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Extreme precipitation trends associated with tropical cyclones in the core of the North American monsoon

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[1] We estimate trends of extreme daily precipitation (P95 > 95th percentile) events in the core of the North American monsoon region in Northwest Mexico during JJAS of 1961–1998. The intensity and seasonal contribution of P95 show significant upward linear trends in the mountain sites, which appear to be related to an increased contribution from heavy precipitation derived from tropical cyclones (TCs). Frequency of P95, total monsoon precipitation, and P95 in coastal stations did not change significantly. TC-derived P95 events are associated with SST anomalies similar to weak La Niña conditions in the eastern Equatorial Pacific, SSTs > 28.5°C in the Caribbean Sea, and strong land-sea thermal contrast over Northwest Mexico and the U.S. Southwest two weeks prior to their onset. **Citation:** Cavazos, T., C. Turrent, and D. P. Lettenmaier (2008), Extreme precipitation trends associated with tropical cyclones in the core of the North American monsoon, *Geophys. Res. Lett.*, *35*, L21703, doi:10.1029/2008GL035832.

1. Introduction

[2] During the 1980s and 1990s the northwestern Mexican states of Sonora, Sinaloa, and Chihuahua, where the core of the North American monsoon (NAM) region is located (Figure 1 (left)), experienced heavy precipitation events that led to severe damage and fatalities [*Bitrán Bitrán*, 2001; *Comisión Nacional del Agua (CNA)*, 2004], but also helped to refill major dams in the region, which are used for irrigation, electric power, and domestic supply [*CNA*, 2004]. There is evidence that the annual frequency and annual amount of heavy precipitation increased significantly in Northwest Mexico [e.g., *Groisman et al.*, 2005; *Alexander et al.*, 2006] during the second half of the XX Century. However, heavy precipitation trends have not previously been documented for the core region during the monsoon season. The core monsoon is characterized by a semiarid climate and the largest precipitation variability within the NAM region [*Gutzler*, 2004]. Seventy percent of its annual precipitation falls during the summer monsoon in JJAS. The core monsoon is also one of the most productive agricultural and livestock regions in Mexico.

[3] Within the NAM core region, extreme precipitation can result either from strong monsoon convective activity due in part to the land-sea thermal contrast and surface heating of moist air along the western slopes of the Sierra Madre Occidental [e.g., *Zhu et al.*, 2007], or from the passage of Pacific tropical cyclones (TC). Synoptic features such as easterly waves, moisture surges, and inverted troughs [e.g., *Douglas and Englehart*, 2007] are common during the summer and influence both TC and non TC activity and may also result in enhanced precipitation.

[4] It has been argued that the impact of climate change will be felt most strongly through changes in precipitation extremes rather than changes in mean precipitation [e.g., *Kharin and Zwiers*, 2005]. A positive and significant trend in surface temperatures has been documented for the U.S. Southwest and NW Mexico for the 1973–2003 period [*Karoli and Wu*, 2005]. It is therefore important to document and understand concurrent changes in extreme precipitation. Hence, the purpose of this article is to estimate trends in extreme daily precipitation in the NAM core region and to examine the role of surface temperature anomalies during the evolution of these events.

2. Data

[5] We used observed daily precipitation during the monsoon season (JJAS) from 1950 to 2003 from the ERIC III data set of the Instituto Mexicano de Tecnología del Agua. A subset of the most continuously operating 39 stations in the core monsoon region (Figure 1 (left)) was selected after a quality control (QC) analysis (described below). Twenty one of the stations are located along the coastal plains of Sonora and northern Sinaloa and 18 are located in mountain sites with elevations ranging from 501 m to 2300 m. As seen in Figure 1 (left), and as discussed by *Gochis et al.* [2004], the distribution of climate stations suffers from a low elevation bias. The best period of observations is 1961–1998, with about 95 percent of all records included; this period is used for the current analysis. A QC of the data was conducted to identify errors and gaps. First, a threshold of 4 standard deviations above the climatological mean was used to identify daily outliers. Visual inspection, comparison with neighboring stations, and checks for the presence of TCs were also used to determine the validity of the outliers, which were only rejected after manual inspection.

