The Drought of Amazonia in 2005

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ABSTRACT

In 2005, large sections of southwestern Amazonia experienced one of the most intense droughts of the last hundred years. The drought severely affected human population along the main channel of the Amazon River and its western and southwestern tributaries, the Solimões (also known as the Amazon River in the other Amazon countries) and the Madeira Rivers, respectively. The river levels fell to historic low levels and navigation along these rivers had to be suspended. The drought did not affect central or eastern Amazonia, a pattern different from the El Niño–related droughts in 1926, 1983, and 1998. The choice of rainfall data used influenced the detection of the drought. While most datasets (station or gridded data) showed negative departures from mean rainfall, one dataset exhibited above-normal rainfall in western Amazonia.

The causes of the drought were not related to El Niño but to (i) the anomalously warm tropical North Atlantic, (ii) the reduced intensity in northeast trade wind moisture transport into southern Amazonia during the peak summertime season, and (iii) the weakened upward motion over this section of Amazonia, resulting in reduced convective development and rainfall. The drought conditions were intensified during the dry season into September 2005 when humidity was lower than normal and air temperatures were 3°–5°C warmer than normal. Because of the extended dry season in the region, forest fires affected part of southwestern Amazonia. Rains returned in October 2005 and generated flooding after February 2006.

1. Introduction

In 2005, large sections of the western Amazon basin experienced the most severe drought in the past 40 yr and one of the most intense of the last hundred years. The international section of the 11 December 2005 issue of *The New York Times* reported that "The drought has evaporated whole lagoons, and kindled forest fires, killed off fish and crops, stranded boats and the villagers who travel by them, brought disease and wreaked economic havoc." Navigation along sections of the Madeira and upper and central Amazon River (known in Brazil as the Solimões River) had to be suspended because the water levels fell to extremely low levels, which led various countries of the Amazon region (Brazil, Bolivia, Peru, and Colombia) to declare a state of public calamity in September 2005. The drought left thousands of people short of food, caused problems with river transportation, agriculture, generation of hydroelectricity, and also affected directly and indirectly the populations living along the rivers of the region.

As the rain forests dried, severe wildfires broke out in the region, damaging hundreds of thousands of hectares of forest. These wildfires produced extensive smoke that affected human health and closed airports,

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schools, and businesses. These ecological impacts affected the feasibility of sustainable forest management in the region, which is currently advanced as a promising basis for the regional economy (Brown et al. 2006). In 1997–98, fires associated with an exceptional drought caused by El Niño devastated large areas of tropical rain forests in northern and eastern Amazonia (Nepstad et al. 1999).

Scientists from various climate research centers in the world [the Hadley Centre for Climate Research and Prediction from the United Kingdom, The Center for Weather Forecasts and Climate Studies (CPTEC/INPE) in Brazil, and the University of California, Los Angeles in the United States] have suggested that a rise in sea surface temperatures (SSTs) in the tropical North Atlantic is most likely the primary cause of the drought of 2005, in the absence of El Niño. A result of this SST anomaly would be a weakening of the northeast trade winds and the moisture transport from the tropical Atlantic into the Amazon region. Some studies (Goldenberg et al. 2001) have attributed these SST increases to a natural climate cycle termed the Atlantic Multidecadal Oscillation (AMO), while others suggest that climate change may instead be playing the dominant role (Emanuel 2005; Webster et al. 2005; Mann and Emanuel 2006; Trenberth and Shea 2006). The AMO pattern implies decadal-scale variations in SST anomalies in this region, superimposed on a warming trend also detected in surface temperature worldwide, and it would be at least partially responsible for circulation changes leading to the drought of 2005 in Amazonia.

The present study focuses on the observational characteristics of the drought of 2005 in Amazonia, on analysis of its major climatic and hydrological features, and on identification of previous drought events in the recent past. We use several rainfall datasets to verify if the depiction of rainfall anomalies corresponds with the observed river flow anomalies in the region. We investigate possible causes of the drought such as changes in sea surface temperature fields in the tropical Pacific and Atlantic Oceans, in circulation, and moisture transport from the tropical Atlantic into Amazonia.

2. Background

Previous studies (Ropelewski and Halpert 1987, 1989; Marengo 1992, 2004; Uvo et al. 1998; Ronchail et al. 2002; among others) have identified negative rainfall anomalies in Amazonia associated with El Niño–Southern Oscillation (ENSO) events and with SST anomalies in the tropical Atlantic as well. The studies have linked some of major droughts in Amazonia to (a) the occurrence of intense El Niño events, (b) strong warming in the surface waters of tropical North Atlantic during the Northern Hemisphere summer–autumn season, or (c) both. Very intense El Niño events have been associated with the extreme droughts in 1925–26, 1982–83, and 1997–98, and the last two also experienced intense warming in the tropical North Atlantic along with warming in the equatorial Pacific.

There is evidence of extensive droughts, and perhaps widespread fires, linked to paleo-ENSO events that occurred in the Amazon basin in 1500, 1000, 700, and 400 BP, and these events might have been substantially more severe than the 1982–83 and 1997–98 events (Meggers 1994). The best documented case of an earlier drought event in Amazonia linked to El Niño event was during 1925–26 (Sternberg 1968, 1987; Williams et al. 2005). Rainfall anomalies in the central-northern Brazilian Amazonia and southern Venezuela in 1926 were about 50% lower than normal. During this particular drought, extensive fires prevailed in Venezuela and the upper Rio Negro basin. Unusually high air temperature anomalies were recorded in Venezuelan and northern Brazilian Amazonian towns for both 1925 and 1926, and it is plausible that the dryness in the northern portion of the Rio Negro basin in 1925 also contributed to the major drought in 1926 by a depletion of soil moisture.

Contrary to the above droughts, the droughts of 2005 as well as those in 1963–64 and in 1979–81 were not associated with El Niño events. While several studies analyze the droughts of 1982–83 (Aceituno 1988; Marengo et al. 1998) and 1997–98 (Nepstad et al. 1999) and their impacts in climate, hydrology, and fires in Amazonia, there are only casual references to the drought event of 1963–64 in some local newspapers. The variability of SST anomalies in the tropical Pacific is responsible for less than 40% of rainfall variability in the Amazon basin (Marengo 1992; Uvo et al. 1998), suggesting that the effect of other sources of variability, such as the meridional SST gradient in the intertropical Atlantic (which affects mostly northern and central Amazonia), or land surface processes and large frequency of transients from the South Atlantic (important for southern Amazonia) may be also important in the interannual rainfall variability in the region (Marengo et al. 2003; Ronchail et al. 2002).

3. Objectives

The main objectives of this study are to explore the main observed climatic and hydrological characteristics of the Amazonian drought of 2005 and can be summarized as follows:

- An assessment of basinwide meteorological and hydrological characteristics during 2005 using river data as well as various rainfall datasets.

- An assessment of the upper- and lower-level large- and regional-scale circulation fields since 2004 and detection of anomalies during 2005 that could lead to the drought.
- An assessment of impacts of tropical Pacific and Atlantic SST variability during the drought in Amazonia in 2005, and comparisons with other drought years.

4. Data and methodology

Rainfall data were obtained from several stations in the Amazon region collected by the following Brazilian institutions: National Institute of Meteorology [Instituto Nacional de Meteorologia (INMET)], the National Water Authority [Agencia Nacional de Aguas (ANA)], the Center for Weather Forecasts and Climate Studies/National Institute for Space Research [Centro de Previsão de Tempo e Estudos Climáticos/Instituto Nacional de Pesquisas Espaciais (CPTEC/INPE)], and the Brazilian Air Force [Centro Tecnologico Aeroespacial (CTA)]. The anomalies were calculated from the 1961–90 long-term mean (LTM).

A new experimental rainfall dataset developed at CPTEC/INPE has also been used. This new dataset includes rainfall records from a very dense and comprehensive network of stations (J. Tomasella 2006, unpublished manuscript). The available information comes from archives of various institutions of Brazil and South America for the period 1951–2000. The sources of data were the meteorological services of Venezuela, Brazil, Colombia, Paraguay, Ecuador, Peru, and Bolivia. In Brazil data also were provided by the regional meteorological centers of the Amazonian states of Amazonas, Acre, Rondônia, Para, Amapá, and Roraima. Most of the rainfall data from Brazil and other Amazon countries were obtained in digital form directly from the sources, while part of the rainfall data from Bolivia, Venezuela, Peru, Ecuador, and Colombia were derived from meteorological and hydrological summaries published in bulletins, available from the national meteorological services Web sites or in printed form.

All data from the CPTEC/INPE experimental rainfall dataset were subjected to quality control and homogenization. Subsequent interpolation was done using the software GSLib (Deutsch and Journel 1997) based on kriging and taking into account the topography in South America by using topographic data from the National Aeronautics and Space Administration (NASA) Space Shuttle radar mission degraded to 0.25°, the resolution of the climatology map. Monthly rainfall anomaly maps from January 2004 to October 2005 were produced as deviations of them 1971–2000 climatology. This period was chosen because more than 80% of the stations have complete information for this time interval.

For tropical South America, other datasets used were the gridded rainfall fields from Chen et al. (2002), Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997), and the Global Precipitation Climatology Center (GPCC; Rudolf et al. 1994; Rudolf and Schneider 2005). The Chen et al. (2002) dataset consists of monthly global (land and ocean) analyses of precipitation for an extended period from 1948 to the present. The land component of the analyses (PREC/L) using a 2.5° latitude–longitude grid is available for 1948–2000. These analyses are derived from rain gauge observations from over 17 000 stations collected in the Global Historical Climatology Network (GHCN), version 2, and the Climate Anomaly Monitoring System (CAMS) datasets. The CMAP used a technique that produces pentad and monthly analyses of global precipitation in which observations from rain gauges are merged with precipitation estimates from several satellite-based algorithms (infrared and microwave). The analyses are on a 2.5° × 2.5° latitude–longitude grid and extend back to 1979 (Xie and Arkin 1997). We used the CPTEC/INPE experimental rainfall dataset and the GPCC data for the mapping of rainfall anomalies during the drought of 2005.

The GPCC gauge-based gridded precipitation dataset is available for the global land surface only. The quality control is done with respect to outliers and homogeneity (both test and removal) as well as the interpolation, and gridding is done as thoroughly as possible in order to obtain optimal results (Rudolf et al. 1994; Beck et al. 2005). The GPCC datasets are available in the spatial resolutions of 1.0° latitude × 1.0° longitude. No comparisons were made for previous drought events (1963–64, 1982–83) since the GPCC-monitoring product is available since 1996 only. These data are available as mean monthly precipitation totals and anomalies from the long-term mean for 1961–90.

River discharge and levels datasets from gauging sites in the Brazilian Amazonia were provided by ANA and the administration of the Port of Manaus. Most of the river data (levels and streamflow) are available since the 1930s, with exception of the levels of the Rio Negro at Manaus that are available since 1903. River information from Peru and Bolivia were extracted from the Web sites and printed bulletins of the hydrological services from those countries. Location of the stations is shown in Table 1.

Circulation fields were extracted from the National Centers for Environmental Prediction (NCEP) global

TABLE 1. River and rainfall stations used in this study. Sources are INMET, CTA, ANA, Federal University of Acre (Brazil), SENAMHI (Bolivia), and SENAMHI (Peru).

