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The Relationship of Transient Upper-Level Troughs to Intraseasonal and Interannual Variability of the North American Monsoon System

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1. Introduction

The frequent presence of upper tropospheric lows in the subtropical North Pacific and North Atlantic during the boreal summer is well documented (e.g. Riehl 1948; Kelley and Mock 1982). Some of these upper tropospheric lows also develop in the Gulf of Mexico and Atlantic in or near the Tropical Upper-Tropospheric Trough (TUTT) according to Whitfield and Lyons (1992). These lows often begin their westward progression from the TUTT into the core North American Monsoon (NAM) region covering the southwest United States and northwest Mexico during the summer months. However, not every transient upper-tropospheric feature develops in or near the TUTT region. For example, Pytlak et al. (2005) documented upper tropospheric lows that formed in the central Mississippi Valley and wrapped around the equatorward side of the subtropical ridge over the southwestern United States and were carried westward by the tropical easterlies across northern Mexico and southern California. Douglas and Leal (2003) suggested that these cyclonic perturbations appeared to enhance the transport of low moisture north through the Gulf of California, a process now commonly termed a "Gulf Surge". The low-level moisture coincident with upper-level cooling subsequently destabilized the atmosphere, resulting in a widespread convective outbreak in the core NAM region. They also found that precipitation was enhanced during this time within the metropolitan areas of Phoenix and Tucson, Arizona.

The NAMS is a large-scale seasonal atmospheric circulation that generates between 50% and 70% of the annual precipitation during summer over the core NAM region (Carleton et al. 1990; Douglas et al. 1993; Higgins et al. 1997; Adams and Comrie 1997; Mitchell et al. 2002; Sheppard et al. 2002). Upper-level winds change from a westerly direction that transports air from the dry, cool eastern Pacific in late spring and early summer to an easterly direction that carries more humid air from the Gulf of Mexico into the NAM region in summer. The shift in the prevailing wind results from the development of a monsoon ridge over the south, central United States (Watson et al. 1994; Adams and Comrie 1997). However, as presented by Douglas et al. (1993), the mountains of the Sierra Madre effectively block low-level moisture of the Gulf of Mexico from directly being transported into the western half of the core monsoon region (defined as the 'Tier 1 Region' in the North American Monsoon Experiment). Thus, the primary source of low-level moisture is from the eastern-tropical Pacific and Gulf of California (Figure 1), which can be provided via intermittent Gulf Surges (Maddox et al. 1995; Adams and Comrie 1997; Higgins et al. 2004; Rogers and Johnson 2007), or moisture from evapotranspiration sources in the Sierra Madre Occidental (Watts et al. 2007).

Monsoon thunderstorms are linked to the diurnal cycle of convection. This process is driven primarily by daytime heating over elevated terrain. Higher potential temperatures in areas of elevated terrain, as compared to adjacent valleys and deserts, leads to upslope flow, moisture convergence and the development of convective clouds over the mountains, typically in the late morning to early afternoon (e.g. Maddox et al. 1995). Thunderstorm development in the afternoon can be further enhanced by upper-level dynamics (Figure 2). Under favorable conditions, propagating convection from the mountains can be sustained into the late afternoon and evening hours (e.g. Johnson et al. 2007). This is an important mechanism for rainfall during the monsoon, especially in the northern part of the NAM region (i.e. southwestern United States) where precipitation is more variable intraseasonally (Castro et al. 2007a).

Variability of monsoon precipitation at interannual and longer time scales is related to the positioning and seasonal evolution of upper level features, namely an upper-level monsoon/subtropical ridge (Carleton 1986; Carleton et al. 1990; Douglas et al. 1993; Watson et al. 1994a; Adams and Comrie 1997; Comrie and Glenn 1998; Grantz et al. 2007). If this ridge migrates anomalously far north or northeast of its climatological location, for example the 4-corners region during late July and early August, the core NAM region experiences enhanced upper-level easterlies and an increase in rainfall amounts and coverage. If the upper-level monsoon ridge is instead anomalously far south, the core NAM region experiences a weaker (or non-existent) tropical influence and convection is normally suppressed. This relationship is out of phase with precipitation anomalies over the Central United States (Carleton 1986; Carleton et al. 1990; Douglas et al. 1993; Watson et al. 1994a; Adams and Comrie 1997; Comrie and Glenn 1998; Grantz et al. 2007). The strength of the monsoon anticyclone during the monsoon onset period in the southwestern United States (late June/early July) is significantly related, in a statistical sense, to the state of the Pacific Sea Surface Temperatures (SSTs) via a mid-latitude atmospheric teleconnection response. If El Niño-like (La Niña-like) conditions prevail in the eastern and central tropical Pacific, and the eastern North Pacific has a horseshoe-shaped positive (negative) SST anomaly, an anomalous southward (northward) displacement of the monsoon ridge is likely to occur (Castro et al. 2001; Castro et al. 2007b).

Castro et al. (2007b) defined a Combined Pacific Variability Mode (CPVM), considering two of the dominant rotated EOFs of global SST which consider interannual and interdecadal Pacific variability (see their Figure 4). They found that if the CPVM is positive (negative), modeled NAMS onset is generally late (early) and summer precipitation is generally below (above) average within the NAM region. As they also note, the CPVM is quite similar to the Pan-Pacific mode of Schubert et al. (2004) associated with dry and wet conditions in the central United States during the 20th century.

An important aspect in Castro et al. (2007b) was the consideration of Regional Climate Model (RCM) simulations of the contiguous U.S. and Mexico (1950-2002) created by dynamically downscaling the NCEP-NCAR Global Reanalysis (Kalnay et al. 1996). These simulations clearly demonstrated that the scale of a RCM (about 50km or less) is necessary to represent the NAM because of the improved representation of the diurnal cycle of convection to a GCM. When considering the CPVM, the changes in the diurnal cycle of convection can dramatically change over relatively short distances, such as the states of Colorado, New Mexico and Arizona. Even more pertinent to the present work, variation in a "synoptic mode" of convection (4 to 15 days) which was more predominant at lower elevations in the NAM region, also exhibited a coherent relationship to the CPVM.