[6] Extreme daily precipitation was separated into TC-derived precipitation and monsoon-derived precipitation (non TC). An extreme precipitation day was considered as derived from TCs when a storm center was located within 550 km (5° latitude) of the limits of the core monsoon region, a criterion also used by *Englehart and Douglas* [2001] and *Larson et al.* [2005]. For this purpose, eastern Pacific tropical cyclone tracks were obtained from the Unisys data set (http://weather.unisys.com/hurricane/e_pacific/index.html) and revised with the National Hurricane Center archive (http://www.nhc.noaa.gov/pastall.shtml). Hurricane

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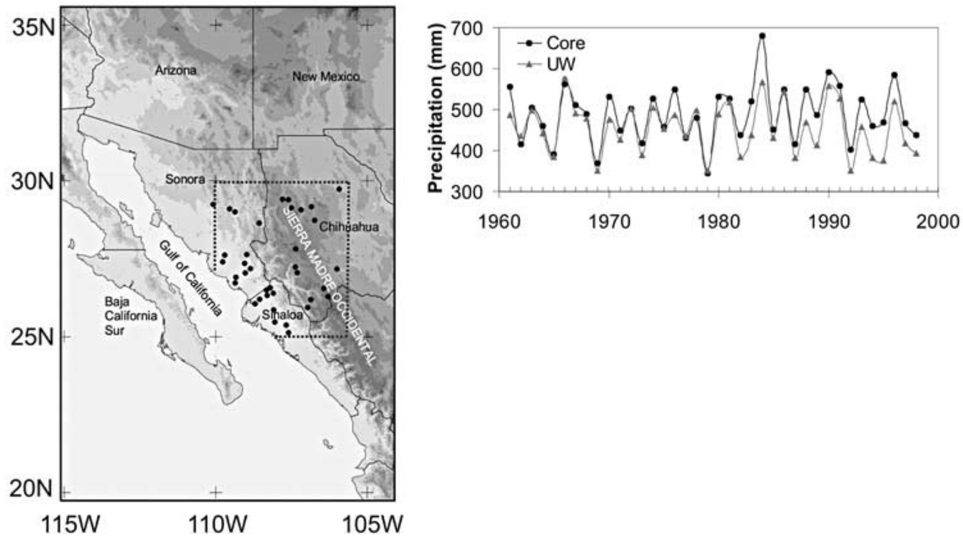

Figure 1. (left) The core monsoon region (delineated by a dashed line). The dots represent the location of the rainfall stations used. (right) Observed total JJAS precipitation (mm) in the core monsoon using station data (Core) and gridded precipitation (UW) data from the University of Washington.

data are more reliable after 1970 when the intensity of TCs began to be estimated by the Dvorak technique based on satellite observations [*Whitney and Hobgood*, 1997]. Therefore, even though trends for daily P95 precipitation events were estimated for 1961–1998, TC- and non TC-derived P95 were only analyzed separately after 1971. To examine the possible role of SST anomalies during the onset of extreme precipitation events, we used the optimally interpolated, weekly, in situ and satellite SST merged dataset (OISSTV2) [*Reynolds et al.*, 2002] at one degree resolution, available from 1981; due to the coarse resolution of this data set, the Gulf of California is not well resolved. We also analyzed surface and atmospheric daily and weekly temperature, outgoing longwave radiation, geopotential heights at 500 mb (Z500), and vector wind composites from the NCEP-NCAR reanalysis data [*Kalnay et al.*, 1996)] for 1981–1998, which were generated from the Mean Daily Composites of NOAA/CDC (http://www.cdc.noaa.gov/Composites/Day).

