

**Spatial and temporal patterns of precipitation intensity as observed by the NAME
Event Rain Gauge Network from 2002 to 2004**

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ABSTRACT

Detailed information on the spatial and temporal characteristics of precipitation intensity from the mountainous region of northwest Mexico has, until recently, been lacking. As part of the 2004 North American Monsoon Experiment (NAME) Enhanced Observing Period (EOP) surface rain gauge networks along with weather radar and orbiting satellites were employed to observe precipitation in a manner heretofore unprecedented for this semi-arid region. The NAME Event Rain gauge Network (NERN), which has been in operation since 2002, contributed to this effort. Building on previous work, this paper presents analyses on the spatial and temporal characteristics of precipitation intensity as observed by NERN gauges. Analyses from the 2004 EOP are compared with the 2002-2004 period and with long-term gauge observations. It was found that total precipitation from Jul-Aug of 2004 was similar in spatial extent and magnitude to the long-term average though substantially wetter than 2003. Statistical analyses of precipitation intensity data from the NERN reveal that large precipitation events at hourly and daily timescales are restricted to coastal and low-elevation areas west of the Sierra Madre Occidental Mountains. At 10-minute timescales, maximum intensity values equal to those at low elevations could be observed at higher elevations though they were comparatively infrequent. It is also shown that inclusion of NERN observations in existing operational analyses helps to correct significant biases, which, on the seasonal timescale, are of similar magnitude as the interannual variability in precipitation in key headwater regions of northwest Mexico.

1. Introduction

The North American Monsoon (NAM) system is increasingly recognized as a dominant, modulating feature of the warm season climate over North America. The establishment of the NAM in mid- to late-June represents a marked transition in the continental-scale hydroclimatology whose influence is most pronounced in the southwestern U.S. and Mexico (c.f. Douglas et al., 1993; Higgins et al., 2003; Hu and Feng, 2002; Gutzler, 2004; and Gochis et al., 2006). Features of this transition include the onset of strong, diurnally-modulated convection over the semi-arid regions of the southwestern U.S. and western Mexico (e.g. Douglas et al., 1993; Gochis et al., 2004, Anderson and Kanamura, 2005), a decrease in precipitation over the Great Plains region of the U.S. (Higgins et al., 1997), and the dramatic invigoration of the regional terrestrial hydroecology (e.g. Brito-Castillo et al., 2003; Viramontes and Descroix, 2003; Biondi et al., 2005; Matsui et al., 2005). The onset of seasonal rains in these regions is critical to the function and sustenance of ecosystems as well as supplying water resources for domestic and agricultural purposes. This fact is particularly true for the region encompassing the Sierra Madre Occidental (SMO) Mountains in western Mexico which receive, on average, between 50-80% of their annual water resource from monsoon precipitation (Gochis et al., 2006).

The general climatology of daily and sub-daily precipitation in the region is becoming increasingly well documented through research using surface-based rain gauge observations, satellite-derived and radar-derived precipitation estimates, and numerical models coordinated under the North American Monsoon Experiment (NAME, 2005).

Features of the daily and sub-daily precipitation regime documented in Gochis et al. (2004-hereafter referred to as G1) include; 1) a core region of frequent, but moderate intensity precipitation centered over the high terrain of the SMO and 2) an elevation-dependent diurnal cycle of precipitation where rainfall occurs earliest and most frequently over high elevations and later in the evening and at night but less frequently and with higher intensity across lower elevations. Anderson and Kanamura (2005), studying Arizona and New Mexico, found that the daily balance of the hydrological cycle components (precipitation, evapotranspiration, moisture flux and vertical eddy diffusion) is strongly linked to the diurnal cycle and that the elevated terrain of the continental divide provides a hydrologic divide in the atmospheric moisture budget. On seasonal timescales Gutzler (2004) found that there is considerable early-to-late-season persistence in a “core” region of monsoon precipitation along the northern SMO. Interannual variability of precipitation in this core region appeared to be linked to teleconnection forcing from the tropical and North Pacific Oceans. Principal components analyses of seasonal precipitation have also delineated various sub-regions of the NAM precipitation regime (c.f. Comrie and Glenn, 1998; Hu and Feng, 2002; Gutzler, 2004). More recently, Brito Castillo et al. (2003) and Gochis et al. (2006), linked these spatial modes with regional, intra-seasonal and seasonal patterns of streamflow emanating from the SMO.

While basic information such as seasonal precipitation totals, the diurnal cycle of precipitation occurrence and the spatial correlation of precipitation occurrence with regional physiography is important for characterizing the overall monsoon climate, additional information on rainfall intensity is essential for improved understanding of the

coupled land-atmosphere hydrological cycle. Detailed information on the frequency and intensity structures of rainfall are critical to developing reliable hydrologic predictions, diagnosing realistic precipitation structures that can be the basis of closing regional water budgets, developing precipitation downscaling procedures, improving characterization of extreme events in a changing climate (e.g. Allen and Ingram, 2002; Meehl et al., 2005), and validating quantitative precipitation estimates from remote sensing platforms (e.g. Wood et. al, 2000; Gebremichael et. al, 2003). In this paper, we extend the findings of G1 to document the seasonal, daily and sub-daily character of precipitation intensity from the NAME Event Rain gauge Network (NERN) in western Mexico. Section 2, describes the data set and rain gauge calibration procedures used in this work, while section 3 presents a suite of analyses examining precipitation intensity structures from the 2002 through 2004 warm seasons. Section 4 provides a summary of the principal findings and discusses their relevance to other research efforts in the NAME region. While it is quite clear that the short period of record for the NERN limits the generalization of the rain rate analyses presented herein, the following diagnostics are useful in the context of characterizing rain rates during the 2004 NAME Enhanced Observing Period whose activities are the subject of this special issue.

2. Data

The NERN consists of 87 automatic-recording, tipping bucket rain gauges distributed primarily along 6 topographic transects which traverse the SMO (Figure 1; see also, G1 and Gochis et al. (2003) for further NERN implementation details). The rain gauge used in the NERN is the Texas Electronics TE525USW tipping bucket (TB) rain gauge

outfitted with a 203.2 mm (8.0 in) screened orifice. Details on the operational maintenance and field calibration of the NERN TB gauges are provided in documentation by Gochis et al. (2005). Rain rate errors associated with the use of TB gauges have been documented in many works (c.f. Humphrey et al, 1997; Habib et al., 2001; and Duchon and Essenberg, 2001) and were reviewed in the context of the NERN in G1. Given the significant sources of error and uncertainty associated with TB rain rate estimates, bias correction of rain rates derived from raw ‘event’ data is generally required if not essential. Here we define ‘event’ data as the information on tips of the tipping bucket, which, for the NERN, is the time series of the time of bucket tips (often called ‘tip-times’). As described in G1, there is no a priori time scale associated with the sampling of the raw events in the NERN gauges independent of the size of the tipping buckets and the time it takes for a full bucket to tip. Error associated with different tipping bucket sizes and sampling intervals are discussed by Habib et al. (2002) who recommend bucket sizes up to 0.254 mm (0.01 in) for high temporally-resolved rain rate estimation. The buckets used in the NERN rain gauges have a nominal design capacity of 0.254 mm (0.01 in) though this volume can be decreased by the deposition of sediment in the buckets during long-term field installations.

One type of error that afflicts TB rain gauges is systematic undercatch of precipitation at high rain rates. In addition to random errors, such as splash-out of raindrops or wind eddy effects, this systematic error is caused by the proportionally greater fraction of rainfall passing through the collection funnel that is ‘spilled’ while the tipping bucket mechanism is in motion. Assume that rainwater is passing through a funnel nozzle in a

continuous stream and at a continuous rate. Once one of the buckets on the tipping bucket mechanism is full the bucket will tip. However, water that is draining from the funnel nozzle will continue to fall into the full side of the bucket until the tip passes through the level position at which point the incoming rainwater will begin to fill the empty bucket on the opposite side. This error has been called the ‘time-to-tip’ error and, assuming that the bucket always tips at nearly the same rate, this undercatch increases with the rate of rainwater passing through the funnel nozzle. At low rain rates this error is typically not significant since the time-to-tip is fast compared to the rate at which rainwater fills the bucket. In their study, Humphrey et al. note that this error is generally not significant at rain rates below 50 mm/hr.

For this study a simplified rain rate bias correction procedure was synthesized from Humphrey et al. (1997), Habib et al. (2001) and Duchon and Essenberg (2001). The approach taken here employs a constant flow-constant head measuring device designed by Hydrological Services, Inc., which dispenses pre-specified flow rates to the TB rain gauge. The dispenser delivers water at 5 nominal flow rates (50, 100, 200, 300 and 500 mm/hr) using 5 calibrated nozzles. Following Humphrey et al., the flow rates of the dispenser were first calibrated in timed tests using a graduated, accumulation rain gauge. The actual flow rates measured during this procedure differed from the design flow rates, sometimes substantially (47, 103, 205, 254, 435 mm/hr), but the standard deviations between multiple tests at each of the nominal flow rates was low (between 0.26 and 3.5 mm/hr). Hence, while the nominal design rates were not found to be highly accurate, the low variability between tests indicates a reasonable degree of precision. The measured

flow rates from the flow device calibration tests were then used for subsequent calibration of the TB rain gauges.