Station	Lat (°S)	Lon (°W)
River stations		
Tabatinga (Solimões River)*	4.25	69.9
Fonte Boa (Solimões River)*	2.53	66.10
Jiparaná (Jiparaná River)	10.88	61.95
Tucuruí (Tocantins River)	3.75	49.68
Lajeado (Tocantins River)	10.00	48.02
Guaporé (Guaporé River)	15.11	58.96
Curua Una (Curua Una River)	2.78	54.28
Balbina (Uatumã River)	1.91	59.46
Rio Branco (Acre River)	9.96	67.80
Manaus (Rio Negro)	3.11	60.01
Muelle Iquitos (Amazon River*)	3.71	73.23
Puerto Varador (Mamoré River)	14.86	64.98
Puerto Almacen (Rio Ibaré)	14.80	64.90
Rainfall stations		
Manaus	3.38	60.01
Rio Branco	9.58	67.48
Porto Velho	8.46	63.55
Porto de Moz	1.44	71.68
Soure	0.37	69.12
Sao Gabriel da Cachoeira	0.43	48.33

* Amazon River is the name of the Solimões River in Peru, Colombia, and Ecuador.

reanalyses (Kalnay et al. 1996) with a resolution of 2.5° latitude–longitude grid that are available from 1958 to the present. SST data were extracted from the geographically complete climatology of SST and sea ice for 1961–90, which was created along with version 2.2 of the Global Sea Ice and SST dataset (GISST2.2; Parker et al. 1995). The mean SST climatology was developed using a globally complete SST background field. These SST data have been updated up to 2005 using the spatial resolution optimum interpolation (OI) SST analysis that has been produced at the National Oceanic and Atmospheric Administration (NOAA) using both in situ and satellite data from November 1981 to the present (Reynolds et al. 2002).

Bimonthly SST anomaly maps were implemented using the GISST2.2 dataset for drought years in Amazonia, 1925–26, 1963–64, 1997–98, and 2004–05, in order to compare drought events in Amazonia that are related to warming in the tropical Pacific and/or to warming in the tropical North Atlantic. The years of 1925–26, 1982–83, and 1997–98 were strong El Niño years while the years 1963–64 and 2004–05 were related to near-normal conditions in the tropical Pacific and to anomalously warm surface waters in the tropical North Atlantic. In addition, time series of bimonthly SST anomalies since 1920–2005 were analyzed for the Niño-3.4 region and the tropical North and South Atlantic sectors, and for the difference between SST anomalies in the tropical North and South Atlantic. The purpose of this procedure was to analyze the behavior of the SST gradient in the tropical Atlantic and to analyze its correlation with rainfall anomalies in Amazonia. Some analyses were performed at the seasonal level: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON).

5. Results and discussion

The river levels in the Amazon region normally follow the seasonal cycle of precipitation. Rainfall in northern Amazonia peaks in March–May while in southern Amazonia the wet season occurs a bit earlier (December–February). The seasonality of rainfall has been discussed in previous studies (Marengo 1992, 2004; Ronchail et al. 2002). It depends on the seasonal cycle of the low-level circulation in the tropical Atlantic sector, with the intertropical convergence zone reaching its southernmost position early in austral summer, and then moving northward, reaching central Amazonia in late summer–early autumn.

Rivers in the region follow rainfall annual cycle, with streamflow of rivers with basins in southern Amazonia peaking during austral summer The southwestern part of the Amazon, where the basins of the Solimões, Madeira, Tapajos, Mamoré, Ichile, and Beni Rivers are located, experiences its peak rainy season in early austral summer (December–February) while the peak of the rainy season in north-central Amazonia (where the basins of the Negro and Uatuma Rivers are located) occurs during autumn (March–May). There is a lag of 2–3 months between the peak of the rainy season and the peak in streamflow/levels. This pattern suggests that drought affecting southern Amazonia in early austral summer may have an impact on river levels but would not necessarily affect rainfall and river levels in northern and central Amazonia since their seasonality is different.

Rainfall in the austral summer and autumn of 2005 was below the long-term average for the western Amazon region, which caused rivers to drop to record low levels.

The following section addresses some of the key issues that have been raised in relation to the drought of 2005.

a. *The rainfall and hydrology characteristics of the Amazon basin during the drought of 2005*

The meteorological services in the Amazon countries reported that the hydrological year 2004–05 exhibited rainfall well below the normal values. In the Peruvian

Amazonia, mean rainfall for the hydrological year September 2004–August 2005 diminished to 39% of the normal rainfall (SENAMHI 2005). CPTEC/INPE has reported that rainfall over the Solimões River basin was between 50% and 60% of the normal values between January and April 2005, 33% between June and August, and 65% between July and September. Rainfall in the basins of the Bolivian Beni and Mamoré Rivers was about 60%–80% of the normal values for the January–April 2005 period.

The sequence of rainfall maps derived from the CPTEC/INPE experimental rainfall dataset maps of Fig. 1a exhibits rainfall anomalies for the entire Amazon basin from November 2004 to October 2005. The anomaly maps show that the rainfall deficiency situation aggravated after November 2004 in northern Amazonia. With the exception of some rainfall episodes in the central and eastern part of Amazonia, most of the region experienced rainfall deficiency during the peak rainfall season in late 2004 and early 2005. After April 2005 rainfall anomalies became largely negative in southern and western Amazonia in Bolivia, Brazil, and Peru, and in particular, in the Solimões River basin. From May through September 2005 negative anomalies larger than 100 mm month^{-1} were observed over western Amazonia.

During the same period central and eastern Amazonia experienced rainfall above normal. Isolated rainfall episodes in the central and eastern Amazonia are depicted by the positive anomalies in those regions. Both the GPCC (not shown) and the experimental rainfall dataset from CPTEC exhibit qualitative similarities in terms of rainfall anomalies in large sections in Amazonia. Some differences can be attributed to the fact that the anomaly maps in Fig. 1 and those derived from GPCC use different climatological baselines. GPCC used the 1961–90 LTM while the CPTEC experimental dataset used 1971–2000 LTM, and more stations are used on this dataset as compared to GPCC. Since precipitation in Amazonia has experienced important changes in magnitude, particularly during the last 40 yr (Marengo 2004), we consider that the 1971–2000 LTM is more reliable and realistic than the 1961–90 period.

Most of central and southwestern Amazonia experienced rainfall deficiency during the peak season in December to February 2004–05, when rainfall was about 50%–60% of the normal in the Solimões and Madeira River basins and about 80%–90% of normal in the Rio Negro basin. In March to May 2005 rainfall in the Solimões and Madeira River basins was about 50%–60% of normal while in the Rio Negro basin rainfall shows values between normal and above normal (100%–110%). After April 2005, rainfall anomalies became largely negative in southern and western Amazonia, encompassing parts of Bolivia, Brazil, and Peru.

It is clear that the drought of 2005 differed from previous recorded events, since it strongly affected the southwest portion of the Amazon basin. Because of the sheer size and significant travel time of river flow in the Amazon basin, the reduced river flows of the southwestern portion occurred when the water levels were already receding at the Manaus station. Therefore, rainfall anomalies strongly affected the water level at Manaus late in the dry season, increasing the river-level recession in October while the peak discharge remains unaffected. Figure 2 shows the time series of the Rio Negro levels at the Manaus station during the June–July peak and September–October lower water seasons. The level in Manaus integrates rainfall over the northern and western portions of the basin. Reduced rainfall over those portions of the Amazon basin would imply anomalously low river levels in Manaus. On the peak season levels, 1926 water levels were by far the most anomalous in this record since observations at the Manaus Port started in 1903, followed by 1992, 1912, and 1906, all El Niño years. The years 1983 and 1998 did not show the extreme negative anomalies in peak river levels, suggesting that the river levels during those drought years were lower during seasons other than the peak season. Thee river anomalies remained between $-1.0\ \sigma$ and $-1.5\ \sigma$ below mean levels. During the low water season, 7 yr had values lower than $-1.5\ \sigma$, below the mean; three out of these years were El Niño years. During 2005 the peak river-level season showed values close to the mean, while the low water season values, however, were extremely low.

The difference in the spatial features of these drought years and 2005 and perhaps the 1963–64 droughts was that the drought struck hardest in western and southwestern Amazonia, a feature not associated with previous El Niño events, but probably associated with an increase in tropical North Atlantic SSTs. Figure 2 shows that the peak water level at Manaus in 2005 was higher than normal, suggesting that the drought of 2005 mostly affected western Amazonia, and its impacts on the Rio Negro levels were detected mainly during the dry season from May to September 2005.

b. The representation of the drought of Amazonia in 2005 by the different available rainfall datasets

Several of the available gridded datasets used in climate studies do not include data from many rainfall stations in Amazonia, and interpolation using various methods has to be applied to fill the gaps and produce rainfall estimates in regions with poor station coverage. The GPCC dataset shows similarities with the rainfall

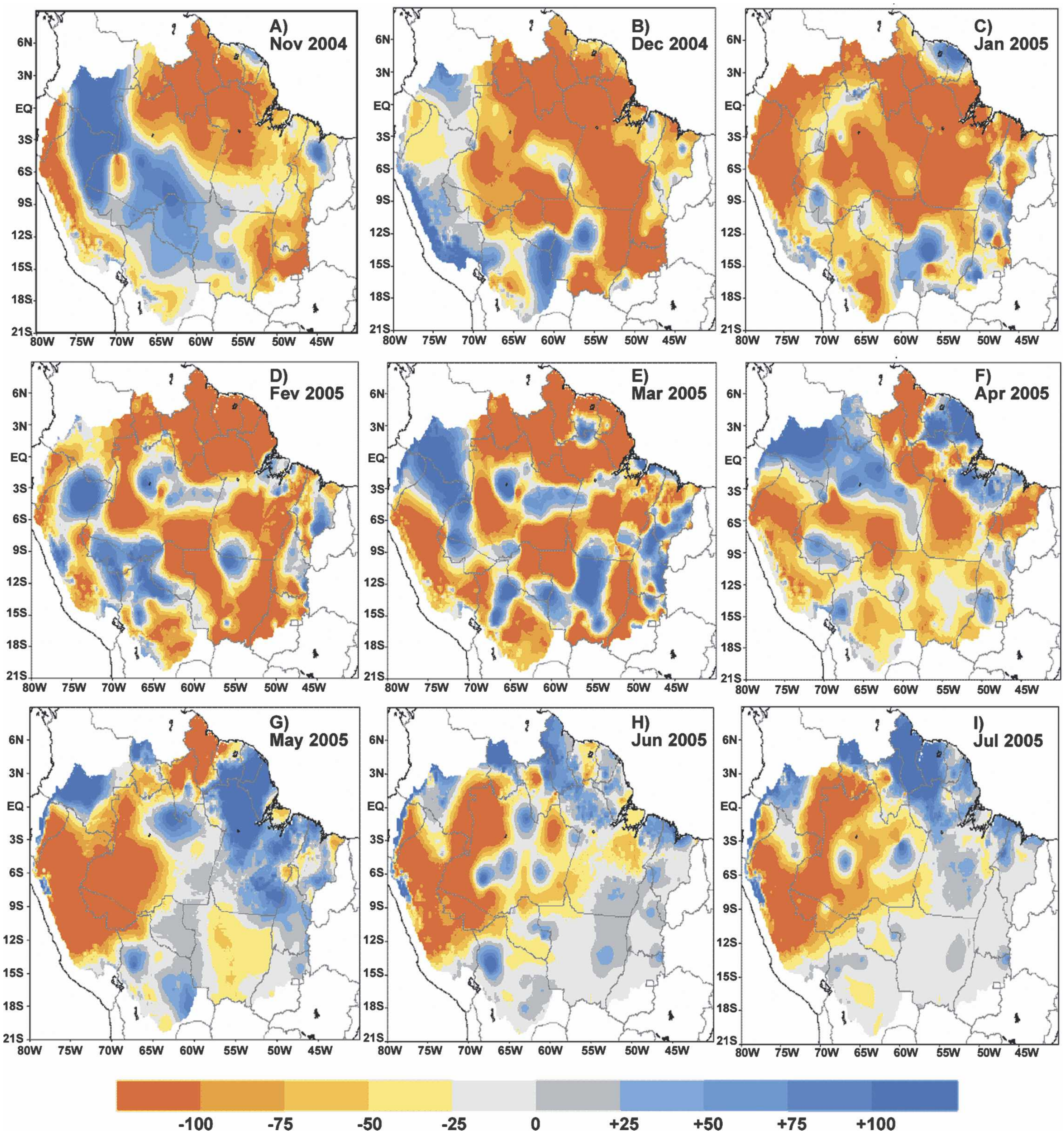


FIG. 1. Rainfall anomalies from November 2004 to October 2005. Anomalies are in relation to the 1971–2000 baseline period. Data are from CPTEC/INPE experimental rainfall product and are available at 0.25° lat–lon gridbox area. Red/blue colors indicate negative/positive rainfall anomalies. Units are in mm month^{-1}. (Source: J. Tomasella, CPTEC/INPE.)

anomaly maps generated by the meteorological services in the Amazon countries. Some small differences among maps can be attributed to the interpolation that the GPCC analyses or any gridded data analyses use for areas with few or no stations.

