A Climatological Perspective of Transient Synoptic Features during NAME 2004

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ABSTRACT

This note provides a first look at a recently developed long-term climatology of transient synoptic features in northern Mexico. Key features investigated include inverted troughs, cutoff lows, cold fronts, and open troughs (westerly short waves). This 35-yr analysis of transient systems crossing northern Mexico (1967–2001) was developed to help place the summer climatology of the 2004 North American Monsoon Experiment (NAME) into a broader perspective. Inverted troughs are found to be the most commonly occurring transient synoptic feature during the monsoon with a mean frequency of occurrence of 55 days per summer season (June–September). Inverted troughs are found to contribute from 20% to 25% of the average summer rainfall observed in northern Mexico. Rainfall doubles during inverted trough days compared to days without transient systems being present.

In 2004 the monsoon season was greatly shortened due to a poorly developed subtropical high. Compared to long-term means, inverted troughs contributed less rainfall to the region in 2004 and this was, in part, associated with the shortened monsoon season. In contrast, frontal penetration into the region was almost double the 35-yr mean. These climatologies are designed to provide NAME researchers with benchmarks to assess model performance relative to how these models handle these systems and their associated rainfall. The work presented is a small portion of a much larger study that aims to determine the impact of all of these rain-bearing transient systems on the monsoon in northern Mexico.

1. Introduction

The 2004 North American Monsoon Experiment (NAME) field campaign focused on enhancing the normally sparse observing network across the monsoon region of northwest Mexico. The field experiment is part of a broader project aimed at improving the predictability of North American warm season precipitation (Higgins 2003). Various papers in this special issue describe the sophisticated observing platforms that were deployed during different stages of the NAME campaign. From its inception, a major goal of the NAME experiment has been the development of a highly refined synoptic database for diagnostic studies of the monsoon system. Based on the enhanced observational datasets produced in the 2004 campaign, the NAME modeling community is now prepared to perform a series of experiments that demonstrate the impact of the NAME datasets on both operational and research models. As expected with any single-season field experiment, a basic question for NAME is, How characteristic were the synoptic weather events sampled during the field experiment relative to the long-term climatologies of transient synoptic systems in this region? This is an important question from both a diagnostic and a modeling perspective. This note reports on work that is aimed at providing a historical climatological perspective on the interannual variability in transient synoptic systems over the core NAME domain.

Due to various resource and logistical considerations, the experimental design of the NAME field campaign emphasized data collection during intensive operation periods (IOPs). During IOPs, radiosonde observations were to be taken every 4 h and P-3 flights could be called to fly transects across a particular region(s) of synoptic interest. During an April 2004 meeting of the NAME Science Working Group (SWG) held in Tucson, Arizona, it was decided that the IOPs would concentrate on specific synoptic features that experience

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TABLE 1. Synoptic features/events of primary interest for the NAME 2004 field campaign.

	Synoptic feature/event
1	The synoptic regime associated with the start of the monsoon in 2004
2	Gulf of California moisture surge events
3	Easterly waves
4	Inverted troughs
5	Cutoff lows
6	Westerly troughs (open waves)
7	Cold fronts entering the domain from either the Great Basin or high plains
8	Tropical cyclones (northeast Pacific or Gulf of Mexico systems)
9	Pronounced breaks in the monsoon

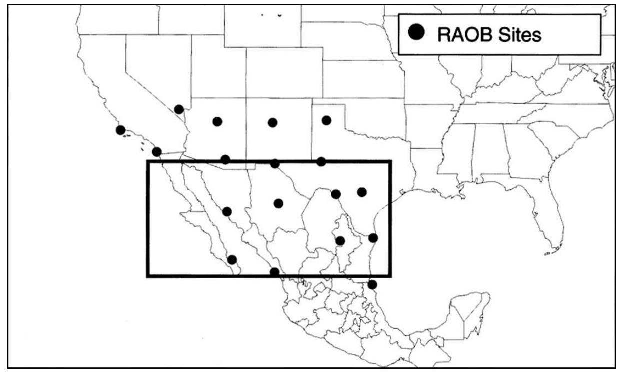

FIG. 1. The geographic domain used to evaluate transient synoptic features: 23°–32°N, 96°–116°W. Location of radiosonde stations plotted on the DWMS and used in the project are indicated by the closed circles.

had shown were the important rain producers during the summer monsoon season in northern Mexico. Principal investigators and forecasters associated with the field experiment agreed that the synoptic features and event phenomena given in Table 1 would be of primary concern during the decision-making process for calling IOPs. With very detailed measurements of these systems and specific phenomena, NAME expects to develop a better understanding of the various components of the monsoon system, ranging from the diurnal cycle to large-scale forcing.