Comparison of TE525USW estimated rain rates and dispenser controlled flow rates are shown in Figure 2a. Consistent with similar TB calibration studies, error in the TE525USW estimated flow rate varies significantly with increasing dispenser-controlled flow rates. Over the range of flow rates tested the relative error of TB estimated flow rates were on the order of 20-25% of the controlled rates though somewhat less for the lowest rate (Fig. 2b). We adopted a second degree, fit through zero expression similar to that of Duchon and Essenberg (2001) as follows:

$$PR_{corr} = C_1 * PR_{raw}^2 + C_2 * PR_{raw} \quad (1)$$

where, PR_{corr} is the bias corrected rain rate, PR_{raw} is the observed rain rate from the TE525USW and C_1 ($= 0.00145$) and C_2 (set equal to 1.0 in accordance with Duchon and Essenberg, 2001) are regression parameters found using a least squares fitting technique and the experimental controlled flow rate data. This functional form, whose resulting bias-corrected values are shown as open circles in Figure 2a, permits the correction for larger errors at higher flow rates while providing negligible correction at rates approaching zero. As shown in Figure 2b, the bias in TE525USW estimated rain rates is reduced on the order of 10-20% depending on the flow rate up to approximately 250 mm/hr.

Errors in TB-estimated rain rates for smaller rain rates associated with drizzle and very light precipitation suffer from additional problems such as wetting losses, wind blockage and eddy effects and insufficient sampling of the rain gauge (c.f. Duchon and Essenberg, 2001) and are not accounted for in the present calibration methodology. Because errors in heavy precipitation events in the monsoon region likely constitute a comparatively greater uncertainty in hydrological inputs in the region and since this study is more focused on characterizing the spatio-temporal distribution of heavy rainfall events compared to light precipitation events, we limit our rain gauge correction methodology to that provided above. Following the guidance of Habib et al., the raw event data were aggregated into 10-minute rain rates prior to bias correction. The bias correction equation was then applied to the uncorrected 10-minute rain rate. The corrected 10-minute rain rates were then used to derive rain rates at other time scales (e.g. 30 min, and 1, 3, 24 hrs), which were used for the analyses described next. It requires note that the above calibration equation is only valid over the range of values used in the calibration tests and should not be extrapolated to larger rainfall intensities. Work on refining the calibration procedure is ongoing.

3. Analyses

a. The 2004 NAME EOP

The NAME research program is principally a climate research program aimed at improving predictions of warm season precipitation at intra-seasonal to interannual timescales (NAME-SWG, 2004). The fact that the 2004 NAME EOP was conducted

during a single summer implies that the observations collected during the EOP need to be taken in context of the long-term regional hydroclimatology, which has been shown to exhibit marked variability on interannual timescales (e.g. Higgins and Shi, 2001; Gutzler et al., 2004; Gochis et al., 2006). Here, we compare the Jul-Aug precipitation total, observed by the NERN during 2004, against a long term Jul-Aug average estimated using data from the ERIC-II database (ERIC, 1996). The cooperative stations archived in the ERIC-II database possess records of varying length but are generally longer than 20 years. Figures 3a and b show that 2004 precipitation was quite similar to the long-term average both in the spatial distribution of rainfall and the magnitudes of the total amounts. While there is an absence of long-term observing sites located along the southeastern portion of the NERN domain in the ERIC-II data, the rest of the regions compare reasonably well. During 2004, precipitation values along the northwestern and eastern periphery of the NERN domain were only slightly lower than the long-term average while precipitation along the SMO foothill region of northern Sinaloa and southern Sonora was at or slightly above normal. The Jul-Aug total precipitation from the NERN during 2003 is provided in Figure 3c. By contrast, 2003 was significantly drier (~ 50 -100 mm) than 2004 and the climatological average. Given the significant spatial variability of monsoon precipitation, the fact that Jul-Aug precipitation in the NERN domain was near normal does not a priori imply that 2004 monsoon precipitation in other regions, such as Arizona or New Mexico, was close to normal.

The most active precipitation days across the NERN domain during 2004 are characterized as those days where the largest number of stations received measurable

precipitation (i.e. ‘maximum widespread days’ shown in Table 1), and days where the largest number of stations received their 2004 seasonal maximum daily precipitation (Table 2). The period 21-24 July was a very active period when a very large fraction of the NERN stations (80 of 86) received measurable precipitation (23 and 24 July) and many stations recorded their seasonal maximum daily total (22, 23 and 21 July). This active period corresponds with the NAME Intensive Observing Period-3 (IOP-3). Synoptic features of these days included a breakdown and westward retrogression of the monsoon ridge towards the west coast, and a westward migrating inverted trough over the Mexican plateau. These synoptic features aided the development of two large Mesoscale Convective Systems (MCSs) over the northern Gulf of California and Sonora on July 23 and 24 (Figs. 4a and 4b) whose outflows produced surges of low level moisture that propagated northward into the desert regions of the southwest U.S. The four day total from 21-24 July is shown in Figure 4c along with fraction of the Jul-Aug total precipitation received from 21-24 July (Figure 4d). In the northern part of the NERN domain, where seasonal precipitation is lowest, these four days comprised well over 30% of the Jul-Aug. total rainfall. Given this large contribution, improved predictability of these kinds of events in northwest Mexico would have a clear benefit on managing local and regional water resources.

b. Statistics of NERN Observed Precipitation Intensity

The distribution of 24 hr NERN-observed rainfall events (i.e. days with measurable rainfall) from all sites combined, shown in the probability density function (pdf) in Figure 5a, is heavily skewed as is typical of rainfall event data. The pdfs of the 60-minute and

10-minute event data (not shown) are similar in shape to that shown in Fig. 5a though they tend to be even more positively skewed. For instance, the estimated skew coefficient for the 24 hr event data is 2.70 while those values for the 60-minute and 10-minute event data, from all sites combined, are 5.19 and 4.98, respectively. Distributions at the shorter time intervals also tend to be narrower as defined by the estimated kurtosis coefficient (=10.44 for the 24-hr estimates versus 40.12 and 33.21 for the 60-minute and 10-minute estimates, respectively). Plots of the cumulative distributions as separated by low (0-1000 m above mean sea level, ASL), medium (1000-2000 m ASL) and high (2000-3000 m ASL) elevations show appreciable separation of event structure as a function of elevation (Figure 5b). A greater fraction of events at high elevations (black circles in Fig. 5b) are smaller in size (i.e. of lighter intensity) than those at middle (light grey circles) and low elevations (dark grey boxes). There is a reasonably clear and consistent progression towards a greater number of heavier precipitation events with decreasing elevation. The shape and relative order of these distributions was largely insensitive to various data withholding experiments (not shown), indicating that the existing sample collected from the NERN is likely to be representative of the true distribution. This stratification of precipitation distributions as a function of elevation is similar at the 60-minute and 10-minute time intervals as well (not shown), though the differences between elevation bands are not as great. Probability distributions of rainfall events separated by location on the eastern versus western side of the SMO topographic divide (not shown) show that precipitation events, at all three time intervals, tend to be heavier and exhibit greater variability on the western side compare to the eastern side.

Table 3 provides summary statistics from the NERN for the 2002-2004 warm seasons (Jul-Aug-Sep). The data are partitioned temporally into 10-minute, hourly and daily intensities and by low, medium and high elevations as defined above. Full network values are also provided for comparison. The values for the 90th percentile, mean and standard deviations of precipitation intensities for each of the time periods all decrease with increasing elevation. Also shown in Table 3 are the maximum observed rain rates for each elevation class and each time interval. The relationship between maximum observed precipitation rates and elevation appears to be somewhat time dependent. The largest events at the hourly and daily time intervals are observed to occur at the lowest elevations, while the maximum 10-minute intensity, 27.7 mm/10 min (equivalent to 166.2 mm/hr), is found to occur at high elevations as well as low elevations. While the period of record for sampling heavy precipitation events is admittedly small, the similarity between low and high elevation maximum 10-minute intensities suggests that it is possible for high elevation locations to receive brief periods of intense rainfall. However, these intense rates are not as likely to be sustained over long time intervals, as is found at lower elevations. Variability in precipitation rates is clearly enhanced at lower elevations as evidenced by the comparatively high estimated coefficients of variation of rain rates shown in Table 3.

c. Maximum Precipitation Characteristics of the NAM

Maximum 10-minute, hourly and daily intensities are mapped in Figure 6 using the inverse distance weighting procedure described in G1. Maximum 10-minute values observed by the NERN from 2002-2004 are not atypical of intensities found in other

semi-tropical environments (> 100 mm/hr). There is comparatively less spatial coherence in maximum rainfall events at the 10-minute time interval compared to the hourly and daily intervals. While there is a general decreasing west to east gradient in the maximum 10-minute rain rate, there are several stations throughout the NERN where the 10-minute rates exceed 100 mm/hr, on both the west and east sides of the SMO divide. These stations are located at a variety of elevations (Note: There are no stations below 1500 m ASL on the east side of the SMO divide.) The largest maximum-precipitation values at the 60-minute and daily time intervals are comparatively more confined to the coastal plain region of the NERN and decrease uniformly moving inland across the SMO. The highest maximum daily rates are clearly confined to the low elevation coastal plains near the base of the SMO.

Figure 7 shows the maximum daily values observed by the NERN from 2002-2004 compared to the maximum values observed from the ERIC-II climatology. Peak daily events from the 2002-2004 NERN data are substantially less than the long-term values. In both figures, there is a strong decrease in maximum rates across SMO. Maximum rates also decrease northward along the coast of the Gulf of California in the ERIC-II climatology. The heaviest events (~ 300 mm/d) in the long-term records are often due to tropical storms making landfall in western Mexico, which have not been observed by NERN as of this writing. Despite having a very limited period of record for sampling maximum events the NERN does appear to be capturing the basic west to east gradient, though the magnitudes of events are substantially lower than those from ERIC-II.