3. Methods

[7] An extreme precipitation event was defined as occurring when daily precipitation from 01 June to 30 September (JJAS) exceeded the 95th percentile (P95) of wet ($P > 1$ mm) days. First, a single daily core monsoon precipitation index (CMI) was constructed as a simple average of all daily station values. A seasonal precipitation CMI for JJAS was also constructed. The P95 minimum threshold from the CMI was 14.5 mm d^{-1}. Extreme events were also evaluated for individual stations and, then, grouped into coastal and mountain sites to adjust for variable station records and missing data. The average P95 threshold at coastal sites was 50 mm d^{-1} and for mountain stations was 42 mm d^{-1}. Based on a more extensive rain gauge network during 2002–2004, *Gochis et al.* [2007b] document that, for P90, heavier events in the core region were also confined to the lower elevations. Frequency, intensity, and seasonal contribution of extremes were obtained for the CMI, for individual stations, and for coastal and mountain stations. The seasonal contribution from P95 events was defined as the sum of all extreme precipitation days divided by the seasonal precipitation. All analyses were tested for statistical significance at the 95% level or greater. Trends in the time series were evaluated with the non-parametric Mann-Kendall test [*Kendall*, 1975; *Dietz and Killeen*, 1981; *Helsel and Hirsch*, 1995] with an adjustment for tied observations. Trend slopes were estimated using Sen's slope estimator [*Sen*, 1968].

4. Trends of Extreme Daily Summer Precipitation

[8] The area-averaged CMI precipitation was compared to a new gridded precipitation data set that has been used in studies of the NAM region: The 1/8° degree resolution daily precipitation data from the University of Washington (UW) [*Zhu and Lettenmaier*, 2007]. The seasonal precipitation index from the UW dataset for the core monsoon agrees well ($r = 0.9$) with the seasonal (Figure 1 (right)) and daily CMI ($r = 0.86$). The JJAS precipitation timeseries in Figure 1 (right) does not show a significant trend during the study period. *Englehart and Douglas* [2006] found that while the intensity of summer rainfall in the state of Sonora increased significantly after 1977, in association with the positive phase of the Pacific Decadal Oscillation, the monsoon season became shorter, and these two trends effectively cancel each other resulting in no trend in seasonal rainfall. This may partially explain why the seasonal CMI in Figure 1 (right) does not show a positive trend, even though the P95 contribution (Figure 2a) increased significantly (1.3% decade^{-1}, $p < 0.05$) during 1961–1998.

[9] Figure 2a shows the total seasonal contribution of daily P95 events based on the CMI and the portion of the contribution from TCs. The difference of the two gives the seasonal contribution of non TC-derived P95 (i.e., monsoon-derived P95). The contribution of P95 in the CMI increased significantly during 1961–1998, but the frequency of P95 showed no evidence of a trend (not shown). *Groisman et al.* [2005] also document that the frequency of very heavy

