NOTES AND CORRESPONDENCE

Enhanced Seasonal Rainfall in Northern Venezuela and the Extreme Events of December 1999

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16 April 2001 and 31 October 2002

ABSTRACT

Torrential rainfall during December 1999 resulted in devastating floods and landslides along the northern coast of Venezuela. These events occurred in an area with a predominantly dry climate, took place during what is regionally the dry season, and were preceded by unusually heavy seasonal rainfall. An observational study was undertaken in an attempt to identify anomalous features of the climate system associated with both the enhanced seasonal rainfall prior to the landslides as well as the extreme December rainfall events that triggered them. Observational data for the period 1950–99 are used to provide historical context. Results indicate that the copious seasonal rainfall prior to the floods was associated with anomalous conditions in both the tropical Pacific and Atlantic basins similar to past events, although some features were unusually strong in 1999. The extreme daily rainfall in December 1999 was associated with atmospheric circulation features originating in the extratropical Northern Hemisphere that penetrated unusually far into the Tropics. Possible physical mechanisms acting to enhance rainfall on both timescales are discussed.

1. Introduction

During mid-December of 1999 exceptionally heavy rain triggered catastrophic floods and landslides along portions of the mountainous coastal region of northern Venezuela (NVE). Especially hard hit were the north-facing slopes of the Cordillera de la Costa where numerous homes built on the steep terrain were completely swept away. Over 10 000 fatalities were reported and the cost of reconstruction has been estimated at over \$1.8 billion. In terms of a meteorological event, the December 1999 rainfall in NVE was the heaviest observed since December 1951. From a climate perspective, the floods are of interest given that they occurred in an area with a predominantly dry climate, took place during what is regionally the dry season, and were preceded by a season of unusually heavy rainfall.

In this study observational data are used to examine anomalous oceanic and atmospheric conditions associated with the enhanced seasonal rainfall in NVE prior to the December 1999 floods and to compare them with similar seasons in the past. Important features of the synoptic-scale atmospheric circulation associated with extreme daily rainfall in NVE are also presented.

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2. Data

Gridded precipitation analyses (2.5° × 3.75° latitude–longitude) compiled at the University of East Anglia (UEA; Hulme 1992; Hulme et al. 1998) were utilized as well as monthly station data for Caracas-Maiquetia, Venezuela, from the Global Historical Climatology Network (GHCN). Precipitation anomalies are computed relative to a 1961–90 base period. Sea surface temperature (SST) anomalies (1951–80 base period) on a 5.0° × 5.0° latitude–longitude grid were used (Kaplan et al. 1998), and atmospheric circulation fields were from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. Daily and pentad outgoing longwave radiation (OLR) data on a 2.5° × 2.5° latitude–longitude grid from the Climate Prediction Center (CPC) were also utilized. All data used in the study were obtained through the International Research Institute for Climate Prediction/Lamont-Doherty Earth Observatory (IRI/LDEO) data library (http://iridl.ldeo.columbia.edu/).

3. Venezuela rainfall—Background

The focus of this study is the Cordillera de la Costa and adjacent coastal areas in northern Venezuela, east of the Maracaibo basin (the NVE region is defined here as 10°N, 60°–70°W). Away from the coast, precipitation