Figure 3 shows that for most rainfall gauging stations, especially those in southwestern Amazonia, late 2004 and early 2005 experienced below-normal rainfall, perhaps associated with a late start of the rainy season that normally starts between September and October. The length of dry seasons can be defined by the number of months with rainfall less than 100 mm month^{-1} (Sombroek 2001). This criterion seems to work better in southern and central Amazonia, while in Sao Gabriel

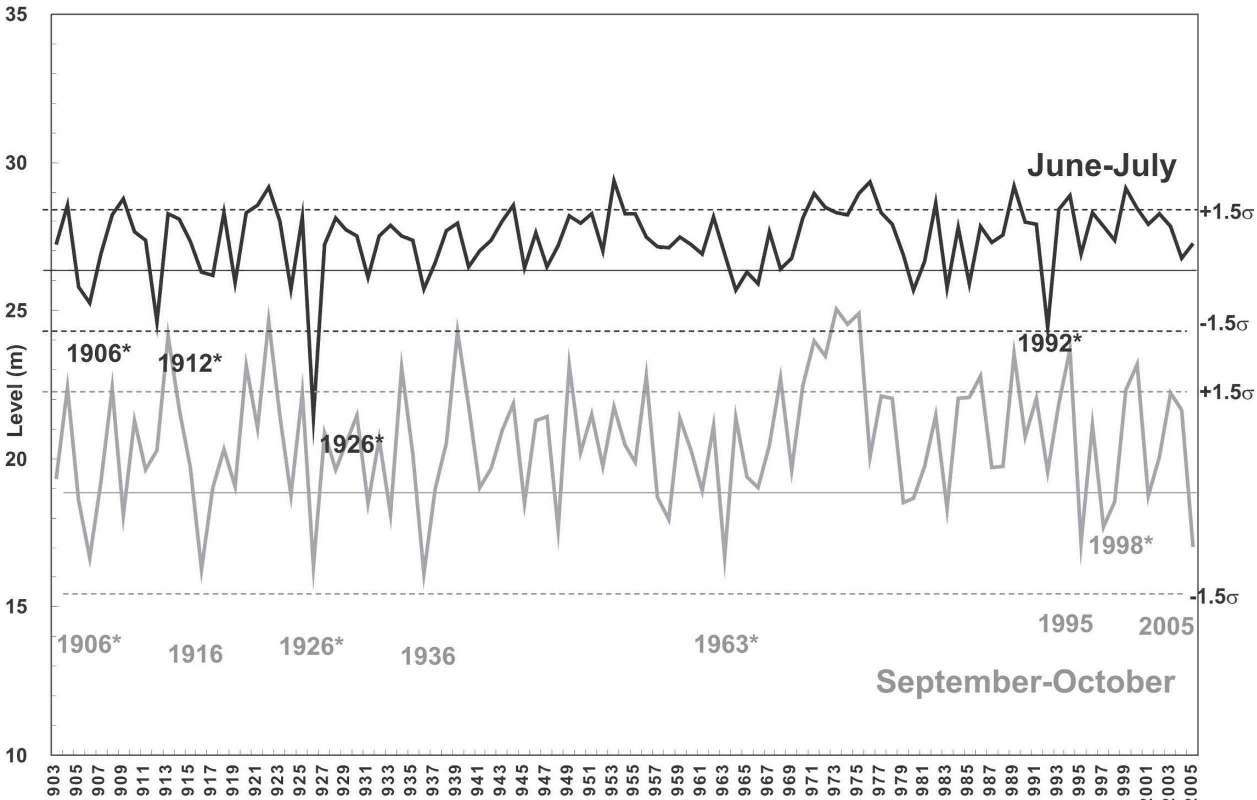


FIG. 2. Rio Negro water levels at Manaus (m) in the Manaus station, Brazil, during the peak water-level season in June–July (black lines) and the low water-level season in September–October (gray lines). Full/thin broken lines represent the mean $\pm$ 1.5 σ. The number indicates years where the levels reached values lower than 1.5 σ. Asterisks depict El Niño years. (Source of river data: ANA, PORTOBRAS.)

da Cachoeira this threshold cannot be applied because of the high rainfall that does not allow for a definition of a dry season length or the onset of the rainy season. The duration of the dry season in 2004 was longer than in a normal year in Porto Velho and Rio Branco, both in southwestern Amazonia. The subsequent rainy season experienced above-average rainfall and then the 2005 dry season was below average at least until October 2005 where rainfall increased again. During other drought years during El Niño events, rainfall during the rainy season is below normal. In Manaus, even though rainfall was below normal during November and December 2004, it recovered later and was about 100 mm month^{-1} above average during the peak season MAM 2005, while during El Niño years of 1983 and 1998 rainfall was well below normal from December through March.

Rainfall time series during the peak rainy season in northern and southern Amazonia are shown in Figs. 4a and 4b, for the peak season February–May (FMAM) for northern Amazonia and December–March (DJFM) for southern Amazonia, respectively, during 1950–2005. The figures show how various rainfall datasets can depict interannual variability and allow for an identification of reduced rainfall in the rainy season and possible droughts. The Chen et al. (2002) and CMAP gridded datasets were assessed for the period 1950–2005. In addition, indices of rainfall for northern and southern Amazonia since 1980 were also calculated, and various reference periods were used to calculate anomalies from these indices (1961–90, 1981–2005, 1979–95, and 1981–2004). Regardless of the systematic differences among all datasets, the rainfall series in northern Amazonia show the large negative departures during the droughts of 1963–64, 1980–81, 1982–83, 1997–98, and 2005 in northern Amazonia. The index derived from rainfall stations shows the year 1998 with negatives anomalies of the order of 1.5 mm day^{-1} while 2005 exhibited 1 mm day^{-1} below normal, implying that the drought of 1998 was more intense than that of 2005. The rainfall index derived from the NCEP reanalysis is the only one that shows positive rainfall anomalies, in contrast with the other rainfall station and gridded datasets.

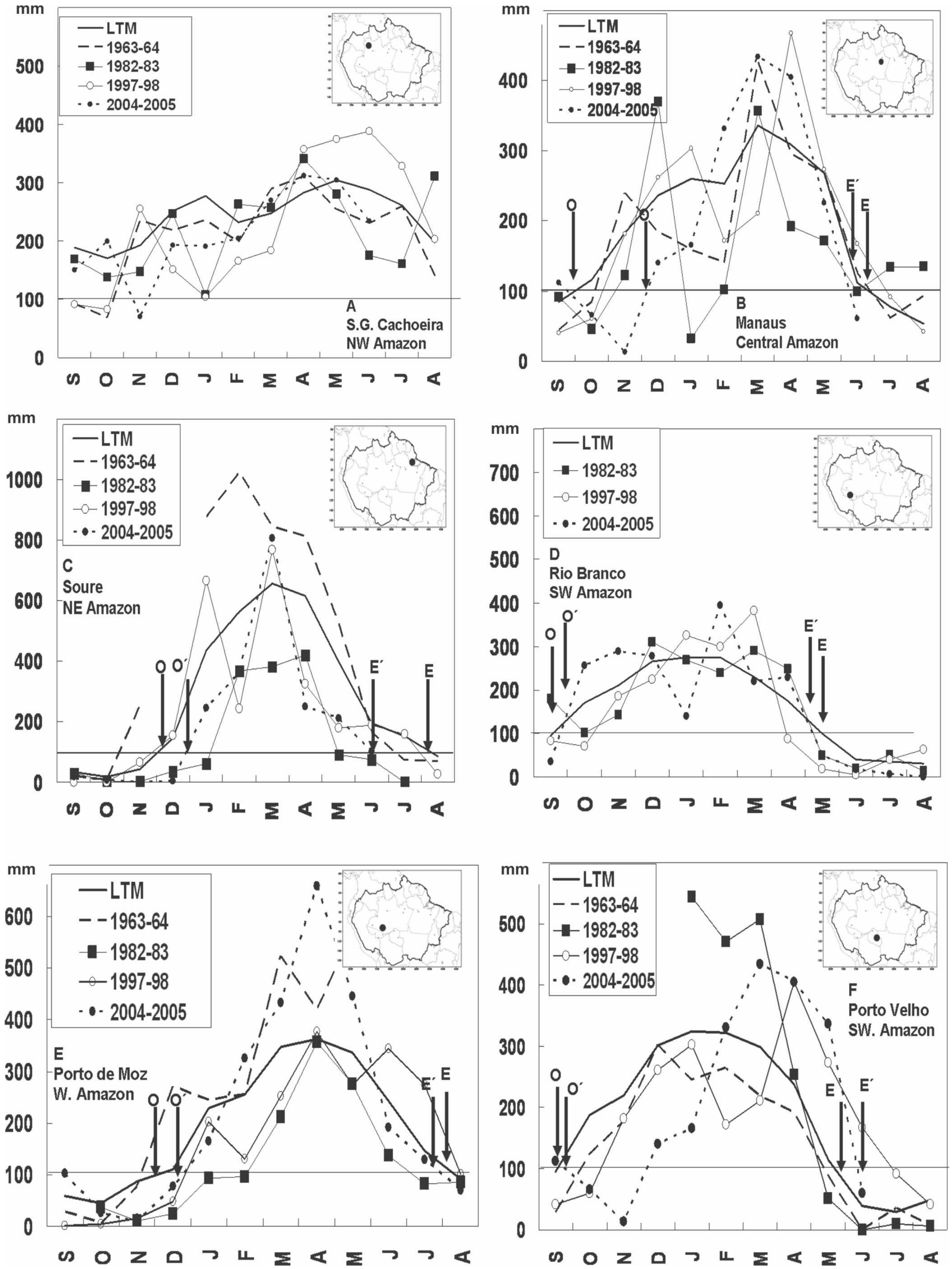


FIG. 3. Rainfall during various drought years (1963–64, 1982–83, 1997–98, and 2004–05) in stations in various sectors of Amazonia (source of data: ANA, CTA). The hydrological year is September–August. The mean is from the 1961–90 LTM. *O/E* represents the climatic onset/end of the rainy season, and *O′/E′* represents the onset/end of the rainy season during 2004–05. The threshold value of 100 mm month^{-1} is shown as indicator of the dry season (Sombroek 2001).