Understanding intraseasonal variability and its relationship to NAM precipitation is a research and forecasting challenge that has motivated several field campaigns (e.g. NAME Science Plan, 2004; Reyes et al., 1994). The westward progression of the aforementioned upper-level troposphere troughs, such as those that form in the TUTT region, occur on the equatorward and west sides of the subtropical anticyclone where easterly and southeasterly flow exists respectively (Whitfield and Lyons 1992; Pytlak et al. 2005, Douglas and Englehart 2007). These features have a distinct influence on convection in the NAM region and came under intense study during the North American Monsoon Experiment (NAME Science Plan 2004). During 2003 and 2004, lower-level and upper-level features were intensely monitored and tracked for research and forecast improvement on the hourly to interannual temporal scale (NAME Science Plan 2004). A Forecast Operating Center (FOC) in Tucson was created to support daily forecast operations (15 June 2004 – 30 August 2004), and forecasters were trained to observe specific features. One of these features was referenced as the Inverted Trough (IV), which were defined as mid- to upper-level tropospheric lows, detected by either water vapor or upper air analysis, that were numbered and tracked as long as they were distinct and translating near the core monsoon region (Pytlak, 2004). Inverted troughs were also targeted for Intense Observation Periods when all National Weather Service (NWS) and Servicio Meteorológico Nacional (SMN) upper air sites participating in NAME launched four to six radiosondes a day. A NOAA-P3 aircraft also monitored possible Gulf of California moisture surges and the surrounding atmosphere (NAME Science Plan 2004). These upper level features pose a challenge for operational forecasts to analyze in real time with a high degree of confidence owing to their formation and propagation over data-sparse areas (e.g. Sierra Madre Occidental) and their modification by underlying terrain and deep convection. In these instances, output from high-resolution data assimilation systems, regional reanalyses (Mesinger et al. 2006) and remote sensing platforms (e.g. water vapor imagery) provide the means to track their evolution over many days.

Literature that focuses on the impact of transient synoptic systems is more limited in number and scope. Pytlak et al. (2005) applied PV thinking (James and Hoskins 1985) to hypothesize a conceptual model for IV's. They hypothesized that two possible and distinct areas of upper level divergence and mid-tropospheric upward vertical motion exist on both the leading (west) and the trailing (east) quadrants of IVs (Figure 2). These regions theoretically favor positive differential vorticity advection given a westward propagating feature. Pytlak et al. (2005) further hypothesized and Douglas and Englehart (2007) later found that upper level cooling can also be expected from these transient IV features. Through this dynamical mechanism, upper level systems can play critical roles in organization Mesoscale Convective Systems (MCSs). Douglas and Englehart (2007) further concluded that IVs were the dominant transient feature of the NAMS. These transient IVs were also classified by their work into warm (500 hPa trough temperatures > -6°C), neutral (-7°C to -8°C) or cold (< -8°C). From this classification they determined that 62% of all inverted troughs were warm-core, 30% were neutral and 8% were cold-core. Though this classification method may be somewhat simple and arbitrary, they did note differences in the physical characteristics of warm and cold IVs. They found cold IVs produce more precipitation on their forward flanks as they approach the core region of the NAMS. The structure and dynamics of the cold IVs are akin to midlatitude wintertime systems that can become cut-off from the both the polar westerlies and tropical easterlies and supply the forcing mechanism for catastrophic amounts of monsoon rainfall. A good example is 27-31 July, 2006, when Tucson, Arizona experienced a serious flooding event underneath a cut off upper level disturbance (Magirl et al. 2007). This event produced 265 mm over 3 days (a rainfall depth with an estimated 1000 year recurrence) and caused major damage in Sabino Canyon, a popular local recreation area. Douglas and Englehart (2007) also concluded that the warmer IVs are wetter on average than cold systems and their structure are akin to easterly waves of tropical origin.

The NAME works of Pytlak et al. (2005) and Douglas and Englehart (2007) on the dynamics and climatology of IVs over the NAMS region leave many fundamental questions unanswered. For example, how does the passage of transients IVs influence the diurnal cycle of precipitation, a dominant temporal band of summertime convection over the NAMS region? How does the phase of intraseasonal and interannual low-frequency modes (e.g. SST forcing) impact the occurrence of synoptic-scale transients? These are two the questions that warrant better physical understanding and thorough statistical quantification. This paper addresses these two questions from a statistical perspective, and it takes advantage of data sets not yet applied *in toto* to upper-level IVs.

The outline for this paper is as follows. Section 2 describes the regional definitions and gives an overview of the key geography that is prerequisite to understanding the weather and climate of the NAM region; datasets and the methodology of analysis are also described there. Section 3 establishes that convective activity during specific hours of diurnal cycle is enhanced by passage transient IVs. Section 4 demonstrates the importance of interannual Pacific SST variability on the frequency and track of transient IVs. Discussion and conclusion is given in Section 5.

2. Data Used

2.1. Regional Definition

The first region of interest is defined by the domain corners of 20°N, 35°N, 105°W and 120°W and is known as the "Tier 1 Region" (NAME Science Plan 2004). The placement was chosen in order to maintain consistency with Moore et al. (1989) and Whitfield and Lyons (1992). The topography of the region (Figure 2) is quite varied and is characterized major by mountain ranges and isolated mountain peaks, complex coastal geometries, warm inland seas (e.g. Gulf of California), and strong SST differences separated by narrow peninsulas.

2.2. Datasets

2.2.1. Cloud-to-Ground Lightning Data

The National Lightning Detection Network (NLDN) provides cloud-to-ground (CG) flash and stroke density for contiguous United States and adjacent environments. Starting in 1996, the NLDN has undergone a series of improvements that has improves its accuracy in detecting lightning. The measured NLDN flash and stroke detection efficiency in southern Arizona was nearly 95% (Biagi et al. 2007). The high temporal and spatial resolution of CG data make them extremely valuable for tracking convection and serving as a proxy for monsoon precipitation, especially over data sparse regions (Tapia et al. 1998; Underwood and Schultz 2004).

The NLDN data, obtained courtesy of Vaisala, Inc., was used in this study to track CG lightning strikes each hour within a domain bounded by 27.5°N, 40°N, 100°W and 120°W. Data for this study was available for the 10 warm seasons (1 June – 30 September) of 1996 to 2005. Over the study domain, the temporal precision is 10^{-3} seconds and location precision is approximately 10 meters (K. Cummins, Personal Communication). Although the NLDN is quite accurate throughout the United States and Canada, the same cannot be said for Mexico and Central America. Murphy and Holle (2005) report that the NLDN's efficiency diminishes below 50% south of latitude 27.5°N. For that reason, the southern boundary was held at 27.5°N to ensure that the majority of the lightning strikes in northern Mexico are counted.

2.2.2. North American Regional Reanalysis (NARR)

The NARR uses the NCEP ETA data assimilation system (EDAS) that was operational in April 2003 to generate 3 hourly fields on a 32-km grid for the North American continent and adjacent ocean regions (Mesinger et al. 2006). Analyses are available starting at 0000UTC, 1 Janury 1979 to present. Despite having a much shorter data period than what is available for the NCEP Global Reanalysis' dataset (Kalnay et al., 1996), NARR fields have a higher spatial and temporal resolution that can provide a better representation of the diurnal cycle and the complex terrain. These two mechanisms exert a strong influence on convective forcing in the NAMS regions (Maddox et al. 1995; Castro et al. 2007a). The time frame that was used to identify these transient inverted troughs was the period of May 15 – September 30 which includes the onset and decay of the monsoon.

