biomass mortality between censuses as the amount of biomass that is lost on an annual basis—by determining whether trees are alive or dead. Biomass of trees was calculated by applying allometric equations that included diameter, height, and wood density [*Feldpausch et al.*, 2012]. For our purposes we selected those plots (approximately 80) that were monitored for at least 10 years and contained three or more census intervals with at least one interval in the 1990s and one in 2000s similar as in *Brienen et al.* [2015]. The mean monitoring time for each plot is 21 years, and the mean number of census intervals is 6.5. For this set of plots, we calculated the long-term mortality trends using linear regressions, taking into account "errors in *x* and *y*" using the algorithm of *York et al.* [2004]. For errors in *x* (time) we assumed a uniform distribution for the probability that trees die during a census interval; thus, the uncertainty is $\tau/\sqrt{12}$ where τ is the census interval length; for errors in *y* (mortality) we combine errors from (i) a lack of knowledge when in a census interval a tree died and thus how much biomass the tree had at time of death, (ii) the uncertainty in allometry which we estimate based on *Feldpausch et al.* [2012], and (iii) errors during field work like missing trees. Mortality time trends estimated for plots located close to one another (distance < 5 km) were combined using a weighted average to obtain a single mortality trend estimate for 26 different sites (the site locations are shown as blue dots in Figure 4). The weights were chosen linearly proportional to the total time during which a plot was monitored. We then related the slopes of the regression lines—the mortality time trends—to the precipitation time trends (Figure 7). We find that sites with drying trends tend to be associated with higher mortality rates, which is consistent with our general considerations, although such an analysis can of course not prove any causality. The sites with increased mortality are located in the southwestern region of the basin where a slight drying trend is being observed. These are also regions with comparably shallow soils and thus rooting depth, as already mentioned [see *Quesada et al.*, 2011, their Figures 4 and 22]. There is another interesting fact revealed by this figure: mortality rates are generally positive, even at sites with no net

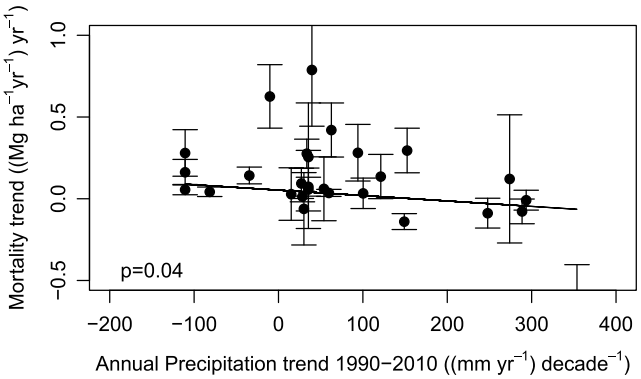

Figure 7. Tree mortality trends at RAINFOR forest plot census sites located in the Amazon basin (blue dots in Figure 4) versus precipitation trends at these sites taken from CRUTS 3.21 [*Harris et al.*, 2013].

drying trend. This result is described in *Brienen et al.* [2015] who hypothesized that it is caused by a lagged demographic effect of past and ongoing growth stimulation on tree turnover times of Amazon rainforests.

A main characteristic of recent changes of the hydrological cycle is an increase in wet season precipitation, not a drying. This raises the obvious question as to what the effects of wetting may be. The general expectation for terra firme forests is that these changes have a near-neutral effect. Possibly, there may be some reduction in productivity as a result of an increase in cloudiness associated with the precipitation increase, and reduction in available sunlight for photosynthesis [*Graham et al.*, 2003]. In contrast to terra firme forests, we expect a stronger direct effect on seasonally flooded forests because the increase in wet season precipitation will cause an increase in the amplitude and duration of the seasonal flood pulse. Seasonally flooded forests are dormant during the flooded period, but an increased flood pulse duration may lead to tree death [*Piedade et al.*, 2013]. Unfortunately, again, existing data on the effect of a prolonged and higher amplitude seasonal flood pulse are very sparse [*Piedade et al.*, 2013]. Nonetheless, based on the work of the same authors some suggestions of expected effects can be derived. Floodplain forest communities are known to exhibit a clear "zonation" parallel to the river main stem. Trees farther away from the main stem are increasingly less adapted to unusually long flooding periods, and thus, an increase in the peak height of the flood pulse may increase mortality for some species [e.g., *Wittmann et al.*, 2004]. On a long term an increase in the flood pulse is expected to cause an upward shift of these forest communities, possibly causing also a decline in species richness, because some of the communities may not be able to keep up with the pace of the changes [*Wittmann et al.*, 2004].