The concept of heavier precipitation being confined to the low elevations of the SMO foothills and coastal plains is further illustrated in Figure 8, which shows a scatterplot of the maximum observed precipitation values for the 10-minute, 60-minute and 24 hour time intervals. The values plotted are each scaled by the respective time-interval mean maximum intensity using all stations. While there is comparatively more variability in maximum precipitation values near the coastline, there is a clear tendency for a tighter, decreasing, relationship between maximum precipitation values and distance from the coast. Pearson correlation values between distance from the coastline and the 10-minute, 60-minute and 24-hr time intervals of -0.41, -0.52 and -0.69, respectively, are all easily statistically significant at the 95% level using a student's t-test. The fact that sustained heavy precipitation is limited to the low elevation foothills and the Gulf of California coastal plain at the longer time intervals, suggests that certain environmental conditions may be required in order to organize and sustain heavy precipitation. These conditions may include deep moist instability and/or favorable dynamical conditions, such as vertical wind shear, which are more likely found nearer the Gulf of California.

Monsoon precipitation intensity is partitioned into classes of light, moderate and heavy precipitation in order to look at the occurrence of certain events at or above specified threshold values. The pdf shown in Figure 5a is heavily skewed, as is typical with precipitation intensity data. This skewness is generally due to the fact that light precipitation amounts are observed much more frequently than moderate or heavy precipitation events. This feature is true of the NERN where the 50th percentile of the distribution, or the median, typically has precipitation intensity substantially lower than

the arithmetic mean and is of a magnitude generally not considered appreciable driving significant runoff events. In this work, all ‘light’ precipitation events are defined as those greater than zero but less than 10.0 mm/d. ‘Moderate’ precipitation events are those greater than 10.0 mm/d but less 50.8 mm/d (2 in/d) while ‘heavy’ precipitation events are characterized as those in excess 50.8 mm/d. From Fig. 5b it is noted that the thresholds for moderate precipitation events are above the 60th percentile values at all elevations and heavy precipitation events are in excess of the 90th percentile values.

Figures 9a and b show that heavy precipitation events at the daily timescale are more commonly found in the foothill and coastal regions of the NERN domain. Over the past three summers (2002-2004, Figure 9b) heavy events have tended to occur farther south along the low elevation regions of Sinaloa and into the foothill and canyon regions of western Durango. The 2004 summer exhibited a comparative extension of this heavy precipitation regime farther northward along the coast where one or two heavy precipitation events were observed. There appears to be a core region in central Sinaloa that is susceptible to receiving a few large events every summer (> 3 events per season). Moderate rainfall events are observed over a much wider portion of the NERN domain (Figs. 9c and d). Maximum occurrence of moderate events tends to occur westward of the SMO and in the south, but farther inland than the heavy events. Moderate intensity events are less common on the eastern slope of the SMO, typically, less than 15 events per season, although certain locations during 2004 did observe between 15-20 moderate events. While the pattern of moderate events occurring during the 2004 EOP was similar to that of the 2002-2004 summer average, more moderate events were observed in nearly

all regions. The occurrence of light precipitation (Figs. 9e and f) exhibits a pattern more similar to the moderate events than the heavy event intensities. The maximum in light precipitation occurrence exists well inland of the Gulf of California over the higher elevations of the SMO. The axis of maximum light precipitation occurrence (between 40-60 events per season) follows the high terrain of the SMO northward and away from the coastline. Moving away from this axis the occurrence of light precipitation decreases to less than 40 events per season. Similar to the heavy and moderate precipitation occurrence, 2004 possessed a greater number of light rain rate events compared to the 2002-2004 average.

The timing of the occurrence of the maximum 10-minute intensity on the diurnal cycle from 2002-2004 is shown in Figure 10a. There is a clear tendency for the maximum 10-minute rain rates to occur at night, from 2000 Local Solar Time (LST – 0300 UTC) to 0500 LST (1200 UTC) in the northwestern portion of the NERN domain, in Sonora. As discussed in G1, this area is prone to receiving infrequent but intense nocturnal rainfall generated from relatively long-lived, organized, mesoscale convective systems. Farther inland, in the higher elevation regions of the SMO, peak rain rates tend to occur during mid- to late-afternoon. Farther south, in Sinaloa and Durango, there is comparatively more variability in the timing of the maximum 10-minute rain rates, though most events tend to fall between mid-afternoon and the late-evening. It is interesting to note that there are no instances where the maximum 10-minute rain rate was observed between the morning hours of 0600 and 1100 LST (1300 – 1800 UTC). Similar patterns are found for the maximum 60-minute rain rates (not shown).

Months of maximum observed daily precipitation from 2002-2004 are mapped in Figure 10b. While there is significant spatial variability in the month of maximum daily precipitation, there is a general north to south pattern, where the heaviest events tend to occur during July or August in the north, compared to August or September in the south. This is interesting from the fact that September is often regarded as a month where the monsoon tends to be waning in intensity and influence. It is also interesting from the standpoint of generating runoff and streamflow. Regional streamflow analyses from Gochis et al. (2006) showed that September and October exhibit significant increases in the fraction of monthly precipitation ending up as streamflow in SMO headwater catchments. This behavior is particularly evident along the southern SMO in Sinaloa and western Durango. One explanation for this behavior was that these watersheds were well ‘conditioned’ to produce runoff after just having passed through the bulk of the rainy season. However, a tendency for heavy precipitation events to occur during September, as suggested by these preliminary analyses, might also be contributing to this runoff response. The reason why the southern SMO are prone to receive their heaviest events in September remains unclear. Over the long-term, it is likely that land-falling tropical storms may contribute to this behavior but, as mentioned earlier, no significant tropical storms impacted the NERN domain during 2002-2004. Because the NERN period of record is short, the robustness of this pattern will be monitored as subsequent seasons of data become available.

d. Validating the CPC gridded product

Key objectives of the NERN include improving the sampling of precipitation at the sub-daily time scale, and in remote locations where precipitation has historically been poorly observed. The paucity of observations at remote, often high elevation, locations can yield significant biases in analyses of precipitation from spatially sparse observing networks. One of the most widely used precipitation analyses in North American Monsoon research has been the NOAA Climate Prediction Center (CPC) unified daily precipitation analyses (Higgins et. al, 2000). This product is generated both operationally and retrospectively, at a horizontal grid spacing of 0.25 deg. and was used as the operational forecast verification product during EOP forecasting activities. Since the NERN is not an operational product available in real-time, we want to assess the impact of including the NERN data on the CPC daily analyses and determine if there were particular locations or regions that suffered from systematic bias due to insufficient sampling and/or the interpolation process. Figure 11 shows the differences in seasonal and monthly precipitation from the 2004 NAME EOP between the CPC product with the daily NERN observations included and the CPC-only product. June, July, August, September (JJAS) differences range -250 to +250 mm for the NERN region. These differences are equivalent to a substantial fraction of the interannual variability of precipitation in this region. The CPC product, without the NERN, largely overestimates precipitation in the mountainous region in eastern Sonora and western Chihuahua in the north, and tends to underestimate precipitation in the higher elevation regions in western Durango and eastern Sinaloa farther south. These biases are relatively stationary for the individual months of July, August and September. Differences at the monthly time scale range from approximately -100 to +100 mm and are relatively consistent from month to month

except in the north where differences are largest during July. The value of including the event data is clearly evident at the daily timescale as shown for the 3-day period during Intensive Observing Period-3 (IOP-3) during the NAME EOP (Figure 12). Differences in the CPC-product with and without the NERN can range up to ± 30 mm for intense, localized events. The signs of these differences, while generally similar to those difference patterns at longer time scales, can be different at the daily timescale. Figures 11 and 12 each show that operational analyses at the daily, monthly and seasonal timescales all possess significant biases in critical headwater regions in the SMO and that inclusion of the NERN in the retrospective CPC gridded analyses should improve spatial estimates of monsoon precipitation.

4. Summary

This study has examined precipitation intensity structures and relationships from the NERN in northwest Mexico. Emphasis was placed on characterizing rainfall intensity behavior at various time intervals and in relation to regional physiography such as terrain elevation and the distance to the Gulf of California. Results from the 2004 NAME EOP were presented as were those from the entire NERN observation period of 2002-2004. Where relevant, comparisons were made between NERN observations and available long-term station data. The principal findings of this study are summarized as follows:

- July-August, NERN-observed precipitation totals during the 2004 NAME EOP were generally similar in spatial distribution and magnitude to long-term averages from cooperative observation sites. Jul-Aug totals from 2003 were found to be

significantly less than 2004 and the long-term average for most all regions in the NERN domain. Maximum NERN-observed 24-hr precipitation intensities from 2002-2004 are significantly lower than those observed by long term gauge records in western Mexico.

- The most active precipitation period during the 2004 EOP as defined by the days where precipitation was most widely observed and days which received their 2004 maximum daily precipitation was centered on IOP-3 (21-24 July). The synoptic setting during this period helped generate widespread precipitation and at least two large MCS events, which produced heavy rainfall at many sites.
- Precipitation intensity statistics from the 2002-2004 NERN record indicate a tendency for higher intensity values and increased variability at low elevations compared to higher elevations. This behavior is generally evident at a range of time scales from 10-minute to daily although large precipitation intensities at the 10-minute timescale can be observed at high elevations.
- Maximum observed precipitation intensity values at the hourly and daily timescale as well as ‘heavy’ precipitation events are generally restricted to the low elevation foothill and coastal plain regions adjacent to the Gulf of California. The number of stations receiving ‘heavy’ precipitation events was greater during 2004 compared to 2002 and 2003.
- There is a statistically significant inverse correlation between the maximum observed precipitation intensity and the distance to the Gulf of California, which is strongest at the daily timescale and weakest at the 10-minute timescale.