It is important, however, to acknowledge the shortcomings of using NARR. Most importantly, it has a very inaccurate representation of the Gulf of California low level jet associated with gulf surges, as it overestimates the strength of this feature (Castro et al. 2007a). While the NARR fields offer clear advantages over the NCEP Global Reanalysis, it was felt that supplemental analyses should be consulted as a consistency check on our initial NARR-based interpretations. Best track reanalysis from the Colorado State Tropical Prediction Center[1] were used to make certain that tropical storms or hurricanes were not inadvertently labeled IV's. The daily DWM series, and for dates after approximately 1 December 1998, the NOAA National Weather Service Storm Prediction Center online map archives provided access to analyses with radiosonde data plotted, and thus they provided a check on the veracity of the NARR analyses. GOES West IR and water vapor imagery for dates after 1997 were obtained from Earth Observing Laboratory[2] portal of the National Center for Atmospheric Research to help pinpoint rotation centers of some upper-level vortices.

3. Analysis Methodology

3.1. Construction of an Inverted Trough Climatology

Subjective interpretation of NARR analyses of geopotential height at four isobaric levels (250, 300, 500, 700 hPa), and temperature and relative vorticity at one level (500 hPa) is the primary means for identifying IVs. Three consecutive analysis times were simultaneously scrutinized for distinguishable upper-tropospheric (250-300 hPa) troughs that possessed clear temporal continuity over all maps. If a temporally continuous feature was not found aloft, the mid-level maps (500 hPa) were next screened, followed by the low-level maps (700 hPa). If no distinguishable center could be confidently identified in the geopotential analysis sequence at any level, that date-time period was classified as a *no-trough* event. On the other hand, if an IV was identified, the latitude-longitude of its center was pinpointed from the location of the 500 hPa vorticity maximum. Through this methodology, latitude-longitude points of IVs were digitally cataloged on a 3-hourly basis, as were dates-times without IVs. Climatology of IVs for the NAM region, along with conditional IV climatologies, can be readily constructed from the inventory.

Composites of CG strike density for periods with and without IV's are formed as follows. Times that had an IV pass within a domain bounded by 23.5° N, 40° N, 100° W and 120° W (as opposed to 27.5° N on the southern border) are classified as *IV days* while times that do not are considered *non-IV days*. The boundary is the expanded south to

[1]Available online at http://www.weather.unisys.com/hurricane/e_pacific/ .
[2]Available online at http://data.eol.ucar.edu/ .

ensure that the influence of the IVs (meridional scales of roughly a few hundred kilometers) centered somewhat south of 27.5° N is included. The approach further stratifies the NLDN data into 24 hour bins to changes in the diurnal cycle of convection and to establish that whether IV days differ significantly from non-IV days. A student's t-test difference of means is used to test for local significance. Field significance tests (e.g. Livezey and Chen 1983) are also performed, considering significance at the 99% level, using 500 realizations with 1218 degrees of freedom (122 days x 10 years - 2).

The IV and non-IV days are used to define composites of the NARR accumulated precipitation dataset. The NARR dataset has a 3-h time sampling and accumulates precipitation over this time period. To maintain consistency between the NLDN dataset and the NARR dataset, the NLDN dataset is summed over the same three hours (i.e. 18 + 19 + 20 UTC for NARR precipitation ending 21 UTC). The hypothesis testing is the same (e.g. t-test difference of means, field significance test) as the aforementioned dataset using 99% significance and 1218 degrees of freedom.

<u>3.2.</u> <u>Interannual Variability of IVs</u>

Composites of IV tracks are classified by the phase of interannual Pacific SST variability, specifically the sign of the CPVM (Castro et al., 2007b). Recall that if this index is positive (negative), NAMS onset is late (early) and precipitation amounts during the NAM season are statistically below (above) average within the core NAM region. The period analyzed in the earlier paper was 1950-2002, whereas our study is limited to 1980-2002. The phase of the CPVM for each year 1980-2002, which is repeated in Table 1 for convenience, shows 9 negative and 10 positive seasons.

The seasonal evolution of IV tracks for the two CPVM phases is based on moving 30-day averages. Composites are computed for overlapping 30-day periods in 15-day increments, starting on Julian Day 155 (June 4) and continuing for days 170 (June 19), 185 (July 4), 200 (July 19), 215 (August 3) and 230 (August 18), consistent with the methodology of Castro et al. (2001, 2007b). These periods were deemed important to track changes in the transient features as the monsoon progresses over the Tier II region. The student's t-test is used to test for local significance (95%), and field significance (e.g. Livezey and Chen 1983) is assessed assuming 17 *dof* (9 negative years + 10 positive years – 2) and 500 realizations.

4. Results

<u>4.1.</u> <u>Diurnal Cycle</u>

Warm season convection over the continents and coastal zones is marked by a strong diurnal signal (Wallace 1975; Zajac and Rutledge, 2001). The NAM region is no exception. Over Arizona for example, the higher terrain of the Mogollon Rim and While Mountains experiences a diurnal maximum during mid-afternoon hours, whereas the lower terrain of central and western Arizona experiences its maximum during the early and late evening hours (Hales 1977; Balling and Brazel 1987; King and Balling 1994; Watson et al. 1994b; Maddox et al. 1995). It stands to reason that the changes in upper-level divergence and static stability associated with transient IVs could strongly affect the diurnal signal, possibly even overwhelming it. Hence, it is of value to quantify the role that IVs have in modifying the diurnal cycle throughout the core NAM region.

Figure 3 shows the 3-h evolution of hourly lightning density for the six times of 18 UTC (1100 LST) to 0900 UTC (0200 LST), inclusive, hours that coincide with the NARR analyses. Results are normalized by the total days in the 10-season composite (1220) to units of km^{-2} h^{-1}. The daily convective cycle commences around 1100 LST (Fig. 3a) over the high terrain of New Mexico (Sacramento Mountains; Sangre de Cristo) and Arizona (Mogollon Rim; White Mountains). Convective activity reaches its peak diurnal values over these mountain regions three hours later (1400 LST, Fig. 3b). Lightning also peaks over the Santa Rita Mountains (southern Arizona) and the northern Sierra Madre Occidental Mountains (northeastern Sonora Mexico), where the CG density increases ten-fold between 1800 and 2100 UTC to its domain maximum of ~25 km^{-2} h^{-1} (e.g Murphy and Holle 2005). Convection moves off of the terrain by late afternoon, 1700 LST (Fig. 3c). It propagates eastward from the Sangre de Cristo range, and westward or southwestward over Arizona and northern Sonora Mexico, consistent with prior analysis of radar echoes (e.g. Knievel et al. 2004, Fig. 9). In most regions, the lightning count decreases markedly from late afternoon to early evening (Fig. 3d). Convection weakens then dies as it approaches the Gulf of California and lower desert of Southern California during the evening hours of 2000 LST to 0200 LST. Domain-averaged CG flash density is a minimum during the early morning daylight hours (1200 and 1500 UTC, results not shown).