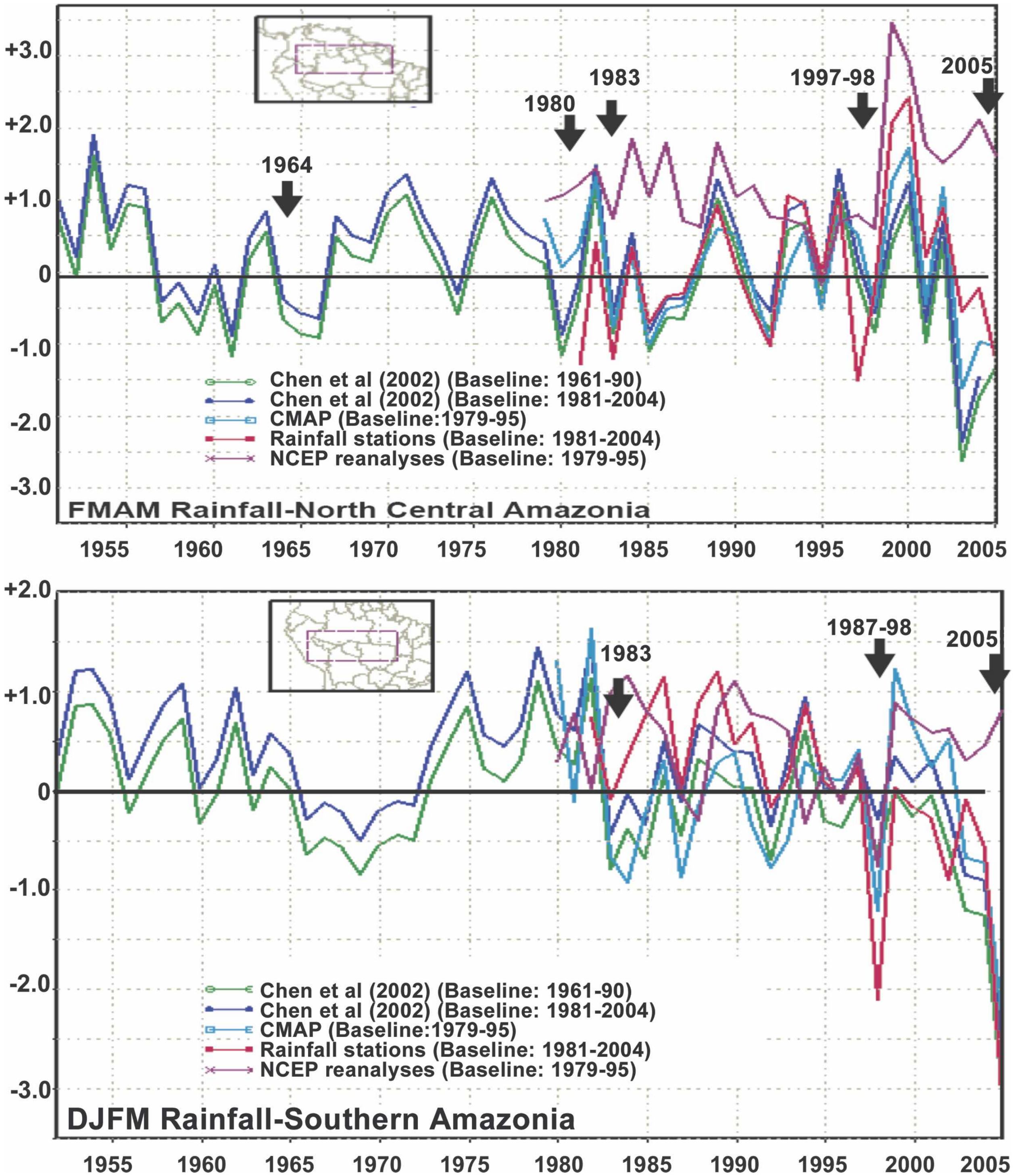


FIG. 4. Time series of rainfall indices for (a) northern Amazonia (FMAM) and (b) southern Amazonia (DJFM) from 1950 to 2005. These seasons correspond to the peak of the rainy season in those sections of the Amazon basin. Rainfall datasets are from Chen et al. (2002), CMAP (Xie and Arkin 1997), and an index derived from rainfall stations. Anomalies (mm day^{-1}) are derived using different baseline periods. Arrows indicate major drought events for this period.

In southern Amazonia, Fig. 4b shows that all rainfall indices characterize large negative departures in 1998 and 2005, with all datasets (except the NCEP data) showing between 2.5 and 3.0 mm day^{-1} below normal in 2005. In fact, the station rainfall dataset shows the drought of 2005 was more intense in southern Amazonia, as compared to the previous drought of 1998 and 1983, being the El Niño impact in 1983 more intense in northern and central Amazonia. While the rainfall index derived from the NCEP reanalysis is consistent with the other indices for the El Niño events of 1987 and 1998, it differed from all the other datasets for 2005, showing a positive rainfall anomaly, both in northern and southern Amazonia. The NCEP rainfall index is the only one that actually ignores the drought in Amazonia and shows positive rainfall anomalies between +0.5 and 1.0 mm day^{-1} above normal. This is inconsistent with the tendencies from other datasets, and also with the situation observed in the level/discharges of rivers in southern Amazonia, possibly indicating systematic errors in the rainfall calculation of these reanalyses.

Therefore, the NCEP global reanalysis precipitation missed completely the drought in 2005 in Amazonia and showed large precipitation contrary to all observational datasets. The divergent positive rainfall anomaly of the NCEP may be a result of adjusting globally the circulation and energy flux fields with observations. As the precipitation and evapotranspiration fields are derived from the dynamic fields and are not calibrated or adjusted regionally, they may incorporate greater uncertainty in their regional values, in this case producing a positive rainfall anomaly not supported by observations.

Figures 4a and 4b show that all datasets exhibit systematic differences. For instance, in Fig. 4a in 2001 most of the datasets show a reduction in the rainfall quantity, while the observed rainfall anomaly (from station data only) showed anomalies of approximately +0.2 mm day^{-1}. The Chen et al. (2002) dataset showed for the same year −1 mm day^{-1} as a departure from 1961–90.

c. *The impact of the drought of Amazonia in 2005 on rivers in the region*

Time series of monthly levels/discharges of rivers in Amazonia (Fig. 5) show large reduction in river levels with basins in northern Amazonia (Uatumã and Curua Una) during the droughts of 1963–64, and the El Niño–related droughts in 1982–83 and 1997–98. The drops in river levels in 2005 were very small or went unnoticed. The levels of the Solimões River in Tabatinga and Fonte Boa were anomalously low during the El Niño events in 1982–83 and in a lesser degree in 1998, while the levels reached very low values during the drought of 2005. In Rio Branco, the lowest values in 2005 were part of a negative trend detected since the middle 1990s. The river level/discharge anomalies vary concomitantly with the rainfall indices over their basins shown in Figs. 4a and 4b.

Figures 6a and 6b show the variability of levels/streamflow in central and eastern and southwestern Amazonia during 2004 and 2005, as compared to the LTM. From December 2004 to the end of the climatological peak water season in May 2005, the levels of the Amazon River in Iquitos, the Solimões River in Tabatinga and Fonte Boa, the Acre River in Rio Branco, the Mamoré in Puerto Varador, and the Ibaré River in Puerto Almacén reached values well below the normal, in some cases up to 2 m below normal in the monthly mean. In the Peruvian Amazonia (SENAMHI 2005) the levels of the Amazon River in Nanay and Iquitos in Peru were about 2.79 and 4.80 m below normal, respectively. The levels of the Marañón River in Nauta reached 2.79 m below normal, and in the Ucayali River in Requena the levels were 2.56 m below normal. These were record low values for the last 35 yr.

The Rio Negro was 1–2 m above normal from January to July 2005 in Manaus (Fig. 7b). Since August 2005 the river levels dropped to values about 3 m below normal. It reached 18.61 m in September 2005 (September average = 22.30 m). For comparison, the river level in Manaus reached 21.74 m in September 2004, and it dropped almost 4 m below normal by September 2005. The levels of the Uatumã River in Balbina and the Tocantins Rivers in Tucurui in eastern Amazonia do not show significant negative anomalies during 2005, indicating that the hydrological impact was not serious in northern Amazonia, an inference consistent with rainfall anomalies being between normal and above normal in that region.

The large drop in river levels in Manaus was related to the low levels of the Solimões River upstream of the Manaus region. The water stage of the Rio Negro in Manaus is a combination of the signal produced by the Rio Negro itself and the nearby Solimões River. It is clear that the drought of 2005 has different characteristics with previous recorded events, since it strongly affected the southwest portion of the basin. Because of the sheer size and significant travel time of the Amazon basin, the contribution of that part of the basin occurred when the water levels are already receding at Manaus. Therefore, rainfall anomalies strongly affected the water level at Manaus already deep in the dry season, increasing the recession in October 2005 while the peak discharge remains unaffected. Rainfall increased