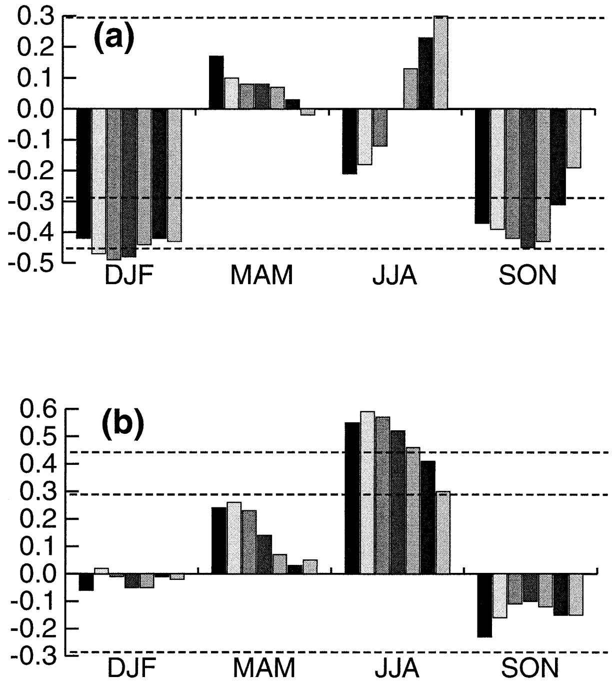

FIG. 1. The 0–6-month lag correlations between rainfall anomalies in NVE and 3-month-average SST anomalies (leading) in the (a) Niño-3 and (b) NATL regions as a function of season. For each season the left-most bar indicates 0 lag while successive bars to the right indicate lags at 1-month intervals. Dashed horizontal lines indicate statistical significance at the 90% and 95% levels.

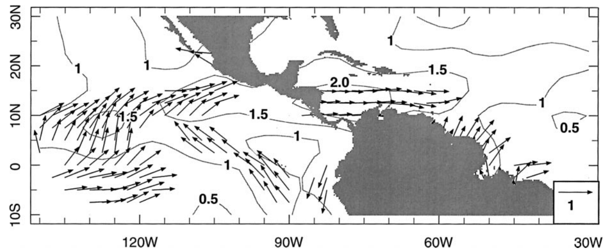

FIG. 2. Wind steadiness vectors (magnitude > 0.75) and standardized resultant wind speed anomaly at 925 hPa for SON 1999. Representative vector is in lower right of plot.

in this region generally peaks during the boreal summer then transitions to a relative dry season during the following winter. For the NVE region June–July–August (JJA) represents 45%, September–October–November (SON) 30%, December–January–February 9%, and March–April–May (MAM) 16% of annual precipitation, respectively. Interestingly, the coastal region of NVE is semiarid with annual precipitation as much as an order of magnitude less than in the Guyana highlands in the southeast of the country.

On seasonal to interannual timescales, rainfall variability in the tropical Americas (including NVE) and the Caribbean has been associated with SST, sea level pressure (SLP), and low-level wind anomalies in both the tropical eastern Pacific and Atlantic basins, as well as the Southern Oscillation (Giannini et al. 2000; Waylen et al. 1996a,b; Enfield 1996; Enfield and Mayer 1997; Enfield and Alfaro 1999; Pulwarty et al. 1992; Rogers 1988; Hastenrath 1976, 1978, 1984, 1990). The current study focuses on enhanced seasonal rainfall in SON and the atmospheric circulation features associated with the extreme daily rainfall events of December 1999.

4. Enhanced SON rainfall

Rainfall in the NVE region during SON 1999 was unusually heavy. Although data for 1999 were not available in the UEA dataset, in the CPC Climate Anomaly Monitoring System OLR Precipitation Index (CAMS_OPI) analysis (Janowiak and Xie 1999) SON 1999 was the wettest in its historical record (1979–2001). Conceivably, this antecedent rainfall served to precondition the soil to the extreme December precipitation that would follow [e.g., Glade et al. (2000) indicate that even a modest rainfall event can trigger landslides if preceded by sufficient precipitation] although here the focus is only on conditions associated with the enhanced seasonal precipitation.

Pulwarty et al. (1992) and others have shown statistically significant correlations between seasonal rainfall in northern Venezuela and SST variability in both the tropical Pacific and Atlantic basins. A summary of these associations is provided in Fig. 1, which shows lagged correlations between season rainfall anomalies in NVE and SST anomalies in the Niño-3 (5°S–5°N, 90°–150°W) and tropical North Atlantic (NATL; 10°–20°N, 20°–80°W) regions. For SON, NVE rainfall shows a statistically significant (negative) correlation with Niño-3. The largest association with tropical North Atlantic SST occurs during boreal summer.