Figure 4 presents the difference in CG density count (km^{-2} hr^{-1}) for IV days minus the non-IV days. Each composite shows field significance at the 99% level, which indicates the presence of an IV has a strong impact on the likelihood of lighting. Despite accounting for only 38% of all sample days, IV days account for the majority of total lightning strikes over Arizona and northern Sonora. The enhancement is already significant by 1100 LST (Fig. 4a), with distinct maximum over the climatologically favored high terrain of the Mogollon Rim and SMO. The differences during mid-afternoon (Fig. 4b) grow, and expand away from these ranges, consistent with the idea of convection propagating from the mountains. Increased likelihood of propagation is very evident starting 1700 LST (Fig. 4c), which shows a marked increase over the lower deserts of south central Arizona and NW Sonora. Largest positive differences are centered over the southern portion of the SMO by early evening (0200 LST, Fig. 4d). Despite the small positive differences, the nighttime panels (Figs. 4e, f) indicate that local significance is essentially confined to extreme southwest of Arizona, western Sonora, and the northern Gulf of California, clear evidence of an increased likelihood of westward propagating convection during IV days.

In view of the strong signal evident in the CG data, it is of interest to examine how IV's impact precipitation. The 0-3 h precipitation fields from the NARR was used to examine this signal from a broad perspective. Although there is broad scale agreement on where and when both the CG and NARR difference fields achieve local significance, there is an apparent physical discrepancy between the two fields in a few key places. For example, the CG composite has a significant local enhancement of lightning activity during IV days at 2100 UTC in western Sonora, whereas the NARR precipitation has a meager (if any) signal. The same inconsistency continues throughout the later hours (e.g. 0000 UTC, 0300 UTC, etc.) over western Sonora. Moreover, we observe similar differences near the Arizona-Sonora border region between the CG data and composites based on the 1° Climate Prediction Center (CPC) precipitation product (results not shown), which is the precipitation input during the NARR assimilation. So these results are not surprising. Alternatively, the discrepancy between the NDLN and NARR may, in good part, reflect actual physical differences if virga was more prevalent over the low deserts. Unfortunately, we do not have a quantitative estimate by how much the ratio of CG to total precipitation varies between high terrain and the low deserts, However, qualitative thermodynamic reasoning that suggests virga should indeed be relatively more frequent underneath the high-based convection of low-desert convection. This raises the general issue of the joint assimilation of CG and precipitation data over semi-arid environments, one that is beyond the scope of this paper. It also points to the value of using NDLN data to document *thunderstorm* activity over the NAM region.

Despite challenges interpreting the CG and NARR precipitation data *in toto*, the NARR composites provide some insight into role played by transient synoptic IV in modulating precipitation. The enhancement of accumulated precipitation during IV-days can be as large as 3 mm over the desert regions. Over some regions such as the low deserts of southwestern Arizona, the enhancement occurs over a prolonged period (0000-0600 UTC). When precipitation is accumulated over the 24 h day, the enhancement of IV days over background non-IV days can add up to 6 mm over the low deserts. Mountainous areas, such as the Mogollon Rim, also have statistically significant enhancements of this magnitude. This suggests the presence of transient IVs can bring conditions conducive to local severe flooding over the bulk of the NAM region.

4.2. Interannual Variability

As already noted, the negative phase of the CPVM is associated with a northward displacement of the monsoon ridge, an earlier monsoon onset, and wetter summer over Arizona, so it stands to reason that the occurrence of IV would be affected too. Therefore, it is of interest to quantify this relationship and estimate its statistical significance.

Climatologically track densities were compiled to diagnose the evolution of the transient IVs during the 'typical' monsoon season. Results are shown in Fig. 6, which gives the seasonal evolution of the climatological IV track density at 15-day intervals, standardized over 17 years. During the early onset period of the NAM season of June 4-18 (Fig. 6a), the total number of IVs averages only 1 per year per 15 days, a much lower frequency compared to the monsoon peak (late July-early August). The low value reflects the monsoon easterlies not being established in early June; by definition and experimental design, transient IVs over the region must track equatorward of the subtropical ridge so the absence of easterlies ensures no IVs. Despite the low values, a well-defined track axis is seen centered approximately along 22°N with maximum density near the mouth of the Gulf of California (Fig. 6a). The latitudinal variability in density is related in part to interannual (shown by the cooler colors) differences in the strength and position of the ridge. As the NAM develops and the easterlies become better established, the climatological track densities increase to their maximum value of about 2.8 IVs per year per 15 days from early July to early August (Figs. 6c and d). The maximum nudges northward, closer to the mouth of the Gulf of California. The shape of the track also changes from June to July, becoming more NW-SE oriented over southern Baja and sharper along its axis, in response to the 500 mb (Douglas et al. 1993) anticyclone moving its center from southeast Arizona to west central Texas during the peak of the monsoon season. During the midst of the monsoon season (July to mid-August, Figs 6c-e), a secondary density maximum develops over the western Gulf of Mexico with peak values of 1.8 IVs per year (Fig. 6d). The primary maximum west of Mexico and secondary maximum east of Mexico are suggestive of two-fold scenario, either where IVs develop *in situ* downwind of the Mexican Plateau, or they impinge against the Plateau from the east, lose their identity over the elevated terrain, then reorganize and strengthen over the west coast of Mexico. Either scenario implies an important role for lee-side cyclogenesis in the track and development of IVs (e.g. Zehnder 1993). As the summer monsoon wanes (August 18 - Sept. 1, Fig. 6f), track densities decline in number and retreat southward as the easterlies weaken and subtropical anticyclone begins its pre-autumnal equatorward drift. The late season tracks west side of Baja California also change characteristic. Instead of IVs tracking into the subtropical East Pacific Ocean, they closely hug the west coast of the peninsula.

A normalized difference of means IV track density between CPVM positive years and negative years (with associated local significance of 90%) are produced and shown in Figures 7a-f. Consistent with the increase in rainfall, when the CPVM index is negative (positive), there is a statistically significant increase in the number of transient IVs and a poleward shift of tracks during the monsoon onset and early part of the peak periods (Figures 7a-d, late June through July). The regions that are most likely affected during the month of June are Texas, New Mexico, the Mexican states of Baja California Norte and Sur, and those Mexican states along 20-22°N. In early July the statistically significant enhancement shifts poleward into New Mexico, Texas and of the west coast of Baja California. While in late July the statistically significant enhancement is primarily in the northern part of the Tier II region, mainly in Arizona, New Mexico and Texas, this enhancement rapidly diminishes in August. These results are entirely consistent with the modeling results of Castro et al. (2007b), which (as mentioned) showed an enhancement in moisture flux convergence in a "synoptic" timescale of 4 – 15 days of the CPVM during July (their figure 12).