- ❑ There is preliminary evidence of a north-south gradient in the month of maximum observed daily precipitation. Maximum daily events are found more often during September in southern portions of the NERN domain versus during July in the northern part of the NERN domain. Given the shortness of the NERN record the robustness of this pattern is highly uncertain.
- ❑ NERN observations serve to correct large and spatially-stationary biases in operational, gauge-based precipitation analyses used during the 2004 EOP. The magnitudes of the biases in the operational product constitute significant fractions of the interannual variability of precipitation in key headwater regions of the SMO.

The NERN record clearly is not of sufficient length to properly characterize the statistical distribution of the magnitudes of extreme events in the NAME region. This is particularly true for characterizing the magnitudes of extreme events as evidenced by the difference between the NERN-observed 24 hr maximums and those observed by the ERIC-II climatologies. However, this preliminary analysis shows that the NERN, despite its short record, is beginning to reveal the spatial patterns of precipitation intensity at a range of timescales. Similar to G1, the data also reveal patterns of precipitation behavior, such as the inverse relationship of precipitation intensity with the distance to the Gulf of California, that are not likely to change over time. Information on the spatial patterns of precipitation frequency and intensity is key to advancing our knowledge of the processes that generate monsoon precipitation as well as understanding the influence of monsoon precipitation on regional hydrology. In reference to the latter point, characterization of

rainfall intensities at sub-daily intervals, which are critical for hydrological prediction, should improve as the NERN period of record lengthens. Similarly, NERN data and the analyses presented should be useful to those attempting to validate remote sensed estimates of precipitation or verify model predictions of precipitation at timescales ranging from minutes to seasonal. Many of these types of studies are found as companion articles in this special issue.

The spatial patterns of precipitation intensity revealed in this work, and those of precipitation frequency discussed in G1, support the regional hydroclimatology described in Gochis et al. (2006). In that work, three coherent regions of seasonal precipitation and streamflow variability were found; a northern region, a southern region and an eastern region. The present findings support the hypothesis posed in Gochis et al. (2006) that there are a few distinct differences in the character of precipitation in these regions that contribute to rainfall-runoff behavior in each of these regions. In the northern regions, precipitation is comparatively infrequent and significant fractions of seasonal total precipitation, which is also low compared to farther south, may be deposited over a few active periods. This means that soils have ample opportunity to dry down between rainfall events and that many in-basin abstractions and storages may never be filled. The magnitude of sustained large events is also less in the north than in the south according to the NERN and long-term records. Combined with greater evaporative demand, the drier regime and lower intensity of sustained rainfall events in the north favors lower runoff yields, which is defined by the fraction of precipitation being converted to streamflow. The tendency for heavy precipitation events to occur later in the summer farther south

(Fig. 10b) when soil moisture is high may also contribute to higher runoff yields there. The differences between northern and southern regions are similar to those found comparing the eastern slope basins of the SMO with those in the southern portion of the NERN domain. In particular, the lack of very heavy precipitation events occurring on the eastern slope likely contributes to its substantially lower runoff yields. Further exploration of the relationship between precipitation character and runoff and its modulation on inter-annual timescales is the subject of ongoing work.

The value of regional climate observing networks, such as the NERN, grows in proportion to their periods of record. While much has been learned since the initial implementation of the NERN in 2002, the interpretation of these findings and the attribution of physical processes that generate monsoon precipitation will improve as the NERN continues to sample both high frequency (e.g. diurnal cycle) and low frequency (e.g. atmospheric transients such as surges and landfalling tropical storms) events. Robust analyses of the influence of low frequency transients await the collection of additional years of data in order to obtain event populations of significant size. The same is true for studies on the interannual variability of precipitation in the NERN domain. Because the statistics of precipitation features, such as intensity, possess a high degree of temporal and spatial variability it is essential to maintain regional climate observing networks, such as the NERN, in order to reduce uncertainty in our understanding of precipitation events and their causative mechanisms. Continued coordination of the NERN with ongoing NAME research should continue to lead to improved understanding and predictions of the North American Monsoon system.

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Figure Captions

Figure 1: Map of northwest Mexico showing the NERN domain and tipping bucket rain gauge locations (black circles). Grey shading indicates topography and bounding box indicates extent of spatially-interpolated products (i.e. NERN domain).

Figure 2: Experimental data used during calibration of the TE525USW tipping bucket rain gauges. a) Controlled flow rate versus TE525USW estimated flow rate (black diamonds) and TE525USW-calibrated flow rates (open circles). b) Average relative error of uncalibrated (black diamonds) and calibrated (open circles) TE525USW flow rate estimates.

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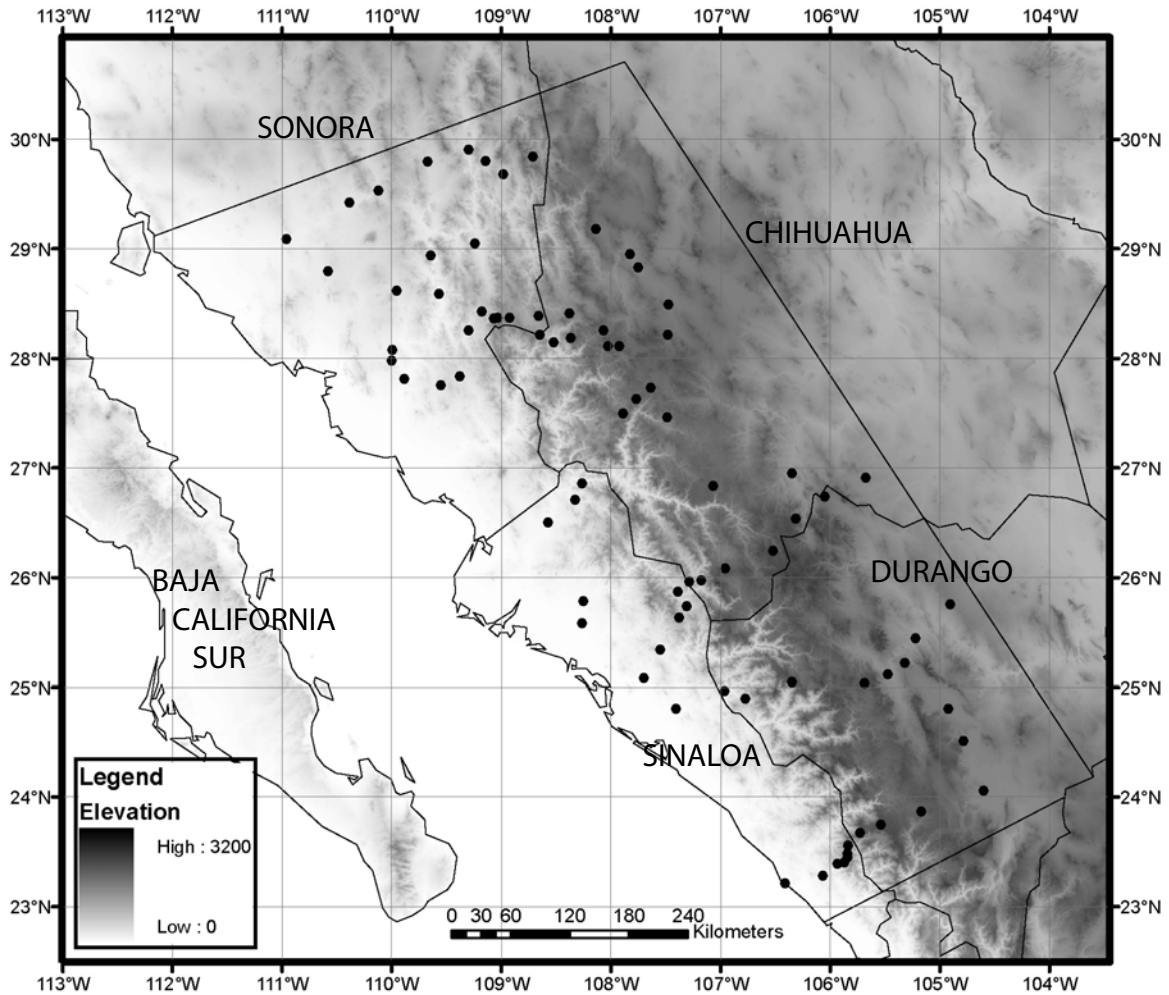