This note focuses on development of a NAME historical climatology for selected transient synoptic features that affect the NAME region. The four features included in this investigation are inverted troughs (warm- and cold-core systems as detected at 50 kPa), cold-core cutoff lows, open troughs in the westerlies, and surface fronts. Bryson and Lowry (1955) first identified the importance of easterly waves on the monsoon of northern Mexico and the desert Southwest. The importance of easterly waves in tropical cyclone development in the eastern tropical Pacific is highlighted in recent papers by Molinari and Vollaro (2000) and Molinari et al. (2000). Mosino and Garcia (1974) have pointed out the importance of cold front penetration into northern and northeast Mexico as an important factor leading to the rainfall peaks in June and September across this region. While fairly rare in the summer in the NAME region, cutoff lows are also know to be important triggers for rainfall primarily due to instability created by their cold temperatures at mid- and upper levels. These cutoff lows are often able to trigger thunderstorm development even when dewpoints are exceptionally low (<10°C) across the desert Southwest.

Section 2 outlines the data sources and basic procedures used in constructing the climatology. Section 3 provides an initial look at some climatological relationships between inverted troughs in the NAME domain and regional monsoon rainfall. Section 4 provides a perspective on synoptic activity during the 2004 field experiment as it compares to the derived climatology.

2. Development of a database of transient synoptic features in northern Mexico

While NAME field operations occurred mainly from late June through mid-August, the historical climatology is constructed over the entire monsoon season in northwest Mexico: June–September. The base period for the climatology is 1967–2001. Its geographic domain is shown in Fig. 1. A variety of data sources were used to identify and track the synoptic features of interest. The recently imaged set of National Oceanic and Atmospheric Administration's (NOAA) "Daily Weather Map" series (DWMS) represents a principal information source for the project. The DWMS contains surface analyses and 50-kPa charts for 1200 UTC (Figs. 1 and 2). The product is now available online from the NOAA Central Library Data Imaging Project (http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html).

To develop the historical climatology, the DWMS charts were examined for each day of the monsoon season (June–September), 1967–2001. The objective was to identify the synoptic features given in Table 1, particularly features 3–7 (easterly waves to cold fronts). For a given chart, the latitude and longitude positions (to the nearest 1°) of each identified feature were read directly from the respective chart. In many instances, synoptic features could be identified and tracked before they entered the domain, but data limitations over the oceans prevented a reliable assessment of position. The