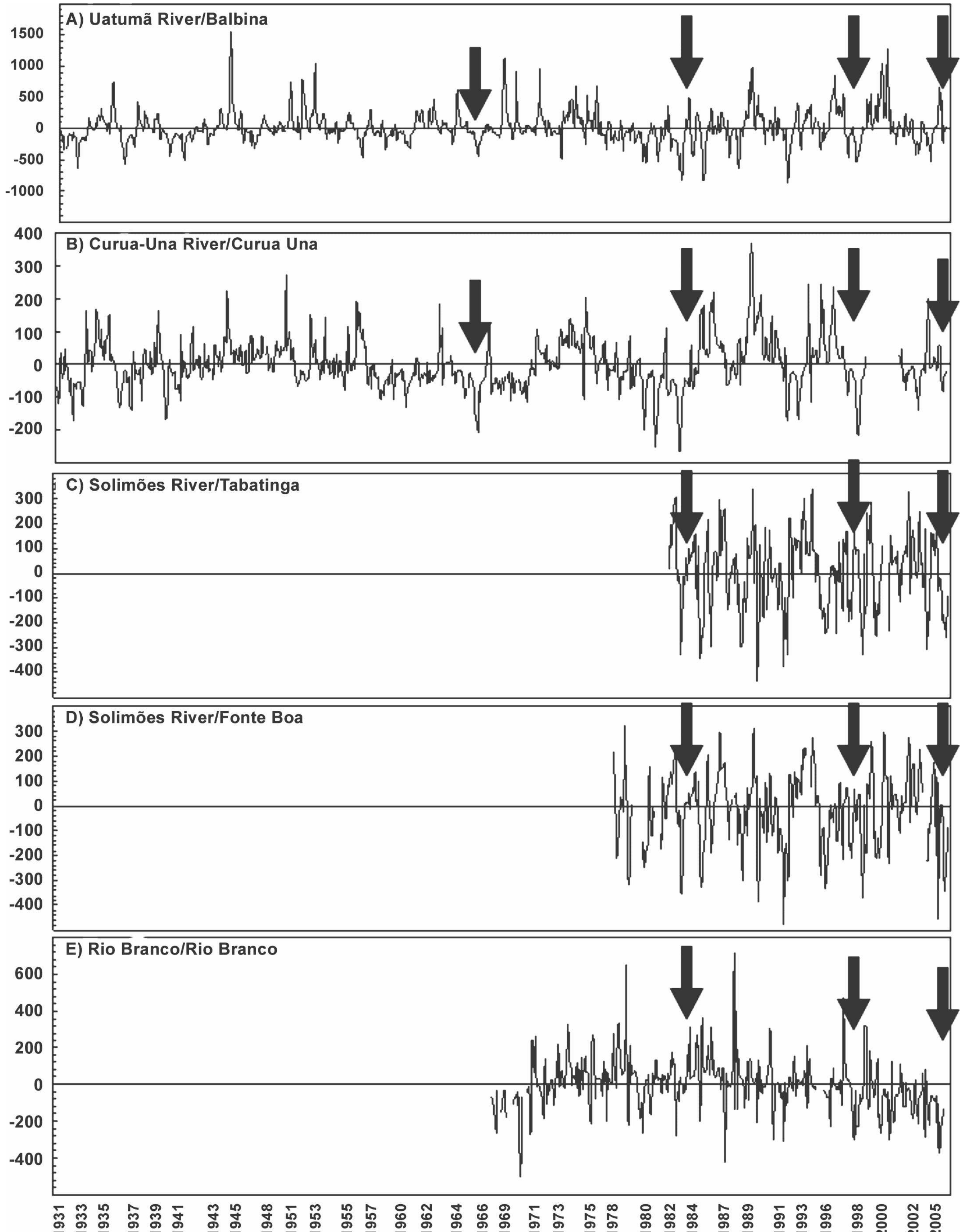
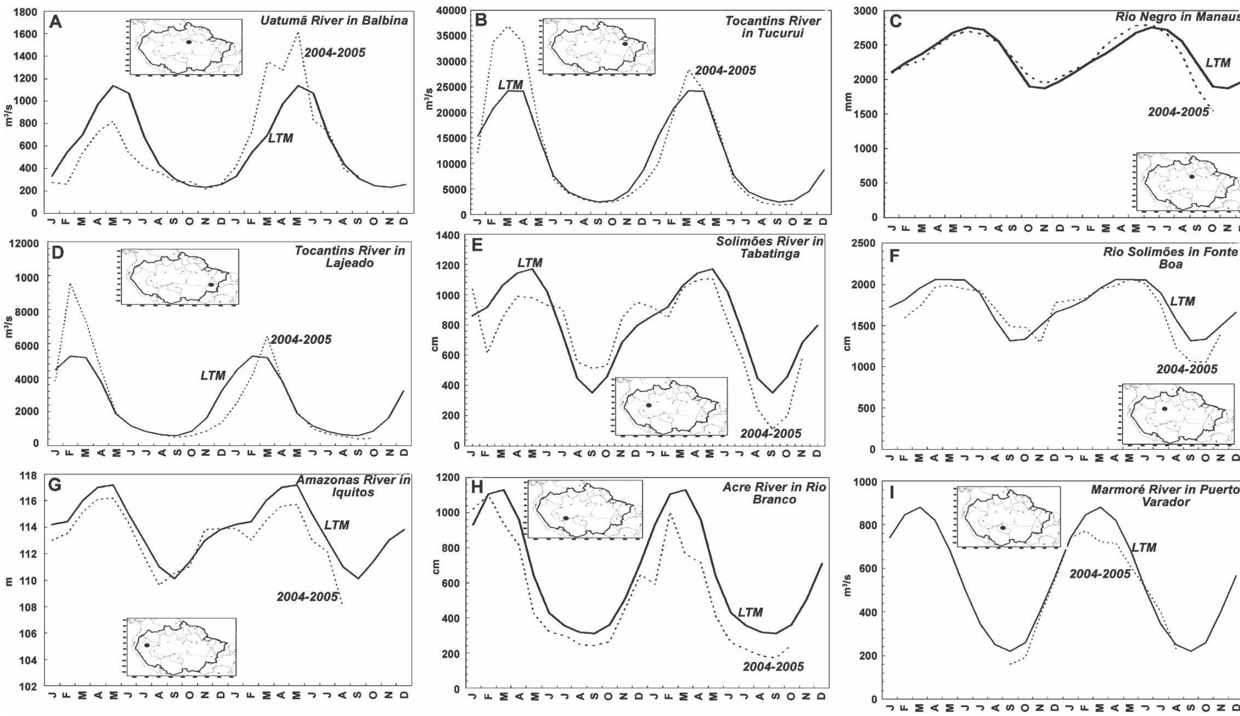


FIG. 5. (a)–(e) Monthly river levels/streamflow anomalies from 1931 to 2005 for the Uatumã River in Balbina and Curua Una River in Curua Una, from Solimões River in Tabatinga (1982–2005), and in Fonte Boa and Acre River in Rio Branco (1971–2005). Arrows indicate dry years 1964, 1983, 1998, and 2005. (Source of data: ANA.)



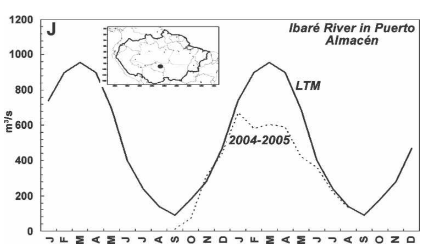


FIG. 6. (a)–(j) River levels/stream series at different gauge stations for rivers with basins extending in central and eastern Amazonia, and in southern and western Amazonia in Brazil, Bolivia, and Peru. Units are in mm (Manaus), cm (Ji-Parana, Rio Branco, Fonte Boa, and Tabatinga), m above sea level (Iquitos), and m^3 s^{-1} (Puerto Varador, Puerto Ibaré, Balbina, Tucurui, and Lajeado).

again in October 2005, and by February 2006 the Acre and Madeira Rivers had experienced anomalously high levels because of the intense rainfall during October 2005–March 2006. The Acre River reached 16.71 m on 21 February 2006, affecting tens of thousands of people in low-lying areas in Rio Branco, Acre. In March 2006, the Madeira River reached the 22.84-m level at Manicoré, where the mean is for that period is only 12.9 m.

Figure 7 shows seasonal rainfall anomalies during both the 1998 and 2005 droughts. The typical features of the 1998 El Niño are drought in Amazonia and northeast Brazil, and abundant rainfall in southern Brazil and northwest Peru and Ecuador during December–February and March–May. The extension of the drought of 1998 was much larger than in 2005 covering most of the Amazon region from December 1997 through May 1998. In 2005 reduced rainfall began to affect southwestern Amazonia during the period December 2004–February 2005 while in March–May rainfall was above normal in central Amazonia, in contrast with the drought in the same season during 1998.

d. Basinwide characteristics of large-scale and regional atmospheric circulation during the drought of 2005

In the context of the large-scale circulation, rainfall in the Amazon basin depends on the development of intense convective activity over the region that is determined by the confluence of the tropical Atlantic trade winds and the meridional displacements of the intertropical convergence zone (ITCZ). The migration of the ITCZ depends on the intensity of the northeast and southeast trades, which is associated with the meridional gradient of sea level pressure and SST in the tropical North and South Atlantic. During very strong El Niño events, intense subsidence over the Amazon and an anomalously northward displaced ITCZ over the tropical Pacific and Atlantic Oceans also tends to inhibit rainfall in central and western Amazonia. There are years in which both phenomena occurred, which is consistent with an Amazon-wide drought, as in 1983 and 1998 as well as on the great drought of 1926.

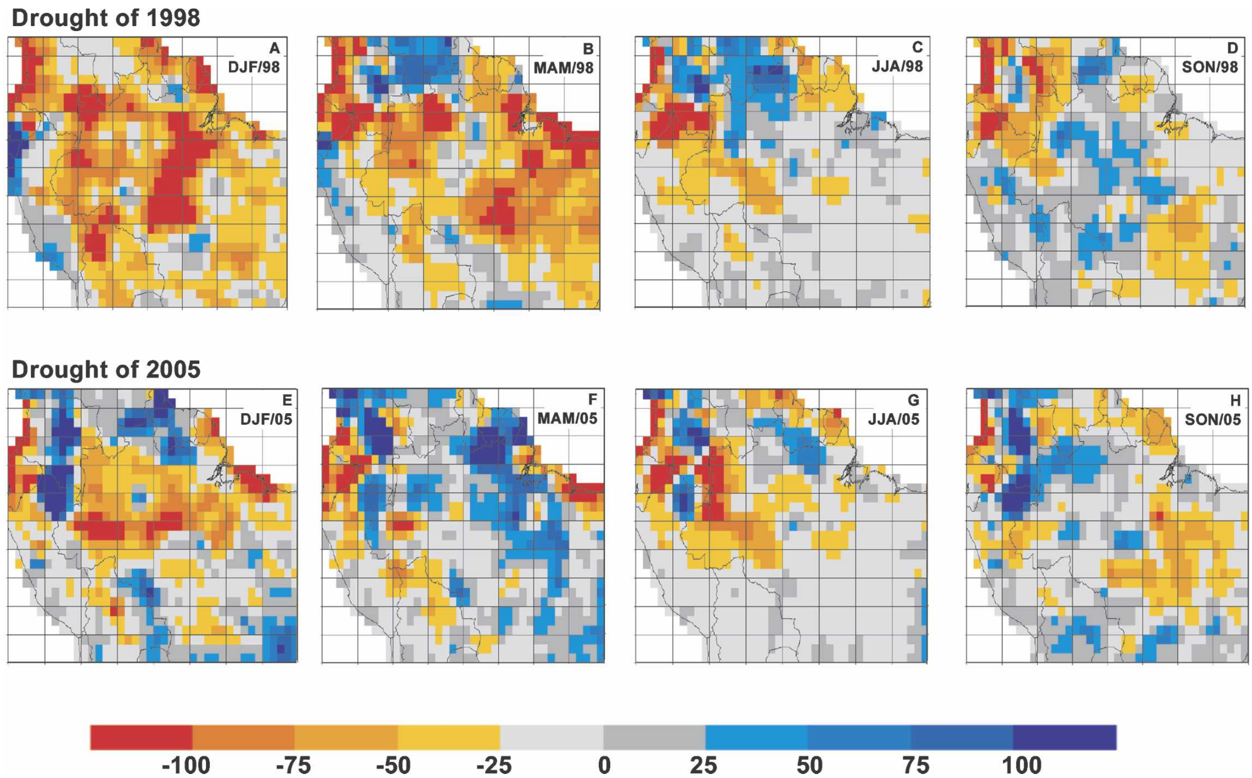


FIG. 7. Seasonal rainfall (mm month^{-1}) maps for tropical South America during two drought events: (a)–(d) 1998 and (e)–(h) 2005. Values as shown as deviations from the 1961–90 long-term mean. Data are from GPCC-monitoring product available at 1.0° lat–lon gridbox area. Red/blue colors indicate negative/positive rainfall anomalies.

At the near-surface level, the wind maps and anomaly fields (Fig. 8) show that the moisture flux from the tropical North Atlantic into Amazonia was weaker than normal during the early rainy season in September–November 2004 and during the peak of the rainy season (December 2004–February 2005) in southern Amazonia. The subtropical North Atlantic high weakened and was displaced northward during this period. The northeast trades and moisture transport into the Amazon weakened, as shown by large moisture transport flux anomalies from the Amazon into the tropical North Atlantic. The presence of a cyclonic anomaly during the peak of the rainy season of 2005 over eastern Bolivia is associated with a strong southerly flow anomaly east of the Andes. This pattern is also indicative of a reduction in the moisture flow from the northern Amazon region to southwestern Amazonia. The southerly flow anomalies suggest a weakening of the low-level jet (LLJ; Marengo et al. 2004) east of the Andes during the December 2004–February 2005 peak season, when this season normally shows the peak of LLJ activity. In fact, no events of LLJ were detected during this season, while the average number of jet events for this season is typically about 12. This pattern confirms that moisture transport from the tropical North Atlantic and northern Amazonia into southern Amazonia during the peak rainy season was extremely reduced. For comparison, the number of LLJ episodes detected during other drought years in Amazonia, as in 1983 and 1998, was 12 and 23, respectively. This altered pattern corroborates the different nature of this drought of 2005 as compared to other droughts. Only during March–May 2005 were the trade winds and the moisture flux stronger than normal, converging with the westerly flow over central Amazonia, consistent with more rainfall in central and eastern Amazonia as shown in Figs. 1 and 2.