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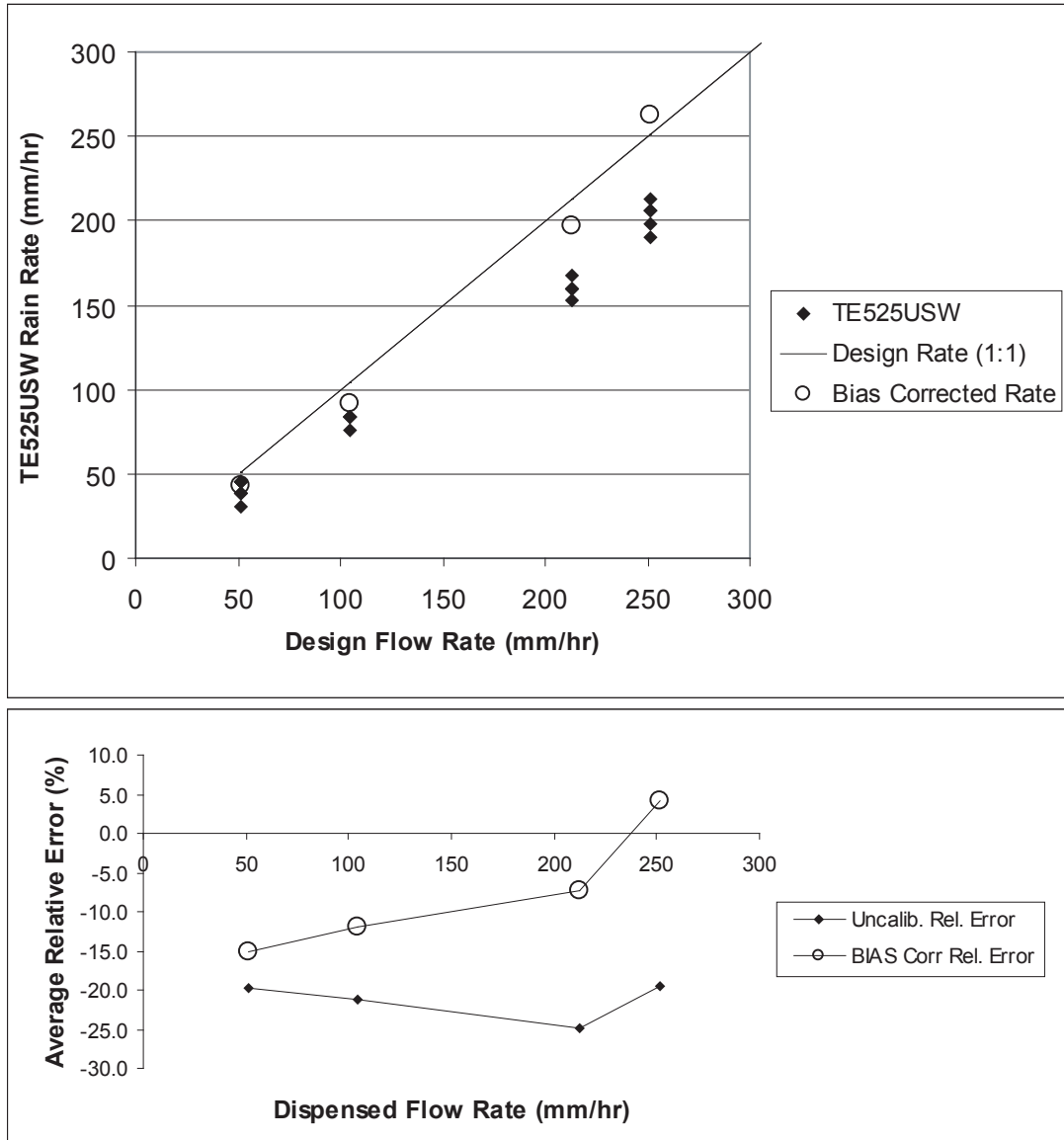


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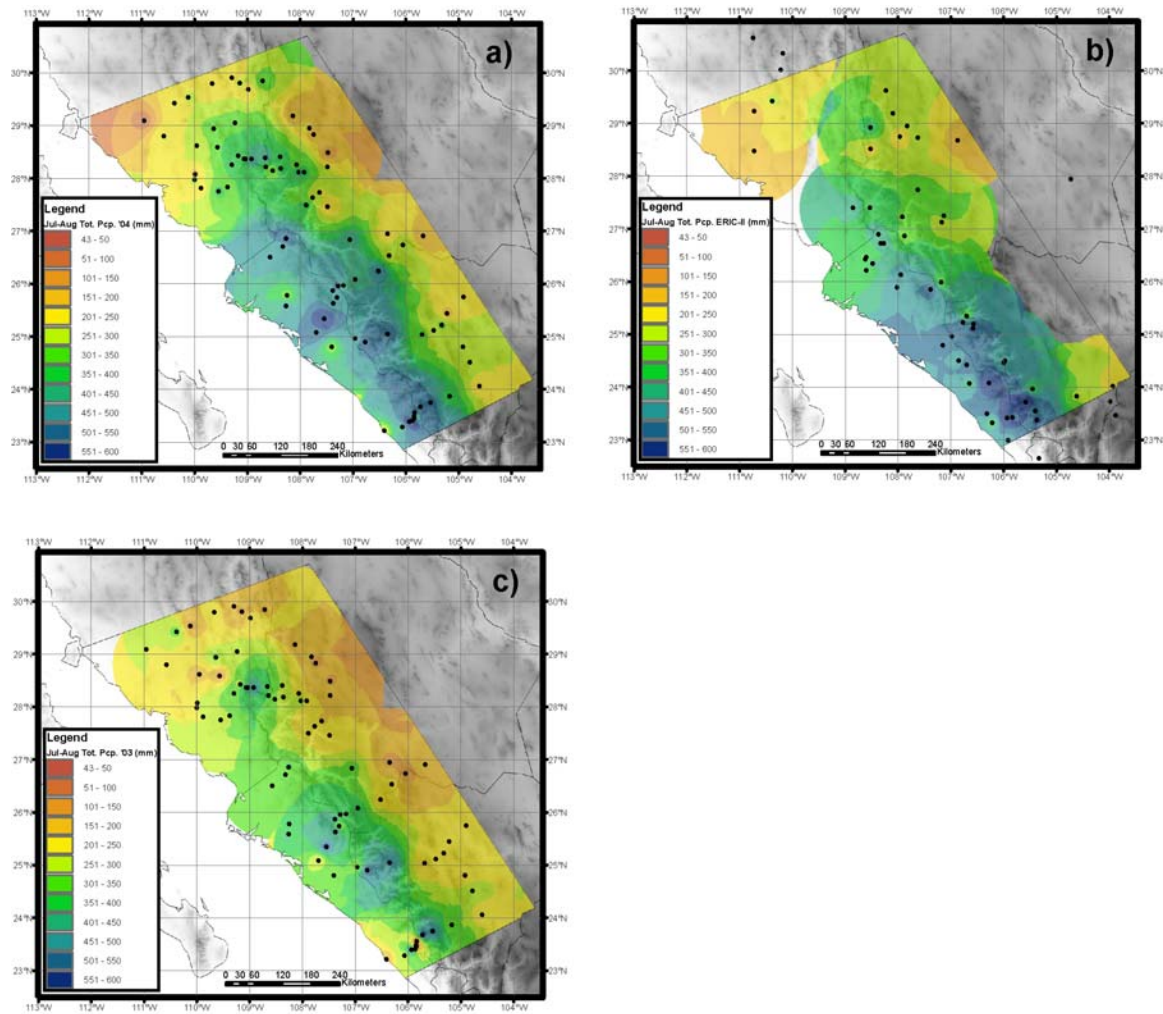


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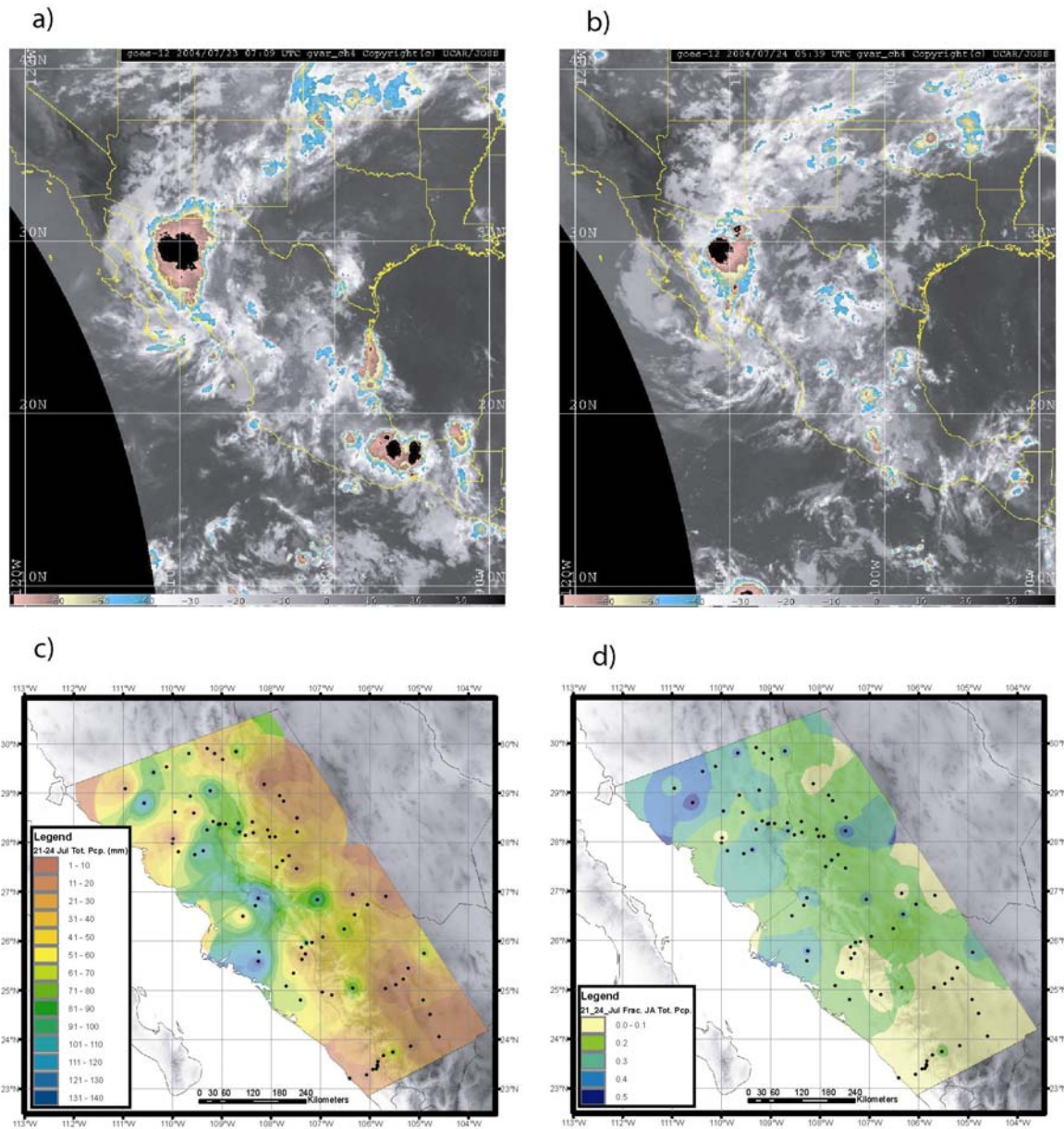