6) Discussion and Conclusions

An aim of this study was to determine whether transient IVs could either enhance or interrupt the diurnal cycle of convection within the study region (in the case the lightning region). When all hours over 1220 days (1996-2005 from June 1- Sept 30) were analyzed, it was determined that lightning counts during the hours of 1800UTC – 0900UTC were significantly different by those days that were considered IV days (453 days) against those days that were not (747 days). As the composite trough could be located anywhere within the lightning region, as well as within 4° latitude south of it, this suggests that IVs influence upper level dynamics over a large area (i.e. 100s of km). The findings support the conclusions by Douglas and Englehart (2007), suggesting that these transient IVs were indeed important and can enhance convective rainfall. Though the study cited was focused within regions of northern Mexico, and our work is more focused within the southwestern United States, we also conclude that lightning data are a useful proxy for precipitation (e.g. Figures 3a-f, 4a-f). In fact this data set is probably the best proxy for Mexico, given the poor quality of precipitation data there.

An enhancement of convection in the western deserts of Arizona during most of the statistically significant hours (e.g. 1800UTC – 0900UTC) was noted during the study. According to the conclusions of Higgins et al. (2004), 'wet' gulf surges were associated with diffluent flow into AZNM and were usually associated with anomalously strong easterly flow (i.e. easterly waves). However, the conclusion of Higgins et al. (2004) was not specific about what type of dynamical and physical mechanism was behind the anomalously strong easterly flow. Rogers and Johnson (2007) documented that a gulf surge during NAME was associated with not only TS Blas, but a strong north-south inverted trough at 200mb located over northern Mexico. It was noted by both Rogers and Johnson (2007) and Pytlak et al. (2005) that upper level divergence associated with the inverted trough aided in the development of convection over the Sierra Madre Occidental. As a result, an MCS formed over the region, and with the aid of TS Blas, the environment was primed for a gulf surge (Higgins et al. 2004). To add further, Johnson et al. (2007) noted another 'strong' gulf surge on July 23rd, 2004 that was due to an upper tropospheric low. As three other studies have concluded that gulf surges, almost all of them strong, were possibly associated with upper tropospheric lows, it is reasonable to conclude that the resurgence of enhancement noted in Figure 4c in the southwestern deserts of Arizona and northwestern Mexico is likely associated with the same factors identified in prior studies.

Synoptic scale enhancement of precipitation and convection in the core NAM region is found to play an important role as a result of this and prior studies. Though not as common as that in the Midwest or East, a determination by Maddox et al. (1995) concluded that three such types of situations existed throughout south central Arizona that allowed for severe weather to occur. Two regimes explored in this study were similar to that represented in Figure 1 of Maddox et al. (1995). Though at the time these features were not considered inverted troughs or even easterly waves, it was interesting to note that such regimes were found in the literature as noted by Adams and Comrie (1997). However, the present temporal and spatial resolution of upper air data in Mexico makes it extremely difficult to forecast these events.

From a climatological standpoint, transient IVs tended to track over central Mexico and tend to reach a maximum over the tip of southern Baja California (or the mouth of the Sea of Cortez). During CPVM negative years, though, transient IVs are more numerous during the months of June and July (by as much as 1 more IV per year) and take more northerly tracks. This likely resulted in more convection to occur over the core monsoon region. Furthermore, knowing that the CPVM is negative could be an important climate diagnostic tool in determining whether the core NAM region will have an early onset as well as having more IVs during the upcoming NAM season. Our future work will quantitatively test whether the CPVM may have value as a potential forecasting tool for NAM interannual and intraseasonal variability. Also, detailed numerical modeling studies of IV events will be considered under different Pacific SST conditions.

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Negative	**Positive**
1981	1982
1984	1983
1985	1986
1988	1987
1989	1990
1999	1991
2000	1992
2001	1993
2002	1994
	1997

Table 1: Years in the 1980-2002 period comprising positive and negative years for the Combined Pacific Variability Mode, as presented in Castro et al. (2007b). Negative years are associated with La Niña-like patterns, and vice-versa.

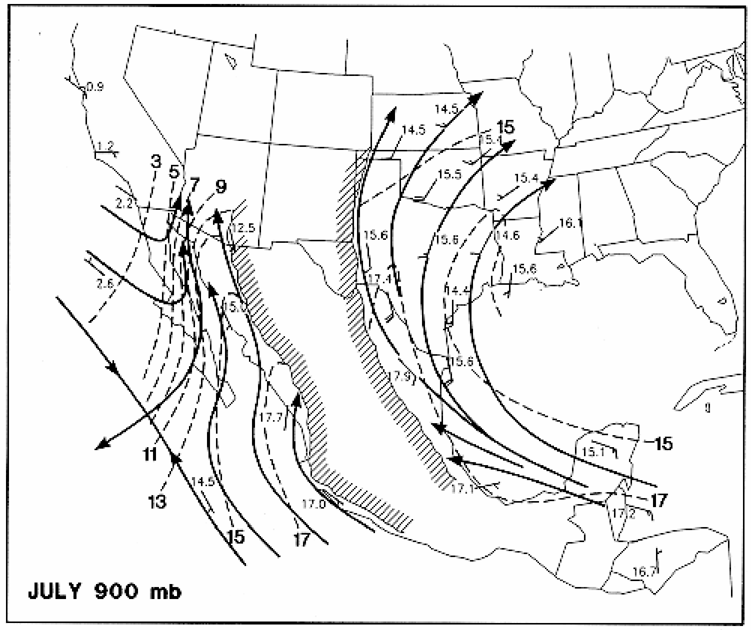


Figure 1: July 900 mb flow chart of wind patterns over the Southern US. Source: Douglas et al. (1993)