Figure 9 shows a Hovmöller diagram of meridional wind anomalies along 5°N–5°S from 1960 to 2005 for the region 75°–25°W in the equatorial Atlantic, and the most important drought years are marked with horizontal black lines. Each of the drought years seems to be different in terms of intensity of the north and southeast trade winds and the position of the ITCZ and equatorial convergence over the continent. In 2005, the ITCZ was displaced anomalously northward, especially in the tropical North Atlantic, a pattern observed since 2003 that is consistent with warming in the tropical

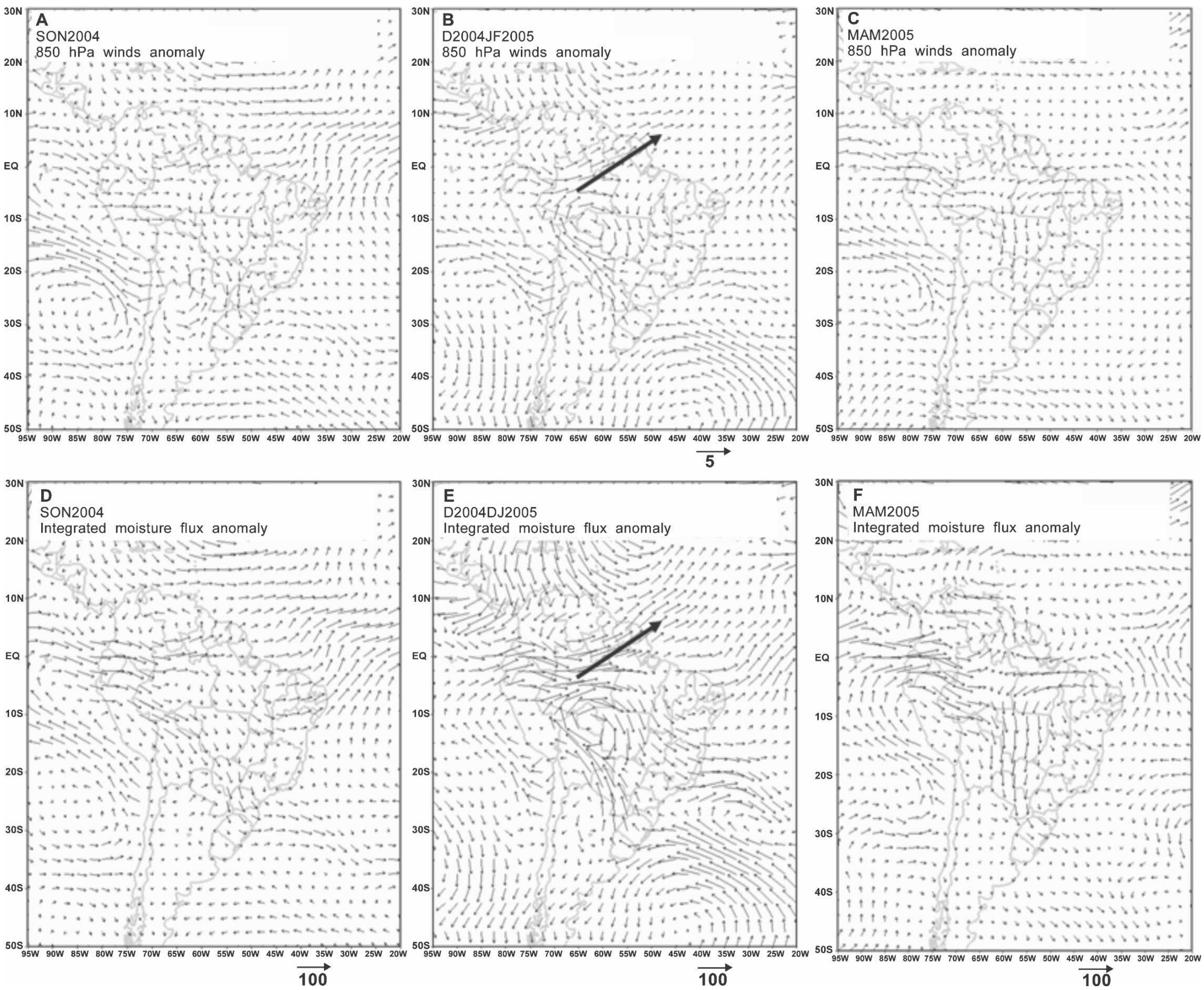


FIG. 8. Low-level circulation and integrated moisture flux anomalies in South America for SON 2004, DJF 2004–05, and MAM 2005. (a)–(c) The circulation anomalies and (d)–(f) the integrated moisture flux anomalies from the 1979–2005 mean. Vector with the scale of the wind/flux is shown at the bottom of each panel.

North Atlantic. In central Amazonia the northeast trades were weaker from most of 2004 to the beginning of 2005. In 1998, central and eastern Amazonia exhibited a weakening of the northeast trades and the anomalies were stronger in these regions of Amazonia as compared to 2005. These observations imply a weakened flow from the tropical North Atlantic, leading to less rainfall and drying conditions in eastern and central Amazonia in 1998 in comparison to 2005.

An analysis of the vertical motion fields together with the near-surface circulation discussed previously can provide a better idea on the regional tridimensional circulation of the region, before and during the peak of the drought of 2005 (Fig. 10). As shown in Figs. 2 and 7, the rainfall reduction was concentrated over southwestern Amazonia, while rainfall was almost normal in central and eastern Amazonia. The north–south vertical motion along 75°–55°W over western Amazonia shows that the drought of 2005 was characterized by weak upward motion over central-western Amazonia along the equator since the beginning of December 2004–February 2005, an even weaker upward motion (as depicted by the subsidence anomalies south of 10°S) that suggests weaker convection or even subsidence in southern Amazonia where rainfall anomalies were negative during most of December 2004–February 2005 and March–May 2005. The east–west circulation along the equatorial zone (5°N–5°S) shows upward motion over equatorial Amazonia during the drought of 2005 with subsidence on the equatorial Pacific. These circulation features are consistent with positive rainfall anomalies along equatorial Amazonia.

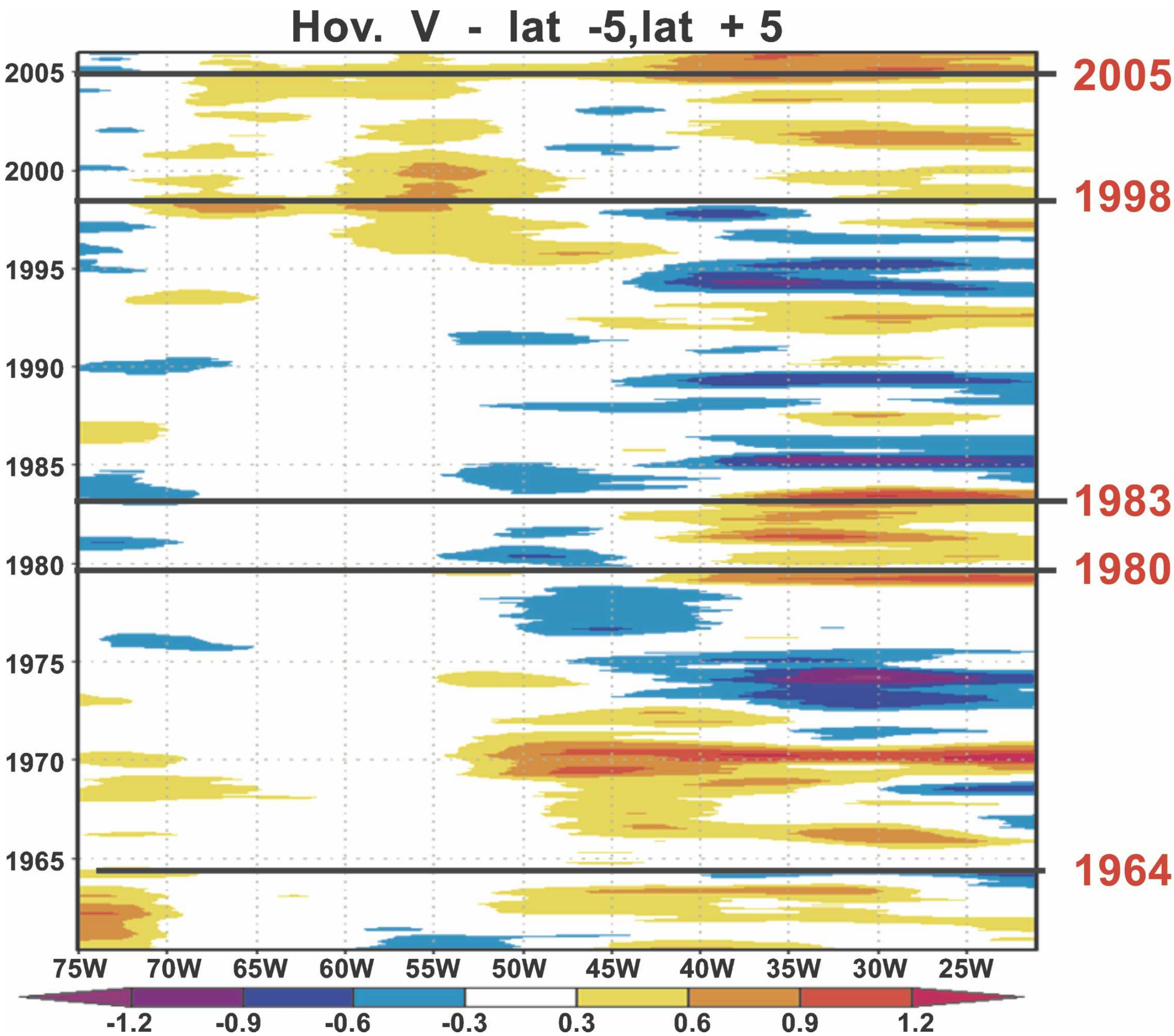


FIG. 9. Hovmöller diagram of meridional wind anomaly between 75° and 20°W, for the equatorial band of 5°N–5°S. Positive/negative values indicate southerly/northerly wind anomalies, with respect to the 1979–2005 mean.

The drought of 1964 (not shown) was characterized by strong subsidence in the region south of 15°S during January to April (similar to the 2005 drought), with strong upward motion in the region between 5°N and 10°S. East–west circulation showing strong convection was detected in the central and eastern equatorial Pacific and weak convergence (or subsidence) from western equatorial Amazonia to northeast Brazil. For both 1964 and 2005 droughts' convective activity appeared over central and eastern Amazonia, consistent with rainfall patterns over these regions.