During SON 1999 negative SST anomalies in the eastern tropical Pacific were related to an evolving La Niña while over much of the Caribbean and central tropical Atlantic positive SST anomalies were observed (not shown). Near the NVE coast, SSTs were initially below average during August and then gradually warmed, becoming the largest positive anomalies in the Caribbean by November. The accompanying low-level wind anomalies for SON 1999 are shown in Fig. 2, which displays the standardized 925-hPa resultant wind speed anomaly along with steadiness vectors for the full wind (defined as the mean wind vector divided by the mean wind speed using pentad winds).

The steadiness vectors over the tropical Pacific in Fig. 2 imply the observed northward shift in the ITCZ associated with ongoing La Niña conditions. Over the southern Caribbean, including the NVE coast, steady zonal wind anomalies with an average magnitude of 1.5–2 standard deviations were observed. The existence of these anomalous low-level westerlies along the NVE coast served to reduce the climatological differential-stress-induced divergence (Bryson and Kuhn 1961; Has-

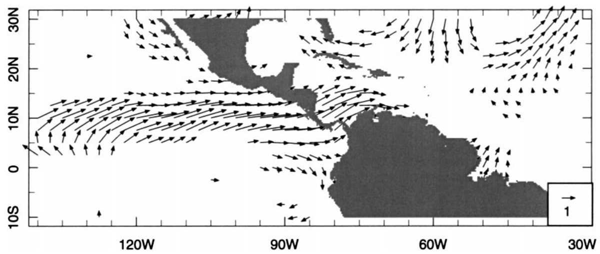

FIG. 3. Differences in composite 925-hPa vector wind anomalies (wet − dry) for the SON season in NVE statistically significant at the 95% level. Units are m s^{-1}; representative vector is in lower right of plot.

TABLE 1. The specific wet and dry SON seasons used in the composites are listed below. To be considered for use, all three months of the season were required to have either above- or below-average precipitation. Note that monthly rainfall data for Caracas was not available for 1985, 1986, 1987, 1989, 1991, and 1992.

NVE wet	NVE dry	Caracas dry	Caracas wet
1955	1953	1953	1952
1961	1957	1959	1954
1971	1958	1962	1966
1973	1960	1970	1973
1979	1962	1971	1984
1985	1976	1972	1988
1988	1977	1974	1990
1994	1978	1977	1994
	1982	1983	1995
		1993	

tenrath 1991), favoring both warmer SST and precipitation. The anomalous westerly winds at 925 hPa over the Caribbean (10°–20°N, 60°–80°W) for SON were the largest observed in the NCEP–NCAR reanalysis over this area during the 1950–99 study period. Over the Caribbean and western tropical North Atlantic (10°–20°N, 50°–80°W), these anomalous westerlies extended upward, on average, to roughly the 500-hPa level then became easterly anomalies up to the tropopause. In addition, the zonal wind shear (200–925 hPa) in this region was reduced by 60%–75% during the period. Given these favorable background conditions, wave disturbances associated with an enhanced African easterly jet contributed to a very active Atlantic hurricane season in 1999 (Bell et al. 2000). It is likely that these wave disturbances also contributed to the unusually wet SON season in NVE.

Many of the anomalous conditions observed in 1999 were characteristic of other SON seasons with enhanced NVE rainfall. For example, Fig. 3 indicates the difference in composite 925-hPa wind anomalies for unusually ‘‘wet’’ and ‘‘dry’’ SON seasons in NVE (cases used listed in Table 1). An anomalous northward shift of the ITCZ in the equatorial Pacific is again suggested, consistent with the observation that the majority of the wet SON seasons used had concurrent negative SST anomalies in the eastern Pacific. Figure 3 also indicates anomalous westerlies extending from the eastern Pacific to the Caribbean as well as along the coastal NVE. This pattern was associated with large-scale moisture flux convergence over the southern Caribbean (not shown) similar to the pattern shown by Giannini et al. (2000) as being associated with enhanced Caribbean rainfall during JJA. It is noted that an analysis of meridional wind differences for wet − dry SON seasons based on rainfall at Caracas-Maquetia indicated a statistically significant anomalous northerly flow along the coast of NVE that was not seen when using the NVE average rainfall. This implies that during unusually wet SON seasons in Caracas there is a tendency for an earlier than average transition to upslope flow than occurs climatologically. This was found to be the case when individual months with enhanced Caracas rainfall were examined for the SON season.