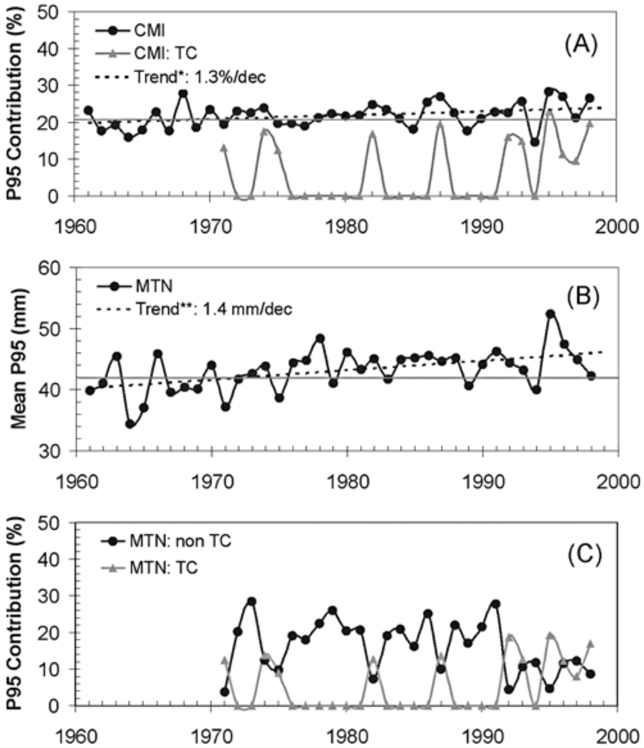

Figure 2. (a) Percent contribution of P95 to seasonal precipitation from the CMI and from the TC-derived P95 in JJAS. (b) Mean P95 intensity in mountain (MTN) sites in JJAS, and (c) percent contribution of P95 to seasonal precipitation in MTN sites from non TC- and TC-derived P95 in JJAS. One (two) asterisk indicates statistical significance at the 95% (99%) level. Straight grey lines in Figures 2a and 2b indicate the mean value of the variable.

summer precipitation (P99) in the high plains of Northern Mexico (east of the core monsoon) has not increased, whereas their intensity has increased significantly. Of particular interest is the significant increase in the intensity (Figure 2b, $p < 0.01$) and seasonal contribution of P95 in mountain sites, with larger values on average in the 1990s. This increase appears to be related to a larger contribution of TC-derived P95 (Figures 2a and 2c). In contrast, the characteristics of P95 in coastal stations did not change significantly, possibly because the coastal sites are more commonly affected by the passage of gulf surges, easterly waves, and TCs than mountain sites [*Gochis et al.*, 2004].

[10] Monsoon precipitation is often supplemented by TCs moving parallel to the Mexican Pacific coast. In the 1990s, for example, mountain sites received less heavy monsoon-derived rainfall (non TC in Figure 2c) than normal, but the region was supplied by heavy precipitation from several TCs (Figures 2a and 2c). The study area has more than 10 major dams that are greatly benefited by the passage of TCs [*CNA*, 2004], especially during long periods of drought, such as those of 1995–2004 [e.g., *Hallack-Alegria and Watkins*, 2007]. Of the 12 TCs that affected the core region during the monsoon season in 1981–1998, 5 entered the core monsoon (Figure 3) and 4 of them occurred in the 1990s (Hurricanes Lidia, Ismael, Fausto, and Isis) during neutral and La Niña summers. The only hurricane that hit the coastline of the core monsoon in the 1980s was Paul (Sep 1982) during a strong El Niño event. According to the Mexican National Water Commission [*CNA*, 2004] during 1980–2003, Sinaloa was the second most affected state (after Baja California Sur) by TCs; Sonora was the 14th most affected state. In agreement with these statistics, the mean daily precipitation composite during the onset of the TC-derived extreme events that impacted the core monsoon (Figure 3) shows maximum precipitation in Sinaloa.

5. Synoptic Conditions Associated With TC-Derived P95 Events

[11] As documented in the last section, significant changes in the intensity of P95 events in the core monsoon and in mountain sites appear to be related to an increased contribution of TC-derived P95 in the 1990s; thus, we examine here the role of surface temperature anomalies (Tsan) and the synoptic conditions before and during the TC-derived P95 events. Figures 4a and 4b show the composite of Tsan two weeks and one week, respectively, before the onset of these events. Positive Tsan (> 0.5°C) in Northwest Mexico and the U.S. Southwest suggest a positive land-sea thermal contrast. In the eastern Equatorial Pacific, in the Niño 3 region, there are neutral to La Niña-type negative anomalies on the order of −0.5°C that persist until the onset of the extreme events, as seen in Figure 4e.