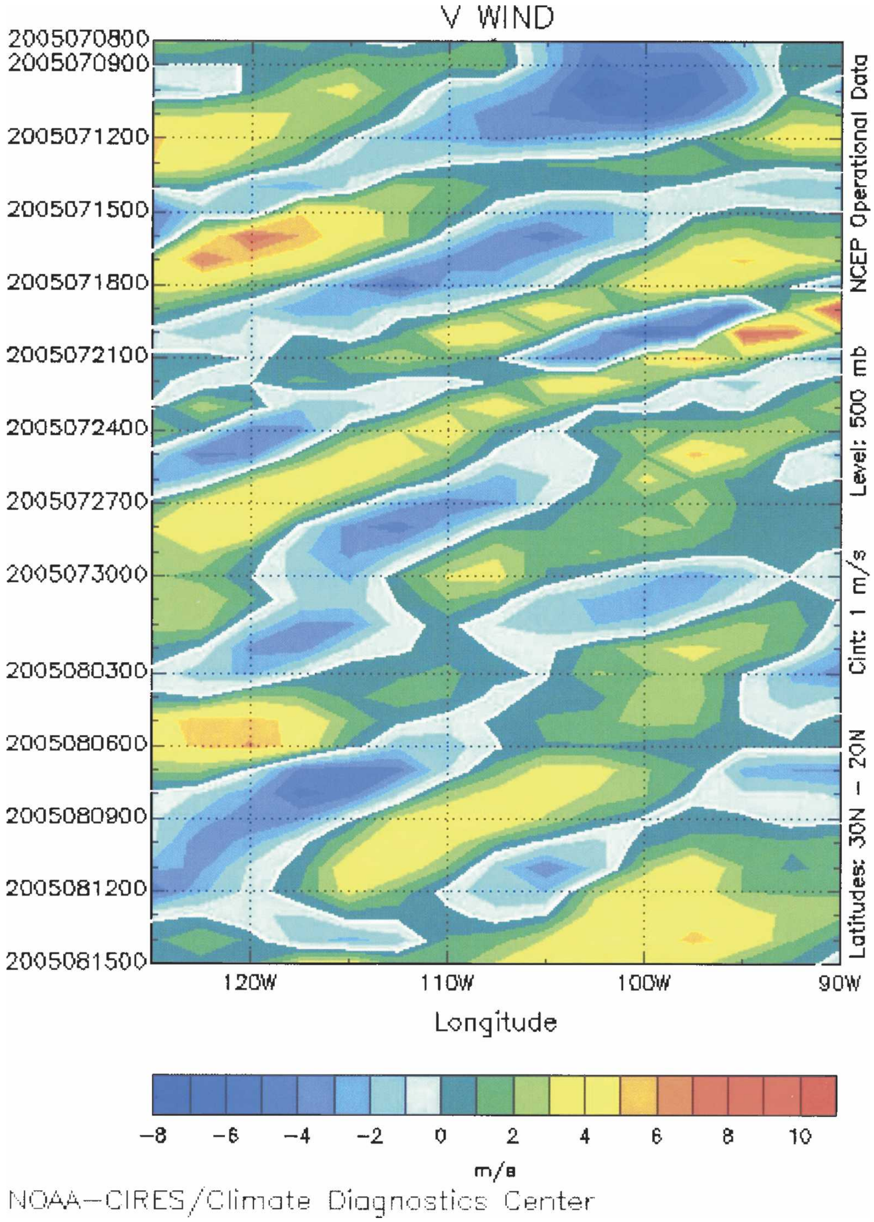

FIG. 2. Example of a time–longitude cross section chart of 50-kPa meridional winds constructed for northern Mexico (20°–30°N and 90°–125°W) for 8 Jul–12 Aug 2005.

geographic boundaries of the DWMS also precluded tracking systems that were present in the southern half of Mexico (south of about 23°N on the 50-kPa charts and 24°N on the surface charts).

In cataloging cold front position, the latitude and longitude of the southernmost position of the front were first recorded. Then for fronts that became "hung up" in the mountains of northern Mexico or moved west (backdoor fronts) into western New Mexico, eastern Arizona, or western Chihuahua, the farthest west location of the front was also recorded. This identification system helped anchor the position of the front across northern Mexico. The tail ends of cold fronts in northern Mexico were scrutinized to make sure that the hand-drawn frontal positions on the map had extended the front far enough to the southwest or west. This second check was necessary to ensure conformity through the entire data record as it was apparent that tail-end frontal position was dependent on the person producing the hand analysis. This second check was accomplished by identifying surface wind shifts and falling temperatures associated with the fronts. The maximum and minimum temperature data on the DWMS were also helpful in determining possible frontal passage. Additional historical maximum and minimum temperature data for Del Rio, Laredo, and Brownsville, Texas, were consulted when attempting to evaluate the southernmost penetration of a front. These data were available from the Web site of the National Weather Service Office in Austin, Texas (http://www.srh.weather.gov/ewx/html/climate.htm). Frontal positions recorded for the NAME domain included cold fronts, stationary fronts, and warm fronts, though warm fronts were found to be extremely rare during the period June–September. Individual frontal systems were numbered sequentially starting with the first front observed on or after 1 June of each year. A comparable numbering system was also used during the NAME field experiment in a fashion consistent with the practices of Mexico's Servicio Meteorologico Nacional (SMN).