The anomalous westerly wind component seen over the southern Caribbean in Fig. 3 was identified as being statistically significant at the 95% level (using a *t* test) from 925 up to the 600-hPa level. Above 400 hPa, anomalous easterlies were found in the composite differences up to the level of the tropopause. Climatologically, westerly wind shear is located over NVE and the southern Caribbean during SON, which is observed to increase in magnitude over the course of the season. For the wet − dry seasons in NVE it was found that this westerly shear was reduced, a factor found by Riehl (1973) to favor increased precipitation during the main rainy season in Venezuela.

The opposite-signed SST anomalies in the Niño-3 (cold) and NATL (warm) regions observed in SON 1999 are of interest. Differences in composite SST anomalies for wet − dry SON seasons showed statistically significant negative SST anomalies in the eastern tropical Pacific but no significant positive values in the Caribbean/tropical Atlantic. The SST data used has a fairly coarse resolution that does not allow smaller-scale features, such as the positive SST anomalies seen along coastal NVE in SON 1999, to be resolved making an assessment of their influence on NVE rainfall beyond the scope of this study. It is interesting to note, however, that the cold Niño-3 and warm NATL SST pattern was a robust feature for JJA composite SST anomaly differences. Given the lag relationship between ENSO and Atlantic SSTs (e.g., Enfield and Mayer 1997) this SST anomaly pattern often occurs during rapid transitions from warm to cold ENSO phases. Five such rapid transitions occurred in the study period with the corresponding JJA rainfall in NVE ranking in the top six wettest JJA seasons in the 1950–99 study period.

5. Extreme daily rainfall along the NVE coast

Torrential rainfall in December 1999 served as the trigger to catastrophic landslides and flooding. As observed at Caracas-Maiquetia, there were two periods of excessive rainfall that month (Wieczorek et al. 2001). More than 210 mm of rainfall was observed between 2

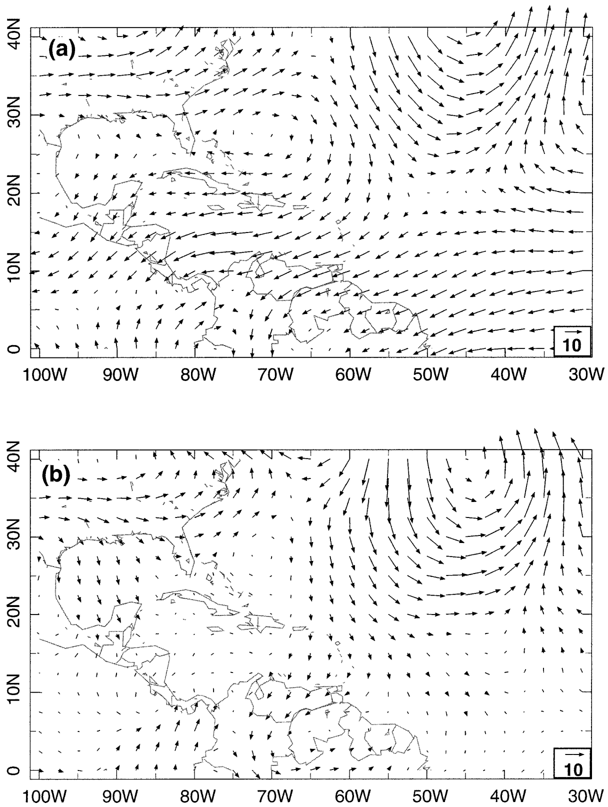

FIG. 4. Average 925-hPa wind for 14–16 Dec 1999: (a) full field and (b) anomalies. Units are m s^{-1}; representative vector is in lower right of plot.

and 4 December while over 911 mm fell between 14 and 16 December, triggering the most devastating landslides. In the 2-day period 15–16 December, Caracas received more than 150% of its annual rainfall. In this section the synoptic-scale atmospheric circulation associated with these two periods of torrential rainfall is briefly explored.