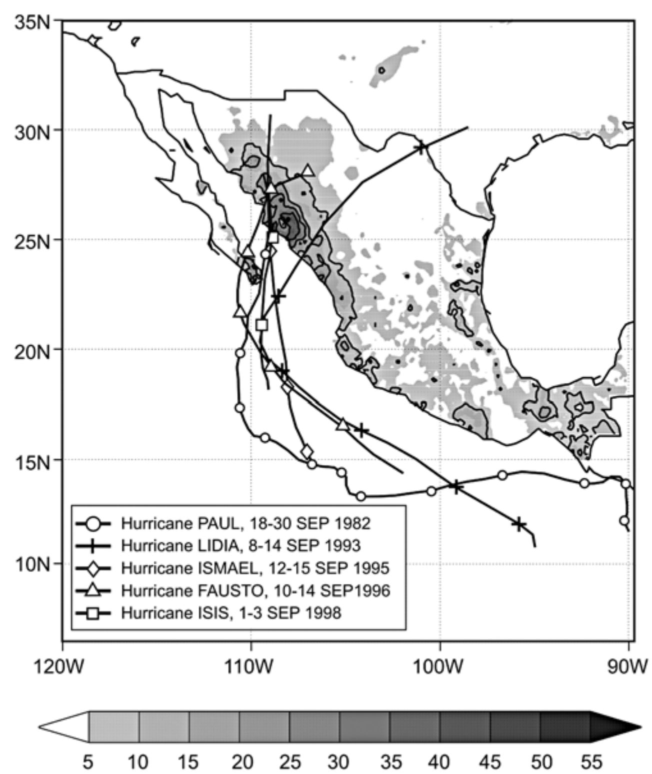

Figure 3. Mean daily precipitation (mm d^{-1}) composite from the UW gridded data set during extreme events derived from 12 TCs that affected the core monsoon (1981–1998). Contour interval is 10 mm d^{-1}. Tracks of hurricanes that entered the core monsoon region in the same period are shown with solid lines, each marker in the lines represents one day.