For cutoff lows, the central position was determined from the height contours on the 50-kPa charts, as well as the plotted station winds at 50 kPa. Westerly waves (open troughs at 50 kPa) were tracked by noting the southernmost position of the trough axis (latitude and longitude) based on the height contours and plotted winds. Inverted troughs detected at the 50-kPa level were tracked by determining the northernmost position of the inverted trough axis (latitude and longitude). The southern boundary of the map analysis is near 23°N as demarcated by the southernmost data plotted for Mazatlan, Monterrey, and Tampico, Mexico. Given the sparse historical data over the Gulf of Mexico and off the west coast of Baja California, we restricted our analysis of synoptic features to the region between 96° and 118°W. Over the southwestern United States and northern Mexico, radiosonde stations are approximately 5° apart from each other and with this spacing, it was decided that reasonable interpolation of synoptic feature position could be done to the nearest 1° of latitude and longitude.

While forecasters with the NAME experiment separately tracked tropical waves numbered by the National Hurricane Center in Miami (best detected from 85 to 70 kPa) and upper-level inverted troughs (best detected in the upper troposphere from 50 to 30 kPa), our climatology focuses on all westward-moving waves identifiable at the 50-kPa level and located south of the subtropical ridge located over North America. Ramage (1995) notes that the National Hurricane Center at Miami (see Simpson et al. 1968) abandoned the use of the term "easterly wave" in the late 1960s after years of experience had shown that many waves in the low-level easterlies actually stemmed from upper-level cyclones (cold lows). The term "tropical wave" was introduced to describe westward-moving systems that had maximum amplitude at low, middle, or upper levels. Our use of the 50-kPa level in this study was dictated by the fact that this was the only level depicted in the DWMS. In this paper westward-moving troughs that are open to the equator are termed inverted troughs. It should be noted that after making two complete passes through the entire 35-yr subset of DWMS charts, it became apparent that inverted troughs detected at 50 kPa can be either cold core or warm core. Frequently, the warm-core systems at 50 kPa were found to be midlevel manifestations of moderate or strong low-level tropical waves that were crossing the elevated Mexican plateau from the Gulf of Mexico. We realize, however, that weaker low-level tropical waves may not have been detected at the 50-kPa level. Throughout this note, all westward-moving waves at 50 kPa will be referred to as inverted troughs with an understanding that they may be either cold core or warm core. As will be shown in section 4, warm-core systems are the most dominant type of inverted trough detected at 50 kPa, with 62% of all inverted trough days being associated with warm-core systems.

Monthly time section charts for 50-kPa meridional winds were constructed for the region 22°–31°N and 95°–125°W to aid in the detection and tracking of inverted troughs across Mexico (Fig. 2). Additionally, monthly time section charts for 50-kPa temperatures were constructed at 1°C intervals in order to determine the thermodynamic nature of the troughs. These plots were constructed at the NOAA Climate Diagnostics Center (CDC) plotting Web site (http://www.cdc.noaa.gov/map/time_plot/).

The time section charts were especially useful in cases where the DWMS 50-kPa charts were unavailable, or when the charts did not include the plotted station winds. The time section charts of meridional wind were constructed with operational data for the period 1979–2001; National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis-1 data were used for the period 1967–78 as operational data were not available for this earlier period at the CDC plotting site. We realize that the data from the reanalysis products can suffer problems associated with tracking weak easterly waves (Hodges et al. 2003), but the NWMS 50-kPa charts with their plotted station data helped to detect the weaker systems.

The mean climatologies (June–September) of the four synoptic features investigated in this note are shown in Fig. 3. Here, the frequency of synoptic activity is represented as the average number of days per year

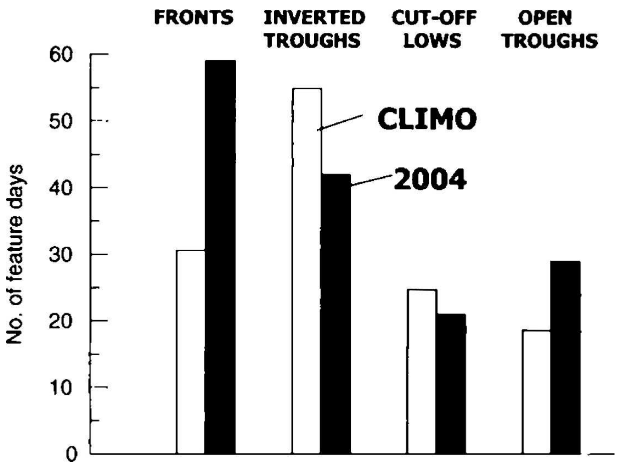

FIG. 3. Synoptic features of Jun–Sep climatology (1967–2001) given by open bars; observed 2004 features given by filled bars. All data are expressed as number of days in which a feature is present in the NAME domain (see Fig. 1).