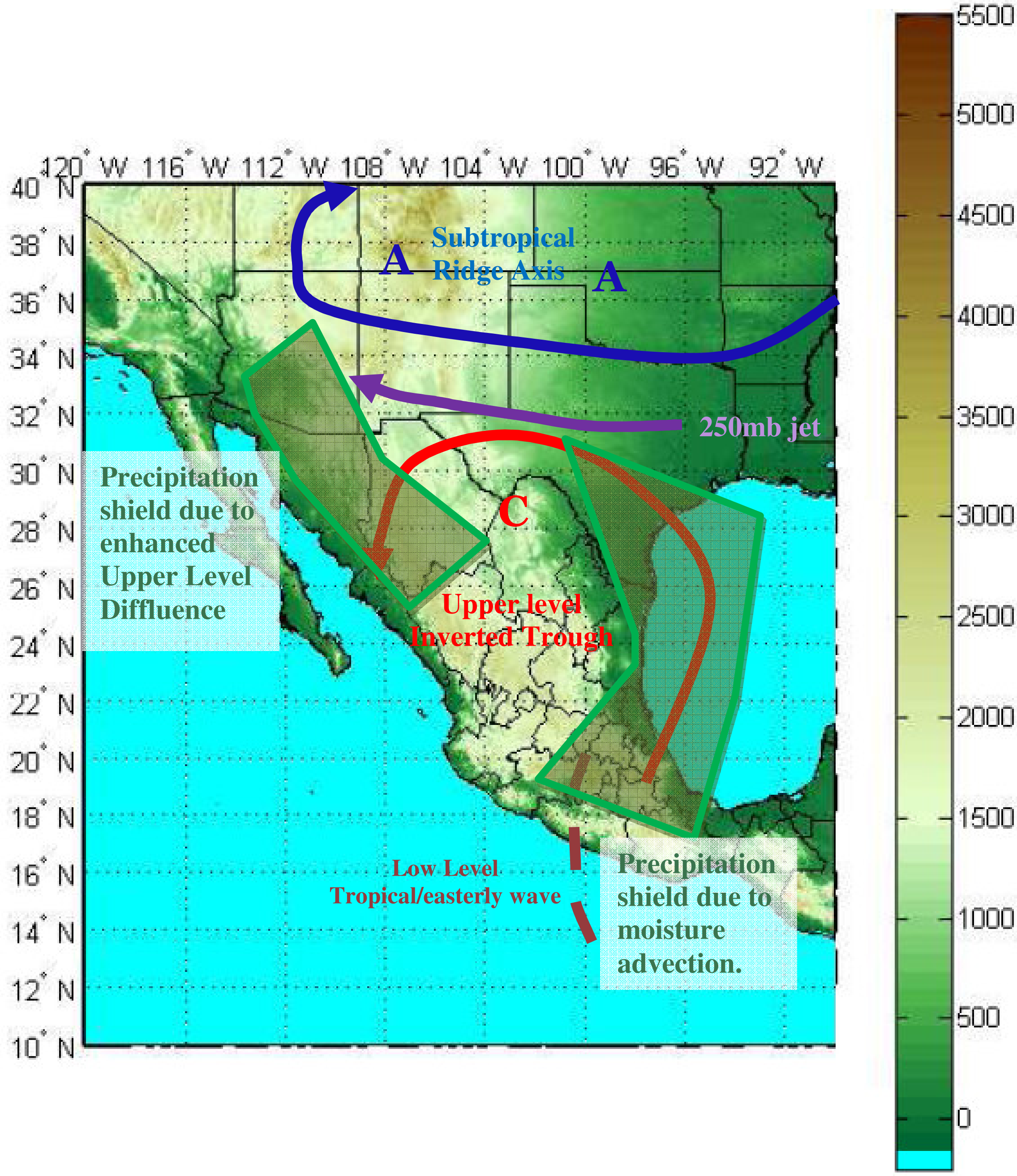


Figure 2: Conceptual Model of Inverted Troughs/Subtropical Ridge interaction, as presented in Pytlak et al. (2005), overlaid on topography of study region (terrain height in meters).

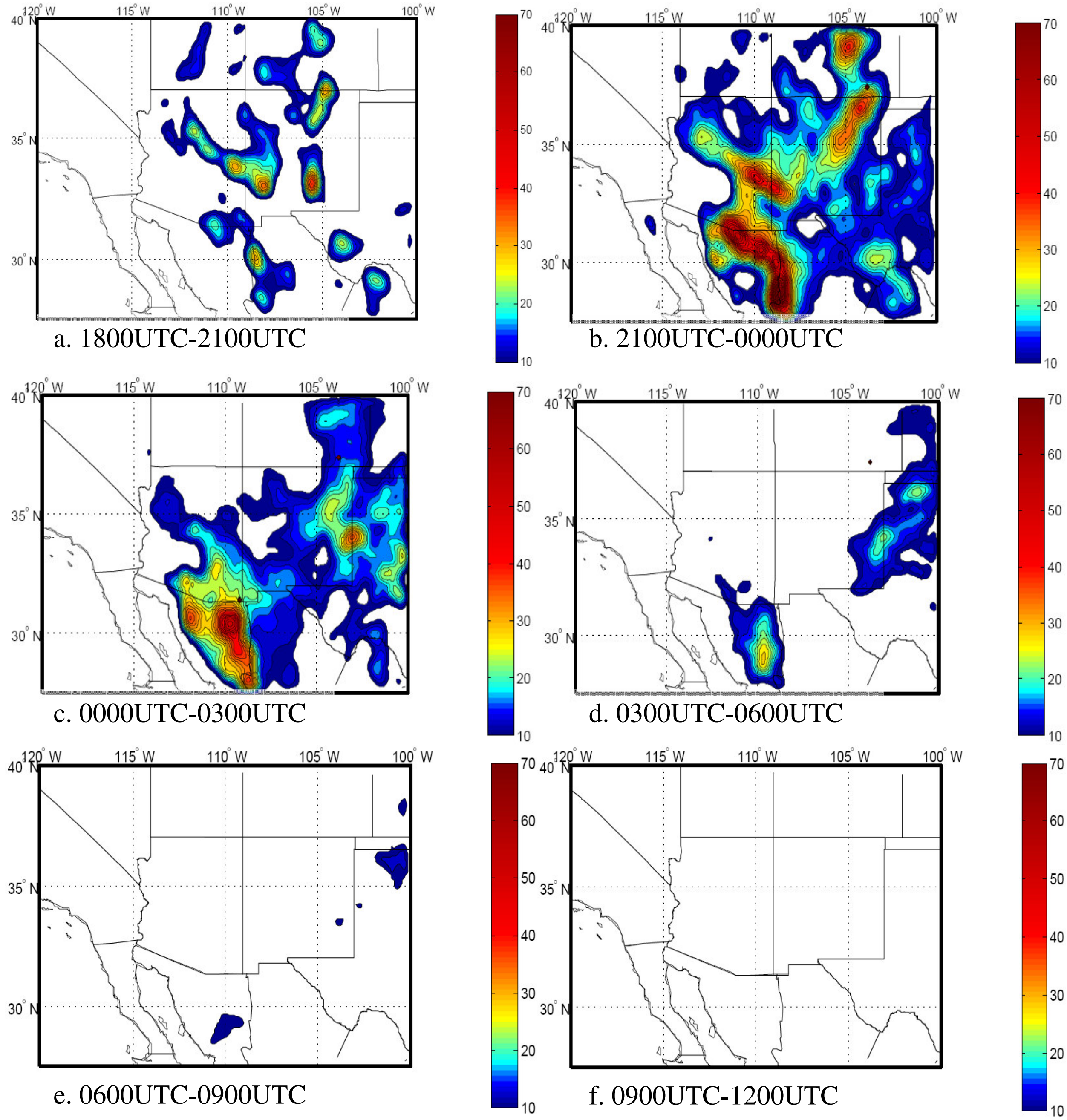


Figure 3a-f: Normalized lightning climatology count km^{-2} (3 hr)$^{-1}$ for the lightning region. Counts above 10 km^{-2} (3 hr)$^{-1}$ shown. Hours in UTC are noted within each figure caption.