Therefore, the near-surface and vertical motion fields suggest the presence of weaker convection—or even subsidence—over the headwaters of the Solimões River in southwestern Amazonia during the onset of the rainy season during late 2004 and early 2005, inhibiting rain formation. Consistent with the upper-level circulation, the near-surface circulation and moisture transport from the tropical Atlantic into southwestern Amazonia was reduced during the onset and peak of the rainy season in 2005. This pattern suggests the important role of the circulation over the tropical North Atlantic during the spring of 2004 and the peak of the rainy season in 2005 in southern Amazonia.

e. Comparison of different droughts: 1925–26, 1963–64, 1997–98, and 2005

The analyses in sections 5b and 5d confirm that the droughts of 2005, 1998, 1983, and 1964 were different in terms of circulation and rainfall distribution. No analy-

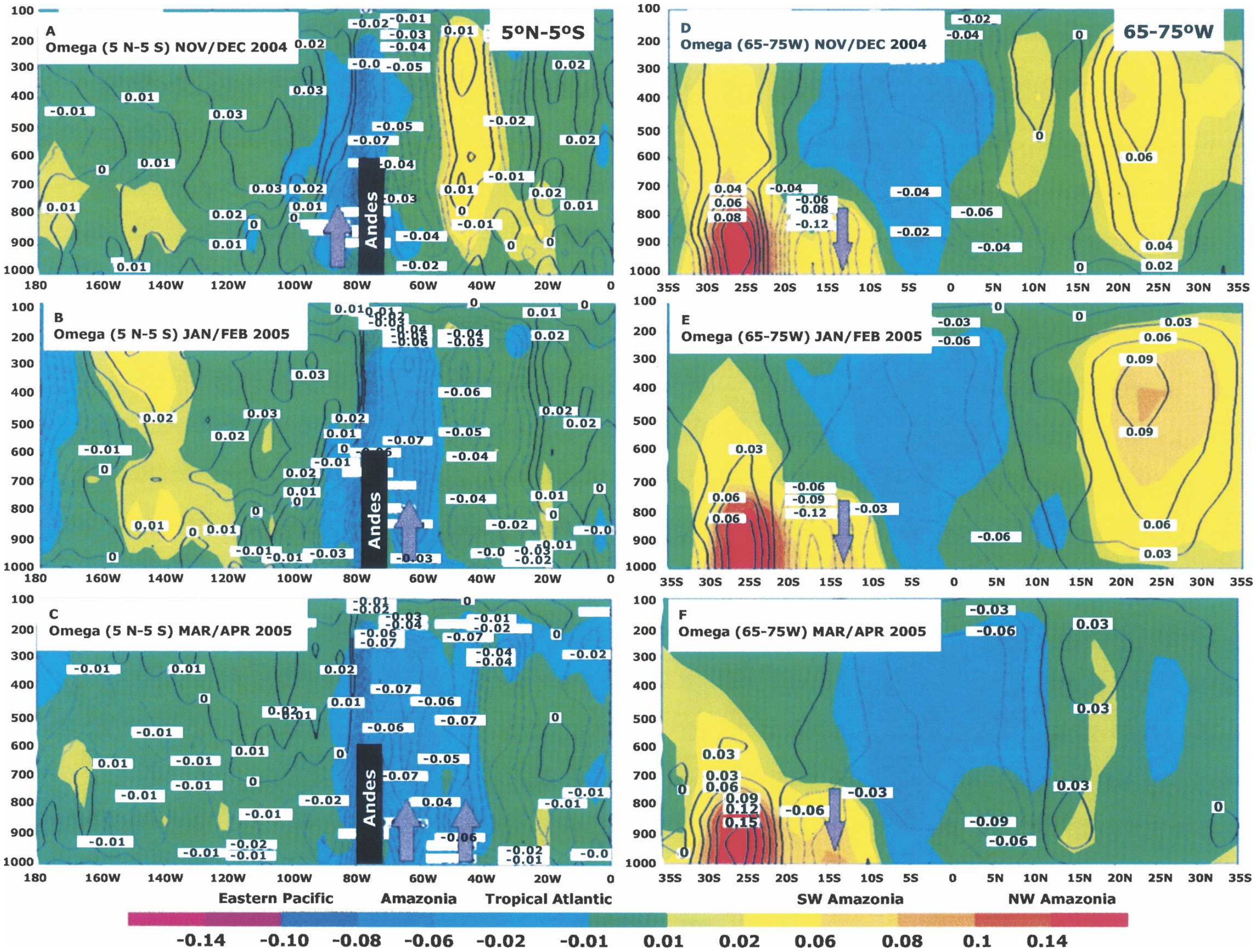


FIG. 10. Vertical cross sections of vertical velocity anomalies during November–December 2004, January–February 2005, and March–April 2005. (left) A zonal equatorial cross section along 5°N–5°S; (right) a meridional cross section along 65°–75°W. Lines represent the observed values of vertical motion (Pa s^{-1}), and anomalies (from the 1979–2005 mean) are in color with the color scale bar at the bottom. The vertical black box represents the approximate location of the Andes.

ses were made for 1926 because of the absence of circulation and sufficient rainfall data at that time, so we based our analysis for that year on published literature. Analyses of SST anomalies during 1925–26 by Allan et al. (1996) show the characteristic warming in the eastern Pacific Ocean as strengthening throughout 1925, reaching a peak in April of 1926. The drought of 1997–98 has been previously investigated and the impacts of El Niño on this drought have been investigated by Marengo and Nobre (2001).

Time series of SST anomalies (Fig. 11) show the typical large positive SST anomalies in the tropical central Pacific during El Niño years, with the years 1926, 1983, and 1998 coinciding with drought. The droughts of 1964 and 2005 show just a weak warming of the tropical central Pacific. Considering the SST anomalies in the tropical North and South Atlantic and the gradient between these two sectors, we can conclude that the droughts of 1998 and 2005 coincide with warm tropical North Atlantic surface waters with 2005 being the warmest since 1920. The meridional SST gradient (difference between North and South Atlantic SSTs) exhibited differences of more than 1.2°C in 2005, greater than during the drought years of 1964 and 1998, and almost similar to other dry years as 1980 and 1983. During 1920–2005, this difference was larger than 1°C on 10 occasions, being about 1.2°C in 2005 and 1.8°C in 1958.

The bimonthly SST anomaly maps shown in Fig. 12 exhibit the warming of the equatorial central and eastern Pacific during the austral spring (September–October) and summer (November–December and January–February) for the 1997–98 and 2004–05 drought years. The warming of the tropical North Atlantic was stronger in 1998 and 2005, while the large warming (>4°C) in the eastern Pacific during El Niño 1998 was not observed in

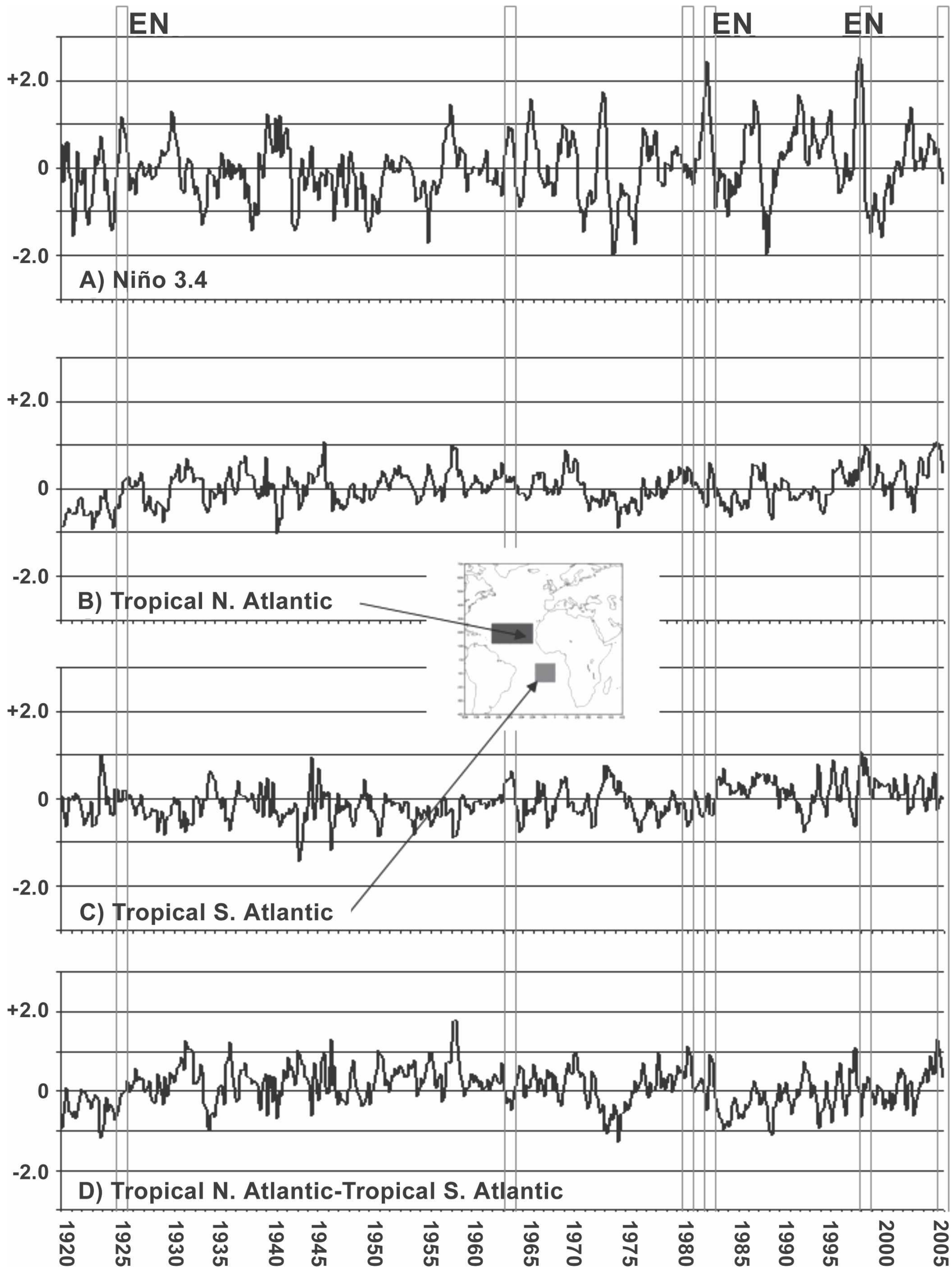


FIG. 11. (a)–(e) Time series of bimonthly SST anomalies since 1920. Series are for the Niño-3.4 region, the tropical North and South Atlantic, as well as the gradient between tropical North and South Atlantic SSTs. Anomalies are with relation to the 1961–90 period. Boxes indicate years with drought in Amazonia.