Table 2. Data Sets Used in This Study

Variable	Data Set	Reference
Precipitation	CRU 3.21 (Climate Research Unit)	*Harris et al.* [2013]
	UDelaware v3.02	Willmott and Matsuura; see also *Nickl et al.* [2010]
	GPCP v6	*Huffman et al.* [2009]
	TRMM v7, remote sensing	*Huffman et al.* [2007]
River discharge	Agencia Nacional de águas (ANA), Brazil (http://hidroweb.ana.gov.br)	
Water vapor	ERA-Interim	*Dee et al.* [2011]
	Microwave Remote sensing	*Santer et al.* [2007]
Temperature		
(a) Land	CRU 3.21	*Harris et al.* [2013]
	UDelaware v3.02	Willmott and Matsuura see also *Nickl et al.* [2010]
(b) Sea surface	ERSST	*Smith et al.* [2008]
	HadSST.3.1.1.0	*Kennedy et al.* [2011]

4. Summary and Conclusions

We have analyzed precipitation and temperature variation of the Amazon basin over the last few decades using various datasets summarized in Table 2. Riverine records and climatologies show an increase in precipitation in most of the basin, except the southwest and some of the south. The increase is concentrated in the wet season, while there is a slight reduction in precipitation during the dry season. There is also an increase in the frequency of extreme floods and drier than usual conditions over the same period. The precipitation trends are in agreement with trends of net water vapor transport into the basin, which is increasing, and the increased water vapor inflow is concentrated in the wet season. Climatologies show that the basin has experienced strong warming over approximately the last three and a half decades (since 1980). Spatial maps of the sea surface temperature trend over several decades pre-1990 and post-1990 reveal strong warming in the tropical North Atlantic over the last decades and a switch from a negative to a positive PDO warming/cooling pattern around 1990. Both the implied increased surface pressure differences between tropical North Atlantic and tropical eastern Pacific and the increase in water vapor over the tropical North Atlantic are consistent with the observed intensification of the hydrological cycle [*McGregor et al.*, 2014].

Overall, an increase in precipitation is likely to have a neutral effect on forests (although very large increases in precipitation would likely lead to some decrease in forest productivity [*Schuur*, 2003]) — with the exception of flood plain forests where the increased amplitude of the flood pulse is expected to lead to shifts of the forest communities. Main negative effects of the increasing climate variability on forests will likely be via occasional drier and hotter episodes particularly in those regions which have experienced a slight drying trend, i.e., the southwest and south of the basin. There are indeed indications from regular censuses of a pan-Amazonian forest plot network (RAINFOR) that there is a link between increased tree mortality and hotter/drier conditions.

Appendix A

Examination whether changes of the seasonal amplitude of Amazon river discharge observed at Obidos may be due to changes in the seasonality of river discharge of the rivers feeding the Amazon mainstem.

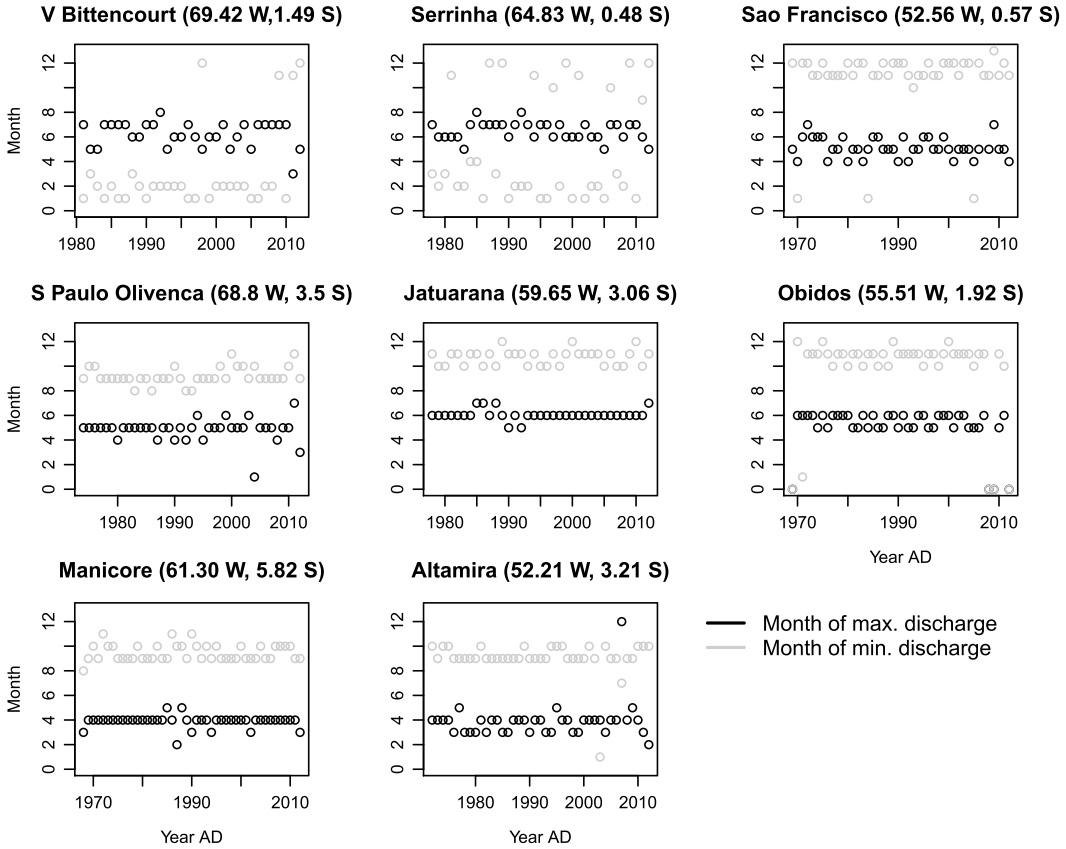

Figure A1. Months of maximum and minimum discharge at the river gauge stations shown in Figure 4.

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Erratum

In the originally published version of this article, a minor error was discovered in the text. The error has since been corrected and this version may be considered the authoritative version of record.