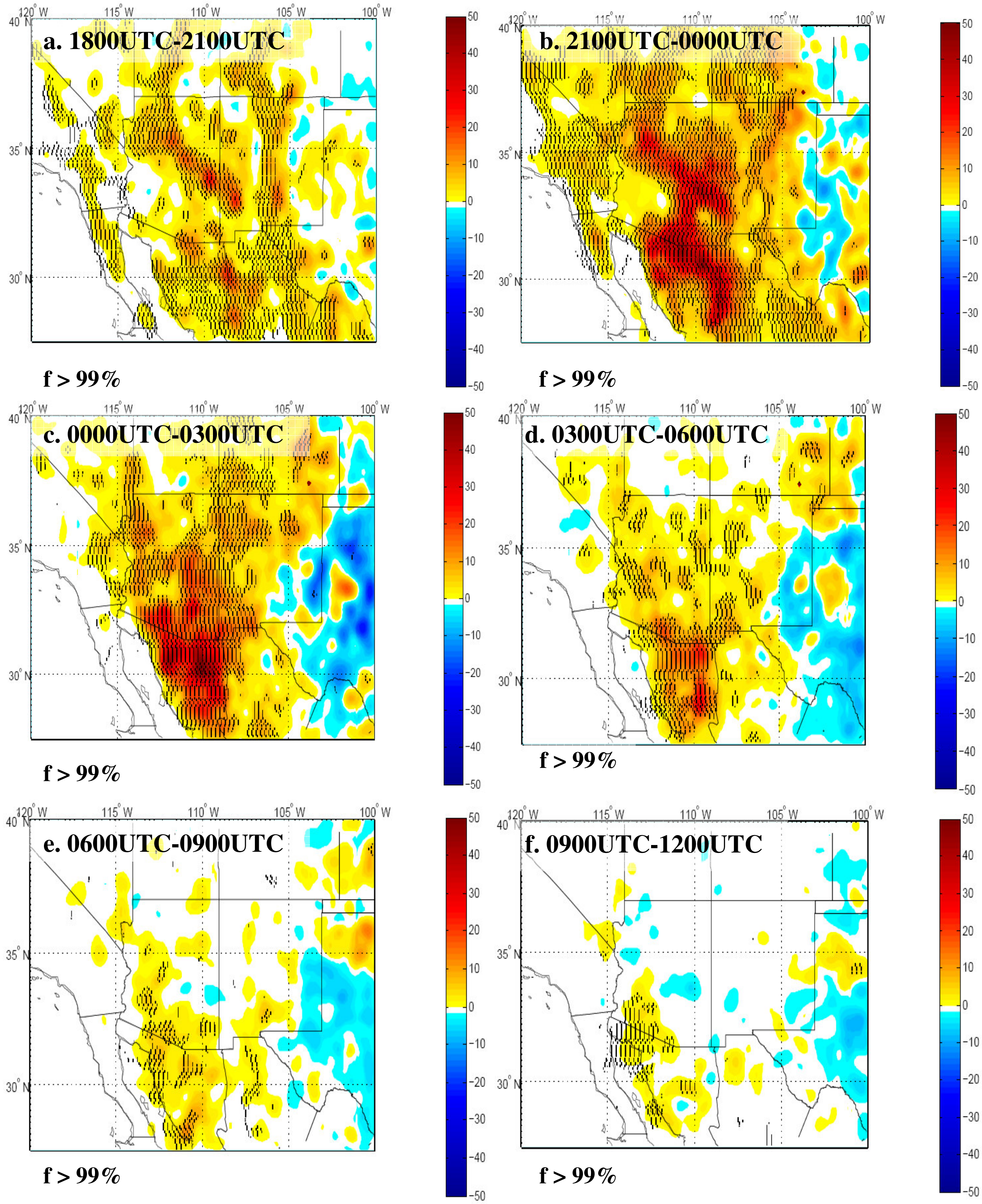


Figure 4a-f: Lightning climatological difference between IV days minus non-IV days every 10 counts km^{-2} (3 hr)$^{-1}$ for the lightning region. Stippling indicates regions of local significance at 99%. Hours in UTC and field significance are noted within each figure caption.