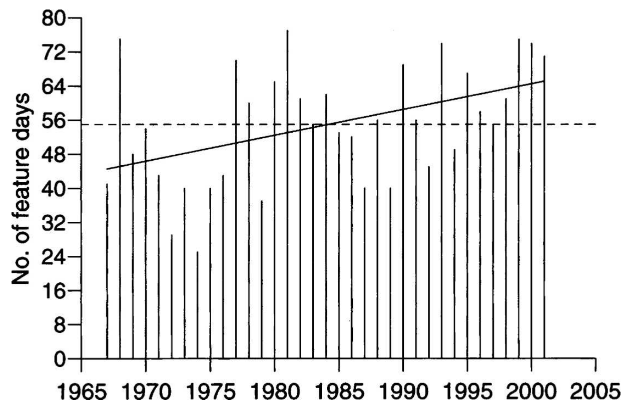

FIG. 4. Time series of inverted trough (IV) days (1967–2001). The dashed line indicates the mean for the time series while the solid line indicates the long-term trend in the time series.

that a given feature was present within the domain (Fig. 1). The long-term climatology of synoptic transient features indicates that inverted trough days in the NAME region of northern Mexico exceed all other types of features by about a factor of 2. The climatology indicates that within the domain, inverted trough days are the dominant transient feature—occurring on average about 55 days [standard deviation (std dev) 13.9 days] as compared to about 30 days for fronts (std dev 9.1 days), 25 days for cutoff lows (std dev 12.7 days), and 19 days for open (westerly) troughs (std dev 8.9 days). Based on the standard deviations, it appears that inverted troughs are typically the most consistent summer feature, while fronts and cutoff lows show large year-to-year variability.

As Fig. 3 indicates, NAME 2004 was not an average monsoon season; contrary to climatology, the number of frontal days was actually greater than the number of inverted trough days. The synoptic pattern that created these differences will be discussed in section 4, while in the next section a preliminary analysis is presented on the impact of inverted troughs on monsoon rainfall in northern Mexico.

3. The climatology of inverted troughs in northern Mexico and relationships with monsoon rainfall

The time series of inverted trough (IV) activity (1967–2001) is presented in Fig. 4. As indicated by this graphic the average frequency of inverted troughs over northern Mexico is about 55 days during the monsoon season of June–September. Using the monthly temperature time section charts, it was determined that 62% of the IV days (1835 days) were associated with warm-core systems (trough temperatures $>-6°C$), 30% were neutral ($-7°$ to $-6°C$), and only 8% were cold core ($<-8°C$).

A linear trend line has been superimposed on the time series. Clearly, the apparent upward trend in IV frequency is anchored by the period of reduced IV activity in the early and mid-1970s. Not surprisingly, this period in the 1970s was characterized by a tendency for summer drought across northwest Mexico and the southwestern United States (Englehart and Douglas 2002; Brito-Castillo et al. 2003). After the drought of the 1970s, there does not appear to be any trend in IV frequency across northern Mexico.

Much of our prior research on the North American monsoon system has been directed toward better understanding the intraseasonal variability in warm season precipitation. For example, in earlier work (Englehart and Douglas 2001) we evaluated the impact of tropical storm (TS) rainfall on seasonal totals for much of western Mexico. To associate rainfall with TS activity, a simple distance criteria was adopted: for any day in which a TS was located within 550 km of an observing station, it was assumed that station rainfall was associated with the TS. This paper adopts a similar approach to characterize the impact of transient synoptic systems on the rainfall patterns of northern Mexico. The IV troughs tend to have horizontal scales of 8°–12° of longitude, and during active periods these troughs can be tightly spaced and separated by an equal range of longitude (e.g., Fig. 2). Our analysis of rainfall associated with these troughs will concentrate on rainfall associated with the systems when they are within $\pm4°$ (longitude) of a given climate region.