Plotted in Fig. 4a is the 925-hPa wind vector for the period 14–16 December 1999. A zone of low-level confluence was observed across a broad region of the Caribbean, just north of the Venezuelan coast. This confluence zone was associated with a cold front that had initially traveled into the Caribbean region from the continental United States at the start of December. Frontal incursions (nortes) are important contributors to boreal winter precipitation in parts of Central America and the Caribbean (e.g., Waylen et al. 1996a,b), especially when persistent (Portig 1965), but are very infrequent in the Caribbean south of 15°N (DiMego et al. 1976; Shultz et al. 1998). Plots of daily OLR (not shown) indicate that convection in the confluence zone during these two periods moved near and along the NVE coast while propagating westward toward Central America. In the period 14–16 December the confluence zone was located closer to the NVE coast than in the case 10 days earlier as the meridional flow across the Caribbean was strengthened in response to an anticyclone moving off the southeast coast of the United States.

The 925-hPa wind vector anomalies for 14–16 December 1999 are shown in Fig. 4b. An anomalous northerly component was observed (extending up to midtroposphere) suggesting moist air from the confluence zone was mechanically lifted up the slopes of the steep local topography, favoring enhanced rainfall at higher elevations. Wieczorek et al. (2001) report that in similar past events in the region, observed rainfall was greater in the higher elevations by as much as a factor of 2. Interestingly, an anomalous northerly low-level flow and confluence zones of extratropical origin (not shown) were observed during other months during the boreal winter in which extreme daily rainfall was observed along coastal NVE (February 1951, December 1951). It appears that the likelihood of extreme rainfall events in coastal NVE (during boreal winter) can be enhanced by the juxtaposition of two simultaneous synoptic conditions: a nearby low-level confluence zone (e.g., associated with cold fronts from the North American continent), and an anomalous northerly flow, which serves to lift moist air up the slopes of the local orography.

Wieczorek et al. (2001) indicate that the majority (five out of eight) of past severe flooding events documented in the region occurred during the November–February period. It is hypothesized that the likelihood of extreme rainfall events during what is generally the dry season in NVE is enhanced because frontal systems (and associated zones of low-level confluence) originating from North America are more likely to penetrate well into the Tropics during that time of year. In addition, Northern Hemisphere extratropical synoptic systems (occasionally providing anomalously strong northerly flow along the coast of NVE) reach their southernmost latitudinal extent during the boreal winter season. The potential influence of ENSO in this regard was considered by Shultz et al. (1998) who indicated that the number of frontal incursions into Central America in a given calendar year was not closely associated with the phase of ENSO, although they did show a tendency for more incursions into the region in the year following an El Niño.

6. Summary and conclusions

The devastating floods and landslides of December 1999 in NVE were triggered by torrential rainfall that fell over a period of a few days. However, an enhanced rainy season had exposed the region to large moisture surpluses weeks prior to the event. This enhanced seasonal rainfall was associated with large-scale atmospheric circulation anomalies similar to those seen in past seasons. Some plausible physical mechanisms associated with enhanced SON rainfall in NVE include reduced low-level stress-induced divergence due to weakened low-level easterlies (especially strong in SON 1999); anomalous moisture flux convergence over the

Caribbean; reduced vertical wind shear; and reduced downslope (and early onset of upslope) flow at Caracas. The differences in low-level winds between composite wet–dry SON seasons indicate a weakened subtropical high pressure area over the North Atlantic and enhanced high pressure in the eastern Pacific. Differences in upper-level winds were generally consistent with those expected during opposite phases of ENSO.

Important synoptic features of the atmospheric circulation during the December 1999 floods appear to include a low-level confluence zone located just to the north of NVE and anomalous northerly upslope flow. This confluence was associated with the remnants of a cold front that had penetrated the Tropics from North America. Similar synoptic features of extratropical origin were identified in two other months with extreme daily rainfall in coastal NVE during boreal winter. It is hypothesized that the likelihood of extreme daily rainfall events is enhanced in coastal NVE during what is generally the dry season due to the influence of extratropical circulation features that occasionally reach the deep Tropics during boreal winter as appears to be the case in 1999.

Acknowledgments. The IRI is supported by the NOAA Office of Global Programs, Columbia University, and the government of Taiwan.

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