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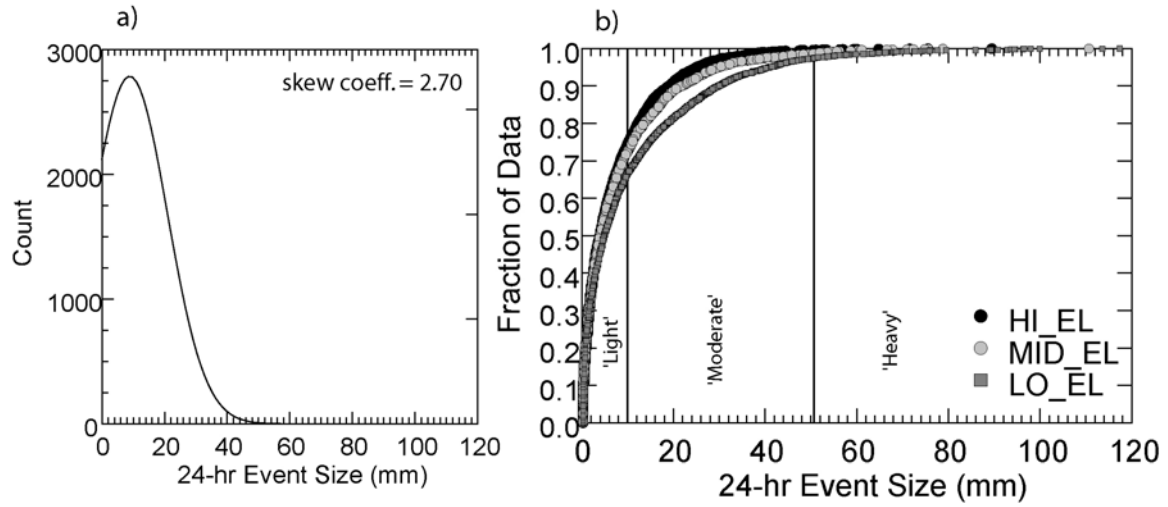


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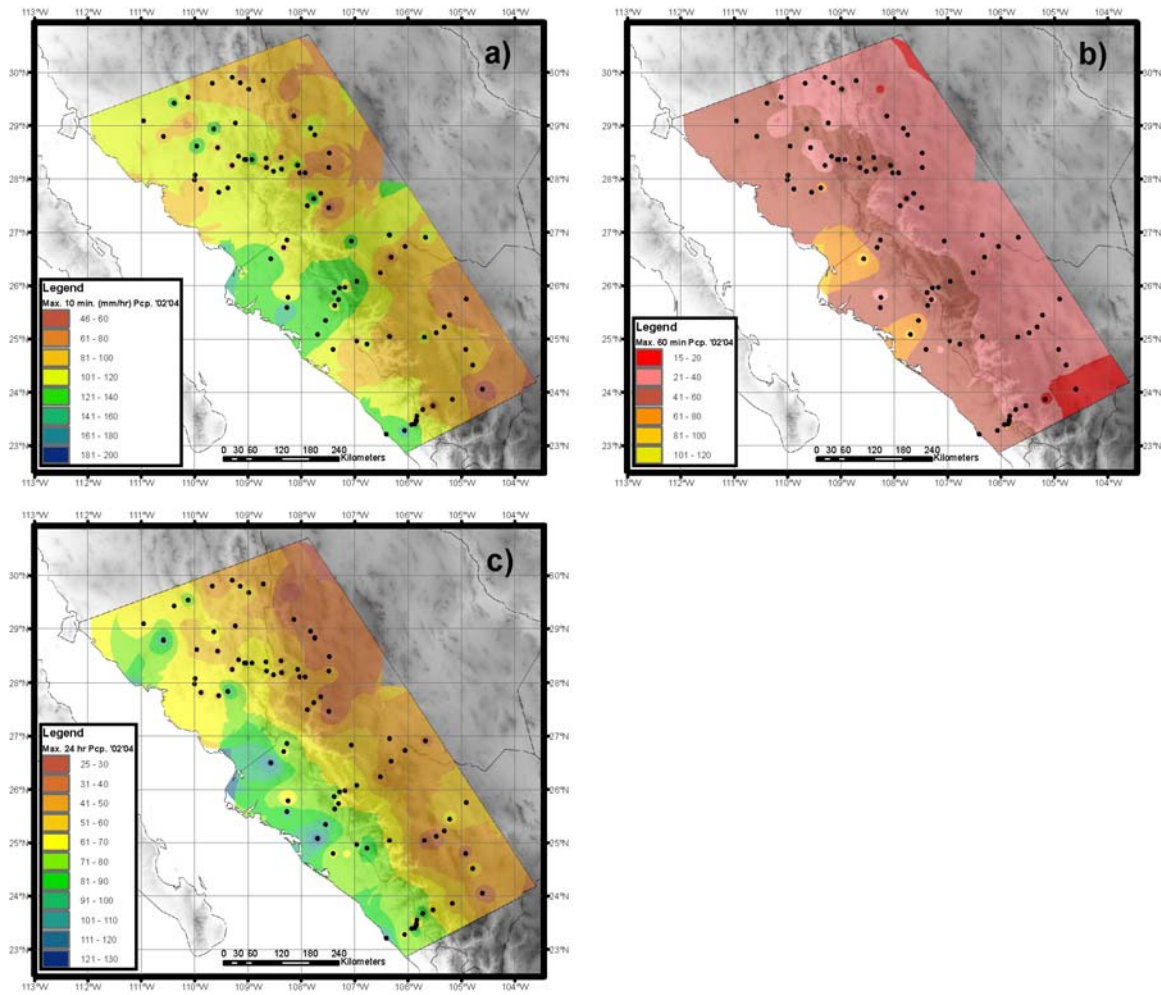


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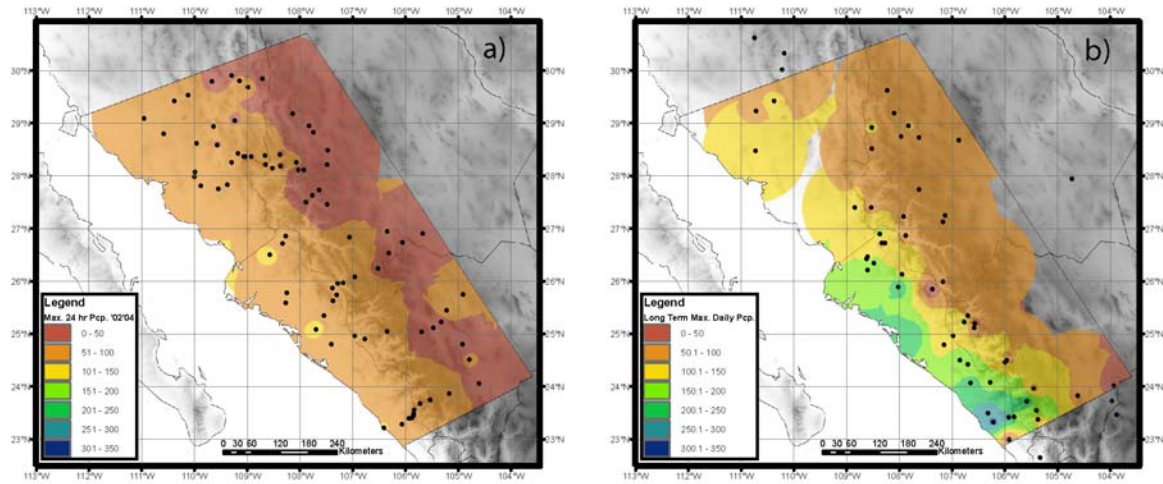