As part of this work, datasets of mean daily rainfall have been developed for seven climate regions across the NAME domain (Fig. 5). These regions of coherent summer rainfall have been identified by principal com-

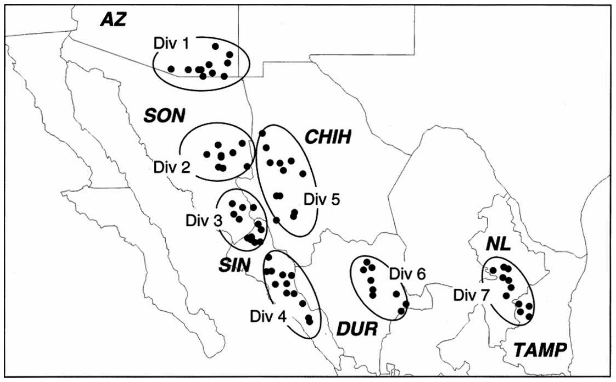

FIG. 5. Location of synoptic climate divisions in northern Mexico and distribution of individual stations within the divisions. For each division, average daily rainfall (mm) was calculated over all available observations (1950–2001).

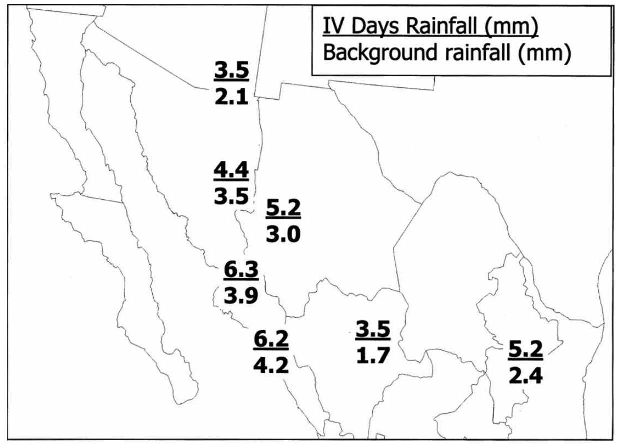

FIG. 6. Comparison of average daily rainfall associated with inverted troughs vs average daily rainfall associated with all days in which no synoptic feature was present in the NAME domain (Fig. 1).

ponent analysis of monthly station rainfall at more than 270 stations in Mexico (see Englehart and Douglas 2002; Brito-Castillo et al. 2003). The size of the climate regions reflects the fact that the space (or correlation) scale for summer rainfall over northern Mexico is fairly small. The small size of the climate regions in summer (as compared to winter) is probably a result of decreased large-scale synoptic forcing with a greater influence from local or mesoscale convective systems during the monsoon. The broader regionalization of rainfall is partially a result of differences in the intraseasonal distribution of summer rainfall. Northeast Mexico is dominated by two rainfall peaks (June and September) while northwest Mexico is dominated by a midsummer peak (July and August). The central plateau lies between these two rainfall regimes and during some summers the plateau will take on characteristics of the regions to the east or west.

It should be noted that fortunately for this study, Mexican rainfall reports are only taken at 0800 LST (1400 UTC for most of this central time zone region). In the statistical analyses of the impact of inverted troughs on regional rainfall, the precipitation reported at 1400 UTC is related back to the position of the wave on the previous morning at 1200 UTC. This lag between system position on the first morning and the total rainfall the next morning provides for a complete diurnal cycle associated with the transient system.

To evaluate the impact of inverted troughs on daily rainfall totals, we considered only those days in which an IV was present, subject to the constraint that it was the only feature evident within the domain. In other words, if another synoptic feature was present on the same day, then this day was excluded from the analysis. The average daily precipitation associated with IV days for the seven climate divisions is shown in Fig. 6. As noted above, the operational distance criterion was that the trough had to be located within ±4° (longitude) of a division's geographic centroid in order for the day's rainfall to be attributed to the system. To provide a comparative perspective, the average daily "background" rainfall also was calculated. This background value represents the mean daily precipitation for all days in which there was no synoptic feature evident in the domain. For north-central and northeast Mexico, the average rainfall for IV days is about double that for days without any synoptic feature being present, while in western Mexico the average daily rainfall on days with inverted troughs increases to about 1.5 times the background rainfall on days without synoptic features.