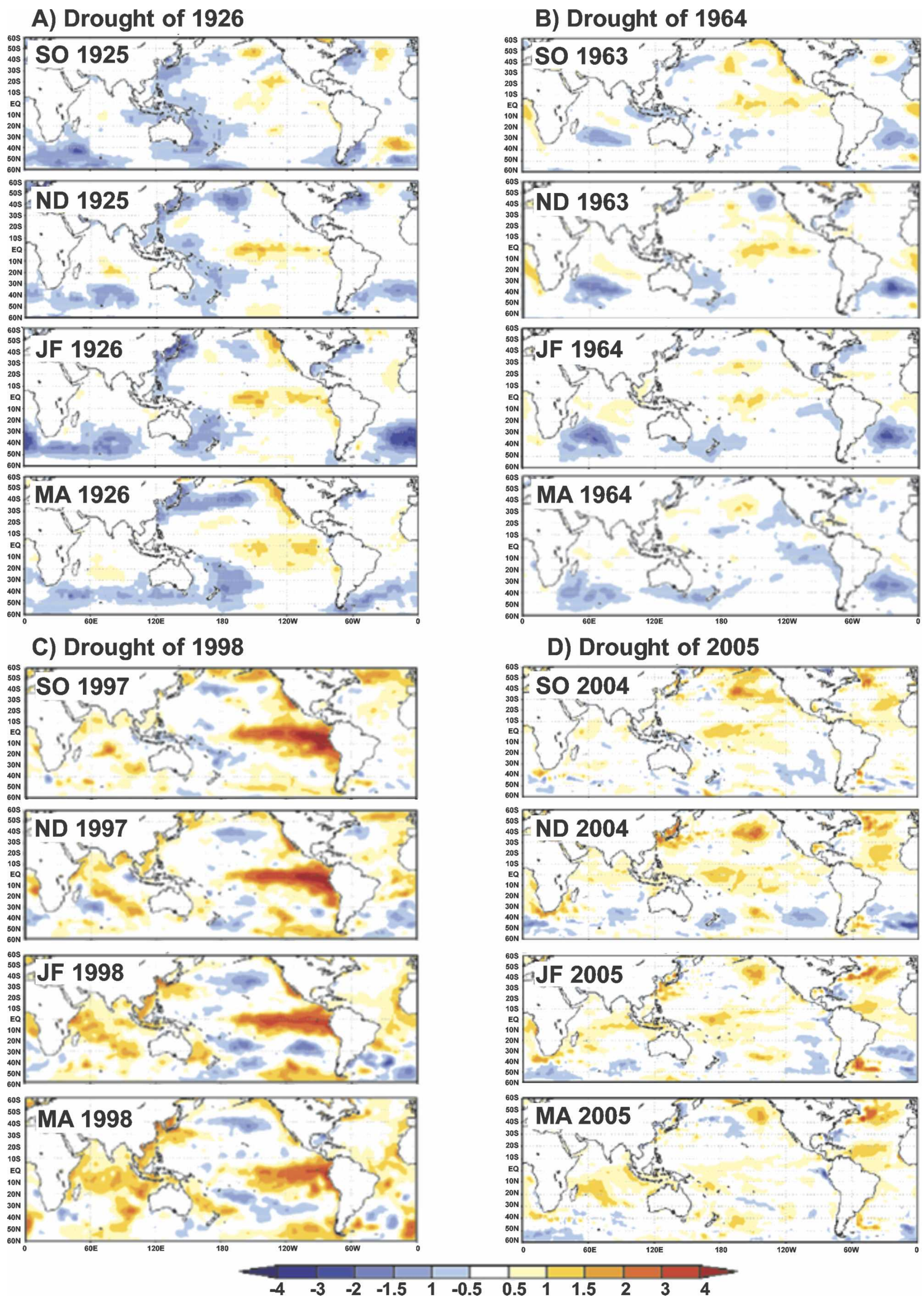


FIG. 12. (a)–(d) SST anomalies (°C) during SO, ND, JF, and MA during some years with drought conditions in Amazonia (1925–26, 1963–64, 1997–98, and 2004–05). SST anomalies are in relation to the 1961–90 baseline period. Color scale is shown at the bottom of the figure.

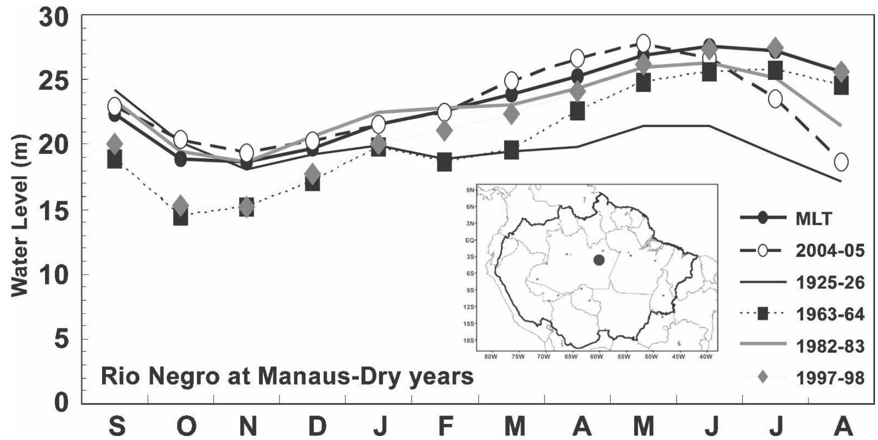


FIG. 13. Rio Negro water levels (m) in Manaus station during selected dry years. The long-term mean is 1903–2000. Location of Manaus is shown by a dot in the inset map.

2005. In 1963 (Fig. 12b) there was warming in the tropical Pacific from November 1963 to February 1964, which is lower than that during 1998 or 2005. In 2005 the warming in the tropical Atlantic was centered along 10–20°N (favoring greater hurricane activity) while in 1998 the warming was around 10°N–10°S. Decadal time-scale variability in the SSTs of the tropical Atlantic have been identified in previous studies (Nobre and Shukla 1996; Zhang et al. 1997; Wagner 1996) as embedded in a warming trend in tropical oceans, especially in the tropical Pacific and North Atlantic Oceans. Therefore, it is possible that a small SST anomaly in the late 1990s would have more impact than a similar anomaly in the 1960s, because the mean SST average in the 1990s is almost 0.5°C warmer than the mean SST average from the 1960s.

Finally, to analyze the differences between droughts associated with extreme El Niño events and droughts in non–El Niño years in Amazonia discussed in section 5c, we use the levels of the Rio Negro in Manaus as a proxy variables. Figure 13 shows the seasonal cycle of water levels during various drought years. The river levels in 1963–64 showed negative anomalies all year long, while the other drought periods exhibited anomalies during specific seasons. In 1925–26 the water levels started to drop from the beginning of the austral summer and intensified throughout 1926, reaching negative anomalies up to 6–8 m during the May–July peak water-level season. During 1983, river levels dropped during the peak season by about 2 m, while in 1998 the levels dropped by about 4 m during spring and summer. In 2004–05, the levels were above normal before May 2005, and then started to drop suddenly since June 2005, reaching 7–8 m below normal by August 2005.

6. Discussion and conclusions

The 2005 drought in the southwestern Amazon, possibly one of the most severe in at least 100 yr, resulted from an extended dry season. Furthermore, the dry season in 2005 was more extreme than normal with drier and warmer conditions especially in southern and southwestern Amazonia. The effects of the drought were detected mainly in the levels of rivers whose drainage extend into southwestern Amazonia.

Some differences exist in the depiction of this drought in Amazonia due to the use of different rainfall station datasets and compared to gridded analysis sources, as well as the consideration of the baseline to define the anomalies. While almost all datasets have shown drastic rainfall reductions in Amazonia during 2005, rainfall derived from the NCEP reanalysis exhibited positive anomalies of the order of up to $+1.0$ mm day^{-1}. A novel rainfall dataset being implemented at CPTEC/INPE has depicted quite well the regional patterns of rainfall anomalies during 2005, consistent with the maps produced by the individual Amazon countries, demonstrating the potential of this new dataset for climate studies.

In northern-central Amazonia the sudden drop of the Rio Negro levels in Manaus since July 2005 was not due to reduced rainfall in northwestern Amazonia, but to the effect of the low Amazon River upstream of its confluence with the Rio Negro due to reduced rainfall on those portions of the basin. In 2004–05 the levels started to drop suddenly since June 2005, reaching 7–8 m below normal by August 2005, in sharp contrast to the levels before May, 1–2 m above normal.

Comparative circulation and SST analyses for 2005 in relation to other years in which there were

El Niño–induced droughts (e.g., 1926, 1983, and 1998) have shown that the recent drought was concentrated in western and southern Amazonia, and not in north-central or eastern Amazonia (regions that typically experience rainfall deficiency and drought during El Niño years). In all of these drought years, the spread of forest fires in the region was noticeable even though in different regions for different droughts. The integrated moisture transport from northern into southern Amazonia was severely reduced during DJF 2005. During 2005 there were anomalously warm surface waters in the tropical North Atlantic, a tendency that has been detected since 2003, while surface waters in the equatorial Pacific were near normal, suggesting a drought induced likely by the warming in the tropical Atlantic. This seems to be the case also for the drought in 1963–64.

The near-surface and upper-level horizontal circulation anomaly fields have shown similarities between the droughts of 1964 and 2005, with subsidence over southwestern Amazonia and upward motion in central Amazonia. In contrast, El Niño–induced drought exhibited subsidence anomalies over most of central and eastern Amazonia. Our analyses also show that droughts are not necessarily restricted to El Niño or El Niño–like events.

In 2005 the contrast between the tropical North and South Atlantic SSTs was about 1.2°C, surpassed only by the 1.8°C in 1958. Furthermore, the long-term positive SST trends in the tropical Pacific and Atlantic Oceans featured a warming of about 0.5°C between 1920 and 2005. A small SST increase on the mean SST field during the relatively colder decade of 1950–60 may have had smaller impacts as compared to similar or even smaller SST increase in the relatively warmer 1990–2000 decade. This aspect is important since rainfall exhibits decadal-scale variability in both northern and southern Amazonia, and there is no evidence of observed trends in hydrological extremes (drought and floods) in Amazonia.

It may be possible to explain the drought of 2005 as linked to an interdecadal SST trend in tropical North Atlantic, and the same SST trend can be linked to the frequency of hurricanes in the North Atlantic. Moreover, the strong intensity of many North Atlantic hurricanes in the 2005 season has been linked to the record high tropical North Atlantic SST anomalies, of which at least 0.5°C can be attributed to global warming (Trenberth and Shea 2006). The drought of Amazonia in 2005 and the North Atlantic hurricane season may have a common cause in the anomalous SST trend, but they do not seem to be correlated to each other.

Future warmer climate change scenarios due to the increase in the concentration the greenhouse gases and to aerosols derived from biomass burning suggest that the probability of events like this drought may increase. Simulations by the U.K. Hadley Centre global coupled model indicate such a trend by the end of the twenty-first century (P. Cox 2007, personal communication). In addition, land use changes and biomass burning due to the increased fires and the subsequent injection of aerosols to the atmosphere have the potential to affect the onset and the amount of rainfall in the region (Andreae et al. 2004).

A word on the prediction and predictability of the drought of 2005: most seasonal forecasts did not predict the observed intense regional drought characteristics of rainfall during the drought of 2005 in southwestern Amazonia. Global climate models used at CPTEC/INPE and the International Research Institute for Climate and Society (IRI) have simulated negative rainfall anomalies in western Amazonia during austral summer and the fall of 2005, when forced with SST anomalies of the preceding period. However, the lower model skill and the size of the negative rainfall anomalies derived from long-term model climatology over the southern and western Amazonia determined that the forecasts for less rainfall were not considered statistically robust for a consensus forecast, since these regions exhibits lower climate predictability on seasonal time scales.

7. Suggestions for future studies

Improving the predictability of severe droughts in Amazonia and of their consequences requires a coordinated approach to integrate diverse datasets and perspectives from multiple disciplines. Such predictability is critical since impact assessments and vulnerability measures have to be taken considering future climate change scenarios, including increases in the frequency and intensity of climate extremes.

The meteorological data indicate that the drought of 2005 differed from the El Niño–related severe droughts of 1926, 1983, or 1998. For the 2005 case, changes in circulation regimes leading to the drought were associated with the warming of the tropical North Atlantic. Our analysis suggests that this drought occurred in the context of the observed warming in the tropical North Atlantic, estimated as +0.5°C in the last 30 yr. Considering this trend and the SST gradients between the tropical North and South Atlantic since 1920, we conclude that the warming in the tropical North Atlantic was the most intense since 1920, but it is still unclear how much of this warming is due to natural climate variability or to anthropogenic effects.

To further explore the subject of drought–climate change in Amazonia, additional research should focus on improving parameterization and incorporating available empirical data [e.g., from the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA)] on land surface models used to model ecosystem responses to drought. As a first priority, we need a better representation of below-ground processes such as root structure and function, phenotypic plasticity, and hydraulic redistribution in these models. In addition we need to have a better mechanistic understanding of the critical thresholds beyond which the forest will become inflammable. This implies the need to develop a better process, based understanding on how Amazonian ecosystems will respond to directional changes in precipitation regimes. Numerical experiments that consider the warming in the tropical Atlantic and that can discriminate between the natural and human-induced forcings could also explain the nature of this drought and explore the possibility of more droughts in the future.

Changing drought frequency and intensity would have profound environmental and social impacts in Amazonia. Further research is needed to analyze the synergies between climate change and land use decisions that can promote/inhibit fire-prone environments and ignition sources and that affect regional hydrological cycles. Finally, we need to establish a research protocol to integrate multiple scales to include the broader ecological, hydrological, climatological, and sociological context of the region. By doing this, we will enhance our understanding of the complexities of the ecologic–hydrologic interactions and improve our ability to generalize about the consequences of changing precipitation regimes due to natural and anthropogenic factors on the functioning of the Amazon basin.

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