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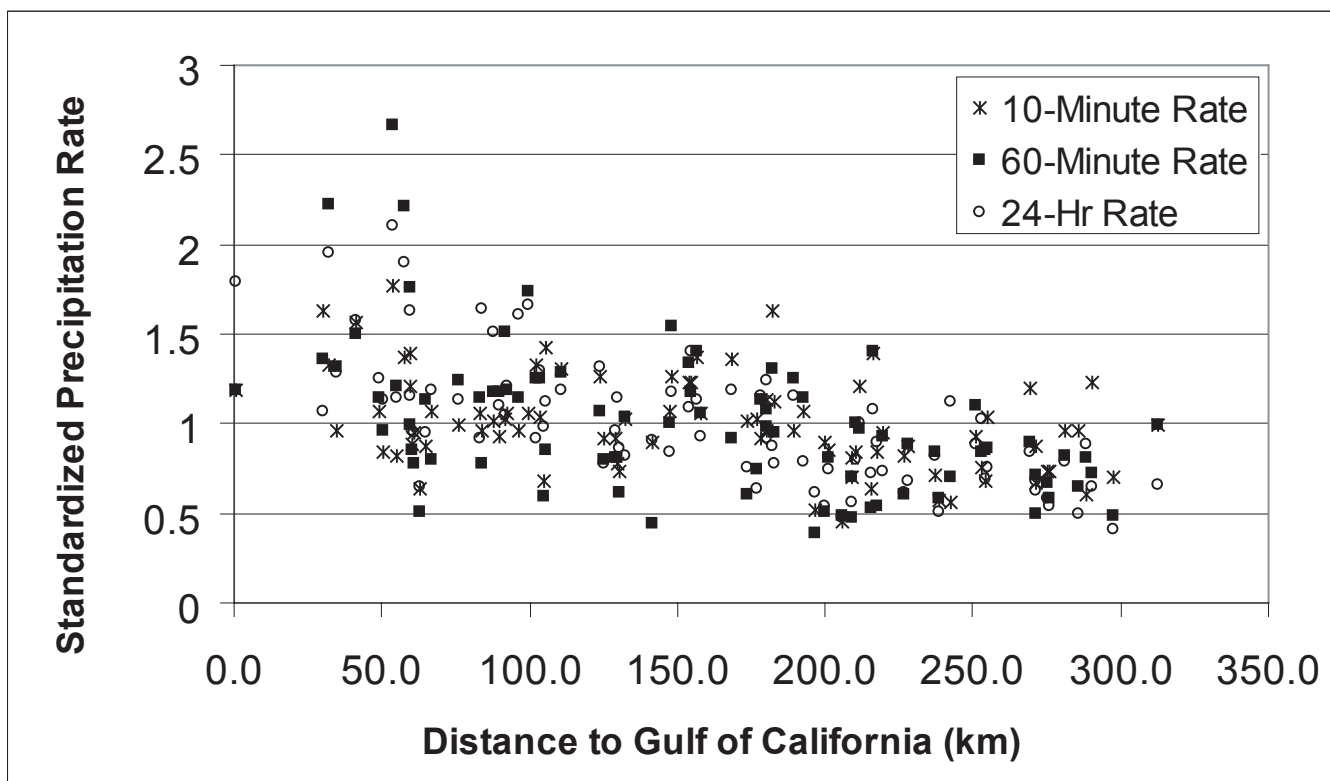


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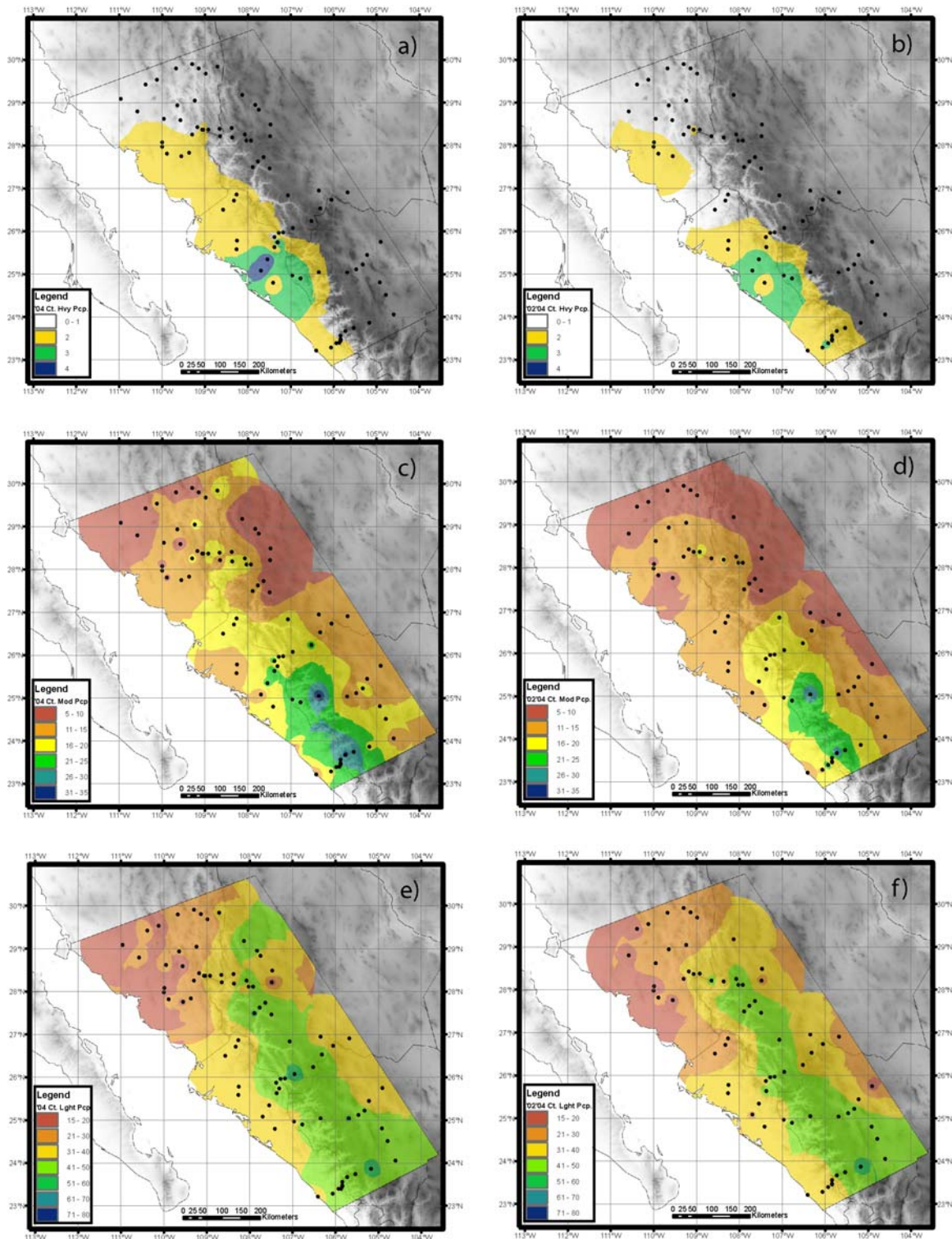


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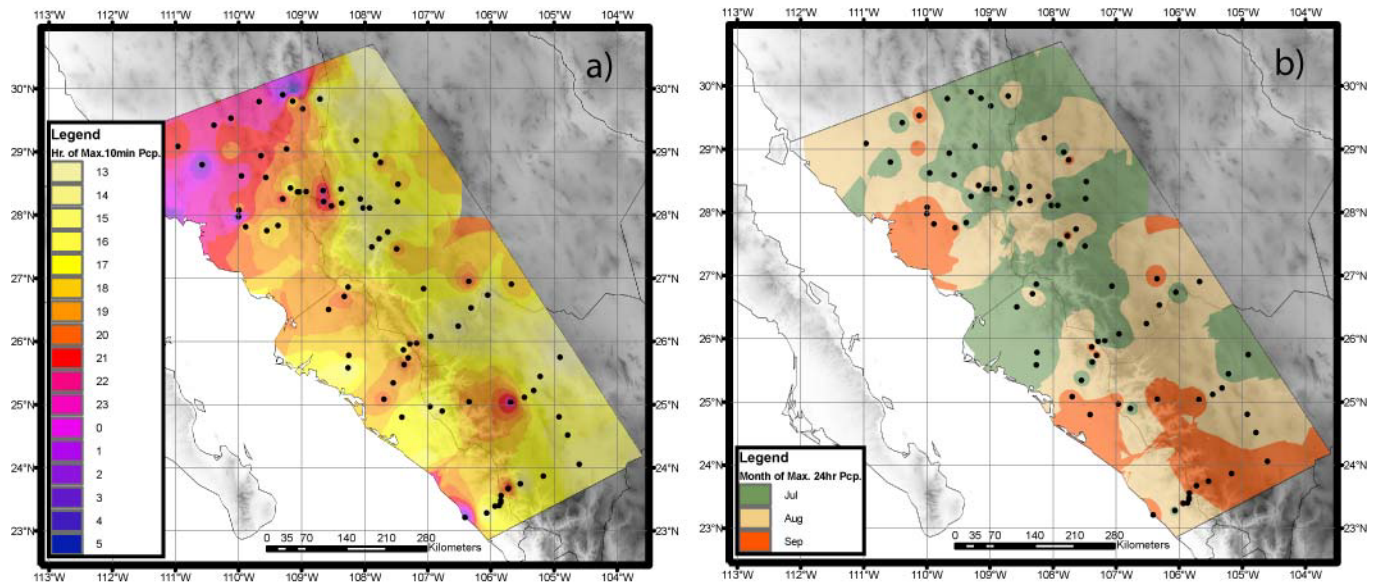