The position of the trough and its relationship with subsequent 24-h precipitation totals is shown in Fig. 7. Average daily rainfall in western Mexico typically is highest when the trough is located 3°–4° to the east of the division. In both Sonora and Sinaloa, weak capping associated with downslope flow is common when a trough is over the plateau and winds are from the east and northeast ahead of the system. As the trough moves west and the cap is broken by intense daytime heating, mesoscale convective systems (MCSs) frequently breakout. This synoptic setup was noted by forecasters throughout the NAME experiment. It is interesting to note that for climate regions 2 and 3 that the fairly rare cold-core systems are on average much drier than the warm-core systems (mean daily precipitation at 3.9 versus 5.5 mm). The cold-core systems tend to be wetter on their forward flank with mean daily rainfalls of 5.2 mm when they are located east of the climate divisions as compared to a mean daily rainfall of 2.5 mm after they have passes to the west. Thus,

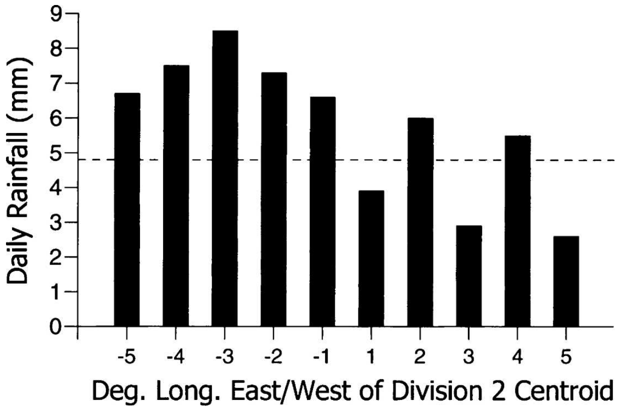

FIG. 7. For rainfall division 2 (see Fig. 5), the relationship between IV trough position and mean daily rainfalls reported in the 24–26-h period following this position. Positions east (−) and west (+) of the region are in 1° longitude intervals (e.g., −1 = 0° to 1°E).

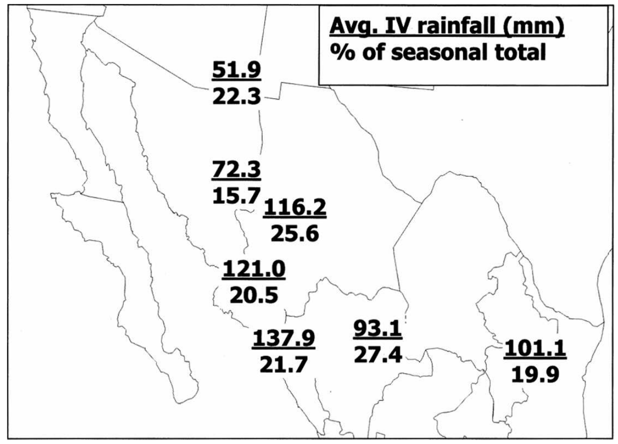

FIG. 8. Average seasonal rainfall (mm) associated with inverted trough days (1967–2001) and the corresponding contribution to seasonal totals (%).

while cold-core systems typically are drier, they trigger their heaviest precipitation as they approach from the east with their cold midlevel temperatures; these systems produce less rainfall due to midlevel warming as they pass to the west.

The overall impact of inverted troughs on total summer precipitation is demonstrated in Fig. 8. Central sections of the plateau receive about 25% of their summer rainfall from these transient inverted troughs, which help to advect moisture into the continent from the Gulf of Mexico. Rainfall in the plateau is probably aided by the dynamics of the transient system with the mean surface flow for the summer being from the east or southeast (Mosino and Garcia 1974). Western sections of the Sierra Madre Occidental receive up to 20% of the summer rainfall from these systems.

4. Analysis of synoptic features during NAME 2004 relative to climatology

Synoptic feature frequencies in 2004 are compared with the 35-yr climatologies given in Fig. 3. The number of days with inverted troughs across northern Mexico was about 70% of the long-term mean. With a reduction in inverted trough days during NAME 2004, it is not surprising that total summer rainfall was less dependent on these transient systems (Fig. 9). In fact in northeast Mexico and the core monsoon region of northern Sinaloa and southern Sonora, inverted trough rainfall was reduced to only about 12% of the summer total compared to the long-term mean of 20%. The monsoon in 2004 was associated with a late start and early retreat across northern Mexico as shown in Fig. 10. An analysis of historical monsoon start dates in Sonora indicates that this was the fourth latest start date based on records from 1943 to 2002(Englehart and Douglas 2006). Despite the shortened monsoon season with reduced IV activity across the NAME domain, IV-related rainfall in central and northern Sonora (e.g., region 2) actually was near normal primarily due to a few nights with very heavy rainfall associated with inverted troughs (Fig. 10). While rainfall during the height of the monsoon exceeded normal daily means (e.g., region 2), the late start and early end of the monsoon season strongly impacted the window when transient inverted troughs normally cross the region.