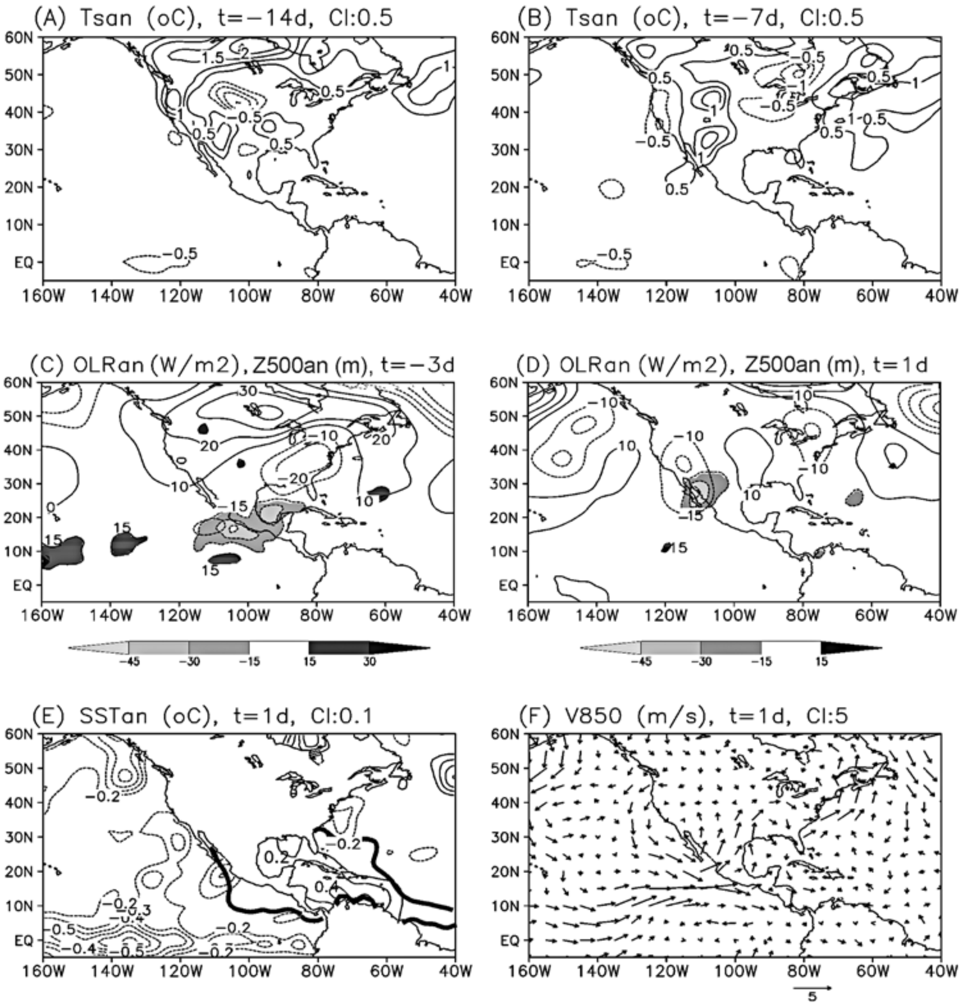

Figure 4. Composite anomalies associated with TC-derived P95 events (1981–1998). Tsan (a) two weeks and (b) one week before onset of P95 events. OLRan (shaded) and Z500an (contours) (c) three days before onset and (d) during the onset of P95. (e) SSTan during the onset of P95. The bold curves indicate the 28.5°C isotherm representing the Western Hemisphere warm pool (WHWP) area. (f) Mean composite of the vector wind at 850 mb (m s^{-1}) during the onset of TC-derived P95 events.

Persistent negative anomalies in this region are known to favor cross equatorial flow and westerly winds (e.g., Figures 4e and 4f) and increased summer rainfall in southern Mexico [e.g., *Cavazos and Hastenrath*, 1990], together with a greater streamflow in the southern part of the core monsoon [*Gochis et al.*, 2007a].

[12] The composite of the TC system is observed in southern Mexico three days prior to the onset of P95 events, as suggested by the strong negative OLRan and the upper-level trough (Z500an) in Figure 4c. The TC system produces subsidence over the U. S. Southwest (partially reflected in the positive Z500an pattern) and cooling in the eastern Pacific off the Mexican Pacific coast (Figure 4e) as it moves northwestward, further enhancing the land-sea thermal contrast; this, in turn, increases the moisture availability (not shown) for the propagating storm.

[13] In the Caribbean Sea, anomalous warming (SSTs > 28.5°C, Figure 4e) tends to weaken the northeast trades (Figure 4f) and the North Atlantic subtropical high [*Wang et al.*, 2007]. These synoptic conditions further intensify the cyclonic circulation near the Gulf of California (Figures 4d and 4f), producing convection (Figure 4d) and heavy rainfall in the core monsoon. The largest frequency of TC-derived P95 events in the core region occurred in September, when climatologically the Western Hemisphere warm pool (WHWP) of water is large [e.g., *Wang and Enfield*, 2003], as seen in Figure 4e. Non TC-derived P95 events occurred more frequently in July–August when the WHWP was much smaller in the Atlantic side (not shown).

6. Conclusions

[14] We found significant upward linear trends in the intensity and seasonal contribution of P95 events in the mountain sites of the North American core monsoon region during 1961–98 which appear to be related to an increased contribution from TC-derived P95, especially in the 1990s. Frequency of P95, total monsoon precipitation, and the characteristics of P95 in coastal stations did not change significantly during the study period. During the 1981–1998 period, TC-derived P95 events in the core region were characterized by persistent negative SST anomalies similar

to weak La Niña conditions, SSTs > 28.5°C in the WHWP area of the Caribbean Sea, and a strong land-sea thermal contrast between Northwest Mexico and the Southwest United States and the eastern Pacific since two weeks prior to the onset of the extreme events. Future work based on coupled modeling of the North American monsoon should help to further elucidate the role of the land-sea thermal contrast on the onset and predictability of monsoon precipitation and heavy precipitation events.

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