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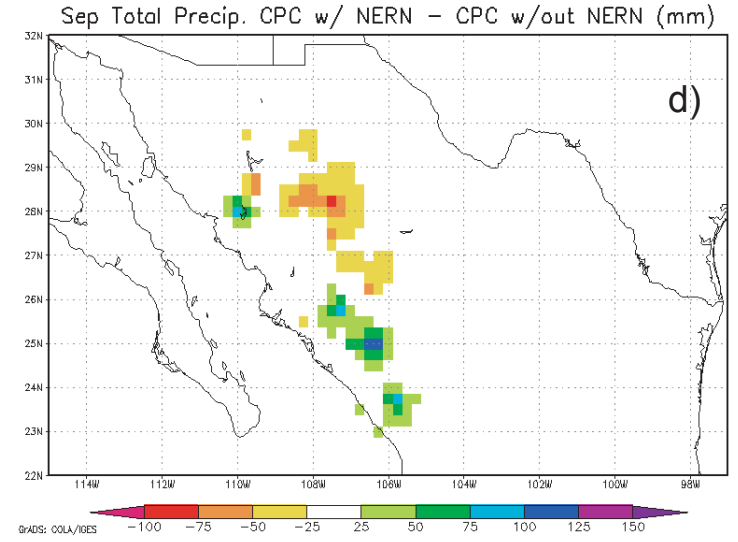
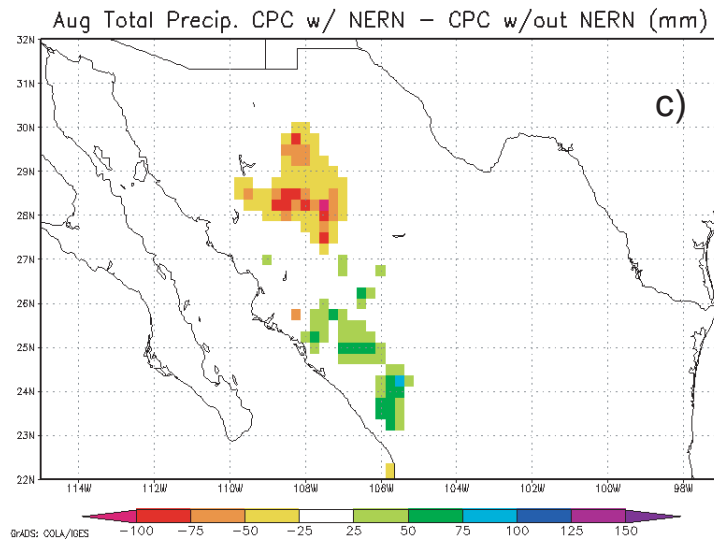
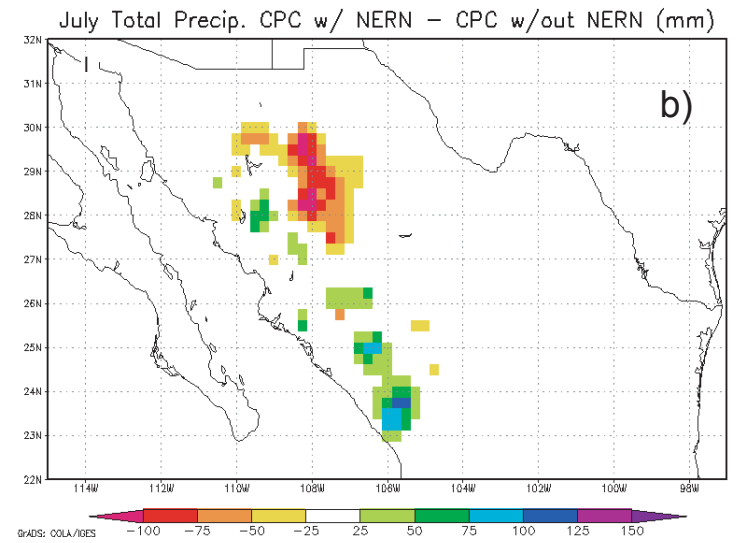
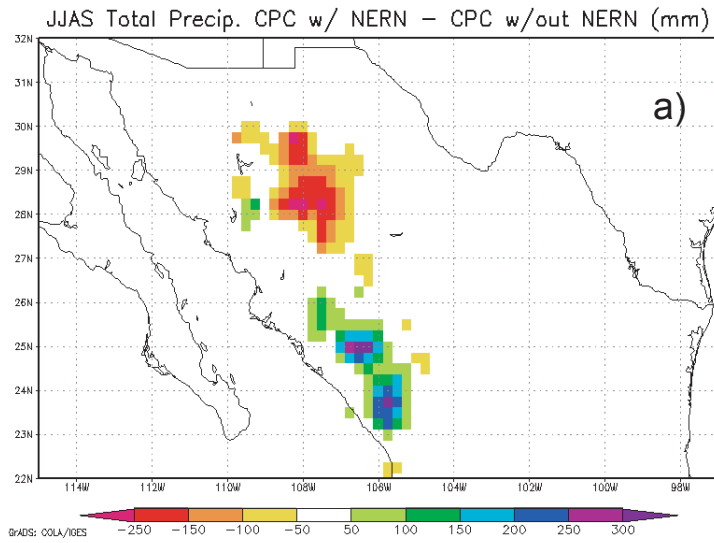


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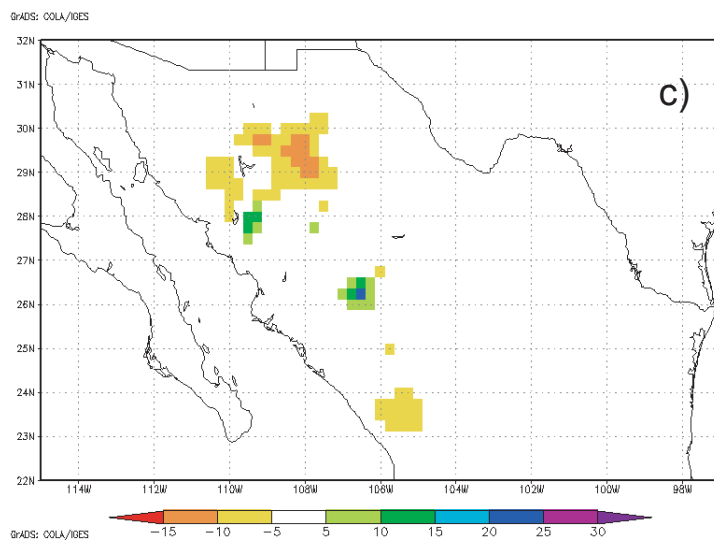
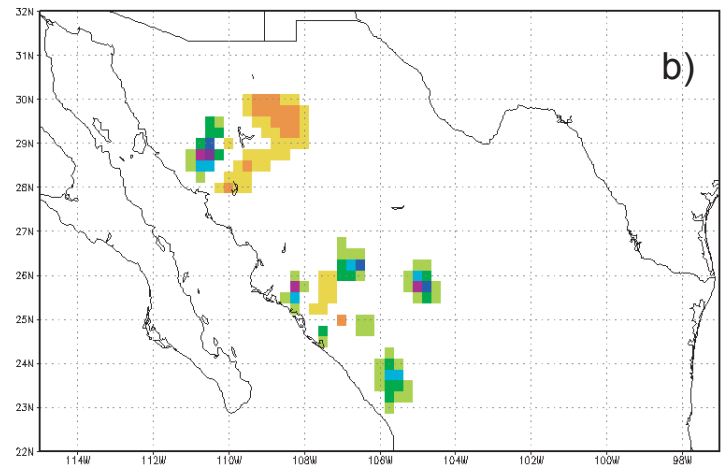
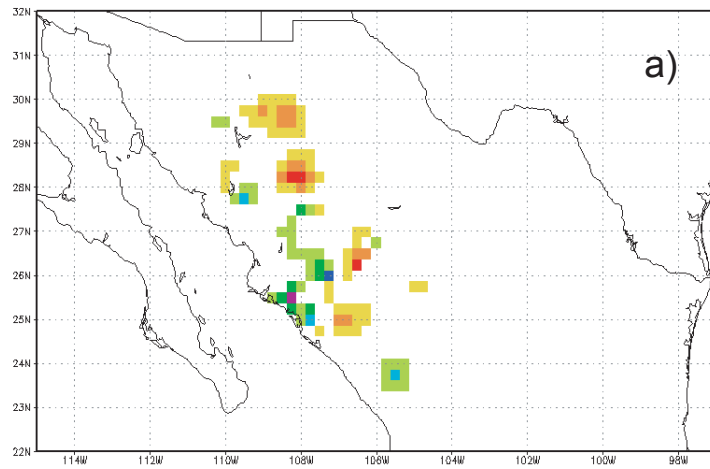


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Table 1: Top five dates where precipitation was observed at a large number of stations (e.g. 'widespread precipitation')

Days of Widespread	No. Stations
Precipitation	Receiving Precipitation
July 23	80
July 24	80
Aug 2	77
July 14	76
Aug 29	74

Table 2: Top five dates where individual station 24 hour maximum intensities were observed.

Dates of Maximum	No. Stations Receiving
Precipitation Occurrence	2004 Maximum Precipitation
July 22	7
Sep 18	6
July 21	5
July 23	5
Aug 28	4

Table 3: Precipitation intensity statistics from NERN observations from 2002-2004.

	Maximum	90th Percentile	Mean	St. Dev.	Coeff. Var.
Intensity	(mm)	(mm)	(mm)	(mm)	
10 Minute					
All Sites	27.7	2.0	0.9	1.7	0.31
Low El.	27.7	2.5	1.2	2.2	0.31
Mid. El.	23.1	1.8	0.9	1.6	0.30
Hi. El.	27.7	1.5	0.7	1.2	0.28
Hourly					
All Sites	87.2	5.1	2.4	4.7	2.00
Low El.	87.2	6.1	3.1	6.3	2.03
Mid. El.	48.0	5.1	2.2	4.1	1.86
Hi. El.	55.4	4.3	1.8	3.2	1.78
Daily					
All Sites	117.4	23.9	8.9	12.0	1.35
Low El.	117.4	27.8	10.8	14.6	1.35
Mid. El.	110.7	20.8	8.2	11.0	1.34
Hi. El.	89.5	19.1	7.3	8.9	1.22