The start of the monsoon was delayed primarily due to the persistence of a strong blocking ridge across the region in late June and July, but the early end of the monsoon was associated with a premature weakening

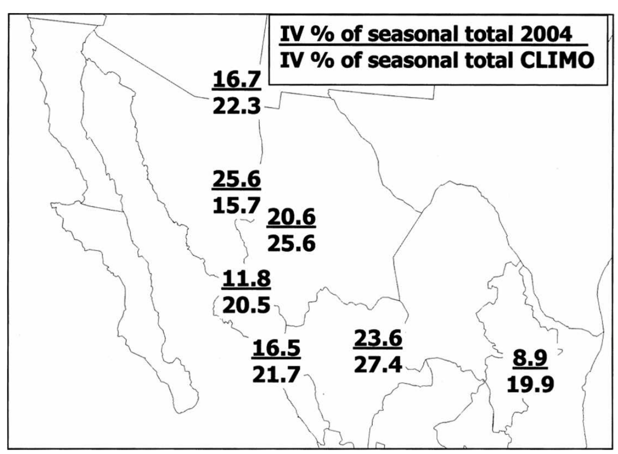

FIG. 9. Comparison of rainfall associated with inverted trough days in 2004 vs climatology. Values are expressed as % contribution to the seasonal total.

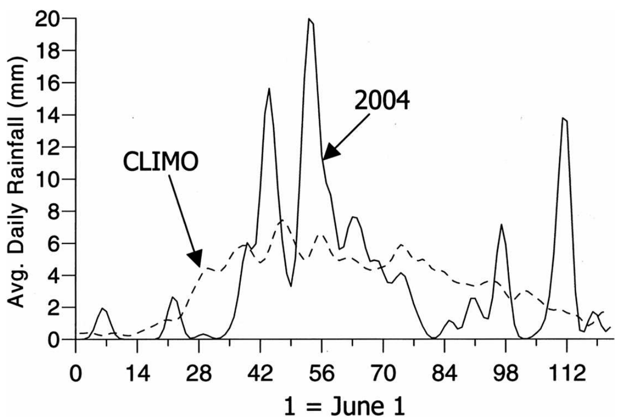

FIG. 10. Daily rainfall in Sonora (division 2, Fig. 5) for the 2004 monsoon season as compared to long-term climatology (1961–90). Note the relatively short period of heavy rains in 2004 compared to the long-term mean.

and southward retreat of the subtropical ridge that began in late July. This mid- and late summer circulation pattern favored a large number of fronts that would eventually push south into the NAME region. In fact, the number of summer days with fronts present in the region was twice the long-term mean (Fig. 3). With a weakened subtropical ridge, westerly troughs were able to penetrate farther south than normal, which led to a 170% increase in the number of open trough days.

5. Summary

This note provides a climatological background for interpreting the frequency of transient synoptic features that normally occur within northern Mexico. For the NAME community, this work indicates that the synoptic activity during the entire summer of 2004 was less than is characteristic of a normal monsoon; however, the main field operations of NAME ended up being keyed to a very wet period from the second week of July to the first week of August (Fig. 10). While IV frequency was below the climatological mean for the entire summer, during this fairly short period when most platforms were operational and all but one of the IOPs was called, IV activity was fairly close to normal.

The work presented here is a small portion of a much larger study that aims to determine the impact of all of these rain-bearing transient systems on the monsoon in northern Mexico. These climatologies are designed to provide NAME researchers with benchmarks to assess model performance in terms of success in generating a realistic set of transient systems in monsoon experiments and in terms of being able to replicate the typical monsoon rainfall associated with each type of transient feature that commonly affects this region of Mexico. Future work will also include an extensive examination of the interaction of these transient systems as many of the major flood events in northern Mexico have occurred when two or three of these synoptic features have been present.

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