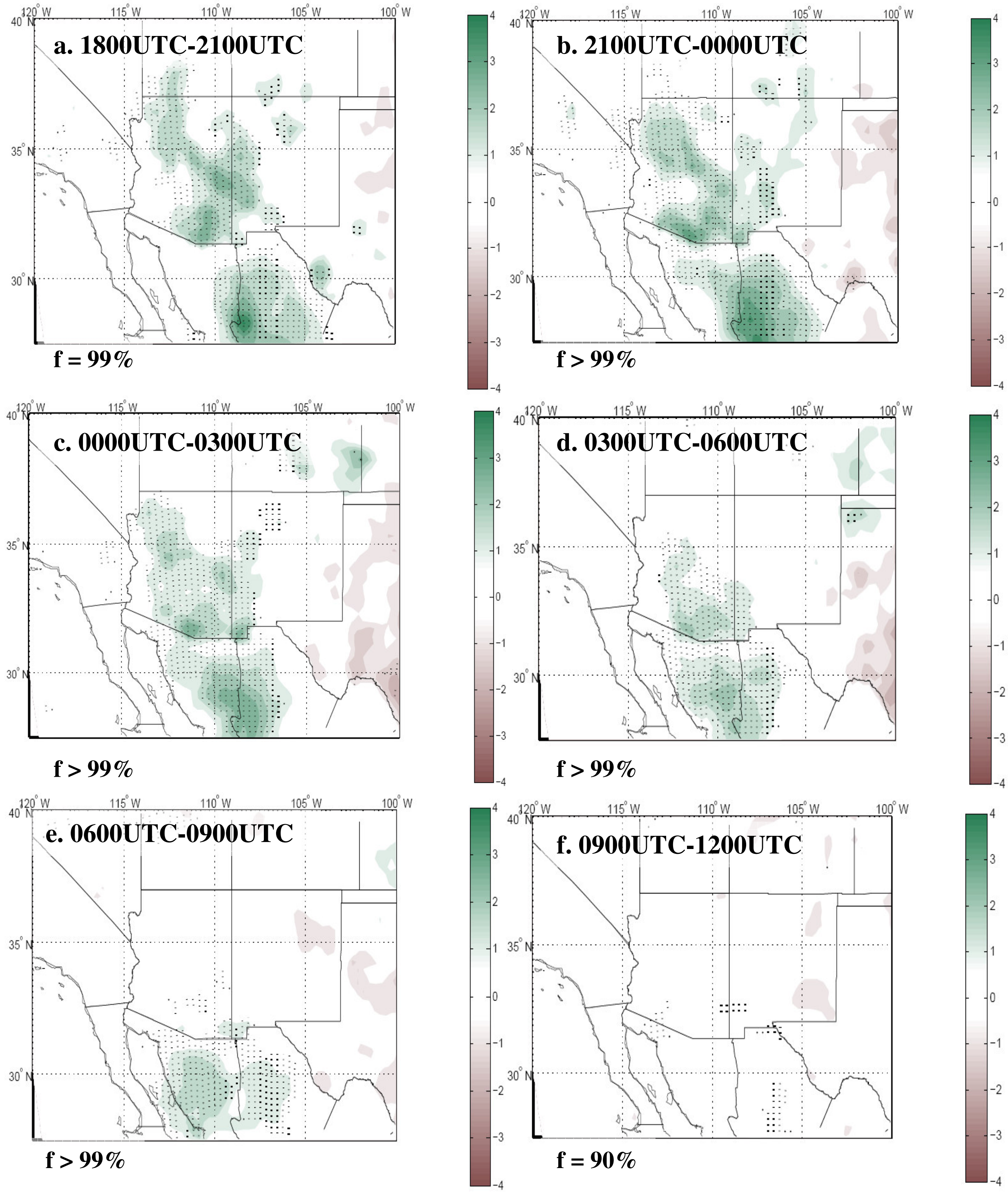
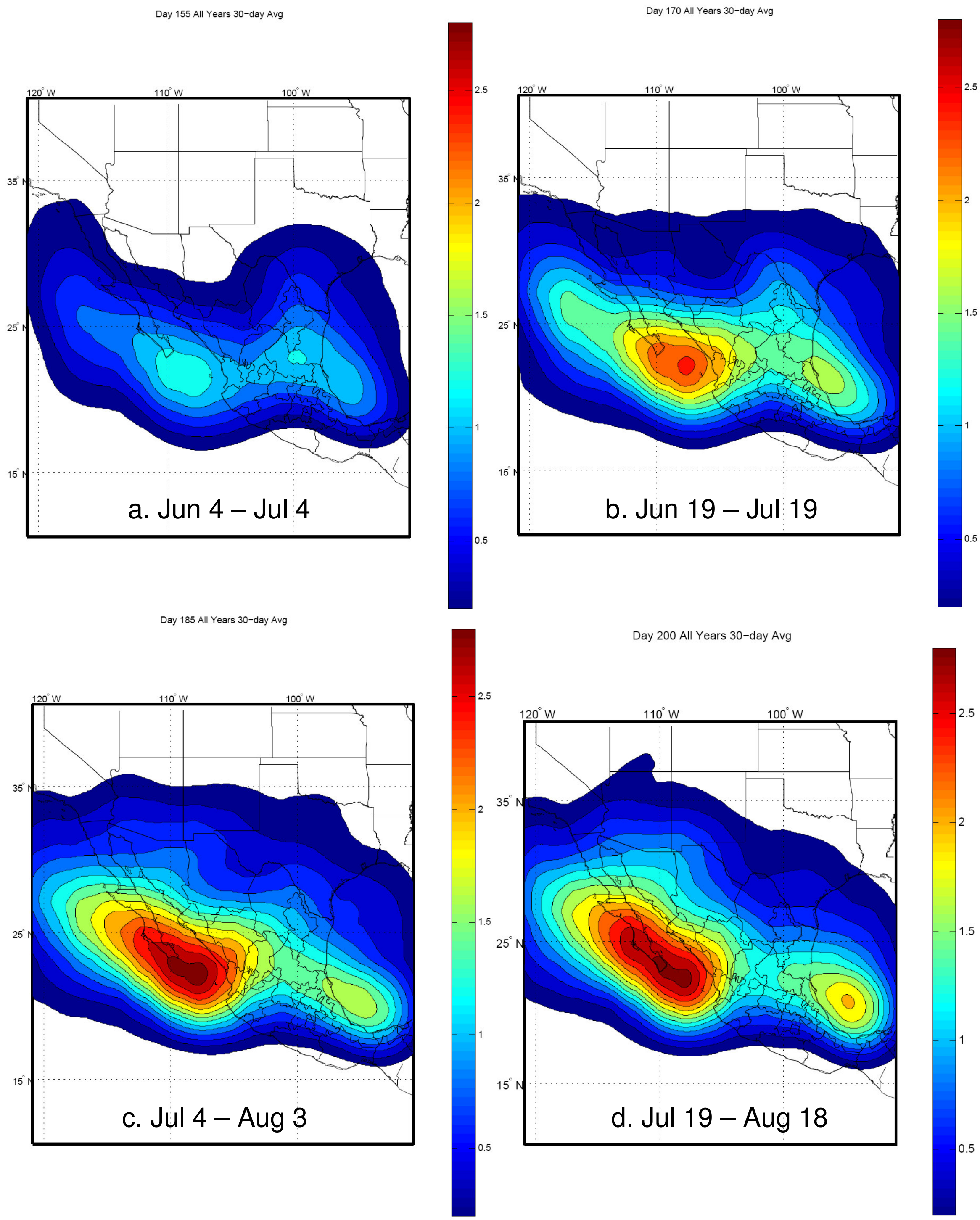


Figure 5a-f: Same as Figures 5a-f, except for NARR Accumulated precipitation every 0.5 mm day^{-1}.


Day 155 All Years 30-day Avg
120° W
110° W
100° W
35° N
25° N
15° N
a. Jun 4 – Jul 4
2.5
2
1.5
1
0.5
Day 170 All Years 30-day Avg
120° W
110° W
100° W
35° N
25° N
15° N
b. Jun 19 – Jul 19
2.5
2
1.5
1
0.5
Day 185 All Years 30-day Avg
120° W
110° W
100° W
35° N
25° N
15° N
c. Jul 4 – Aug 3
2.5
2
1.5
1
0.5
Day 200 All Years 30-day Avg
120° W
110° W
100° W
35° N
25° N
15° N
d. Jul 19 – Aug 18
2.5
2
1.5
1
0.5

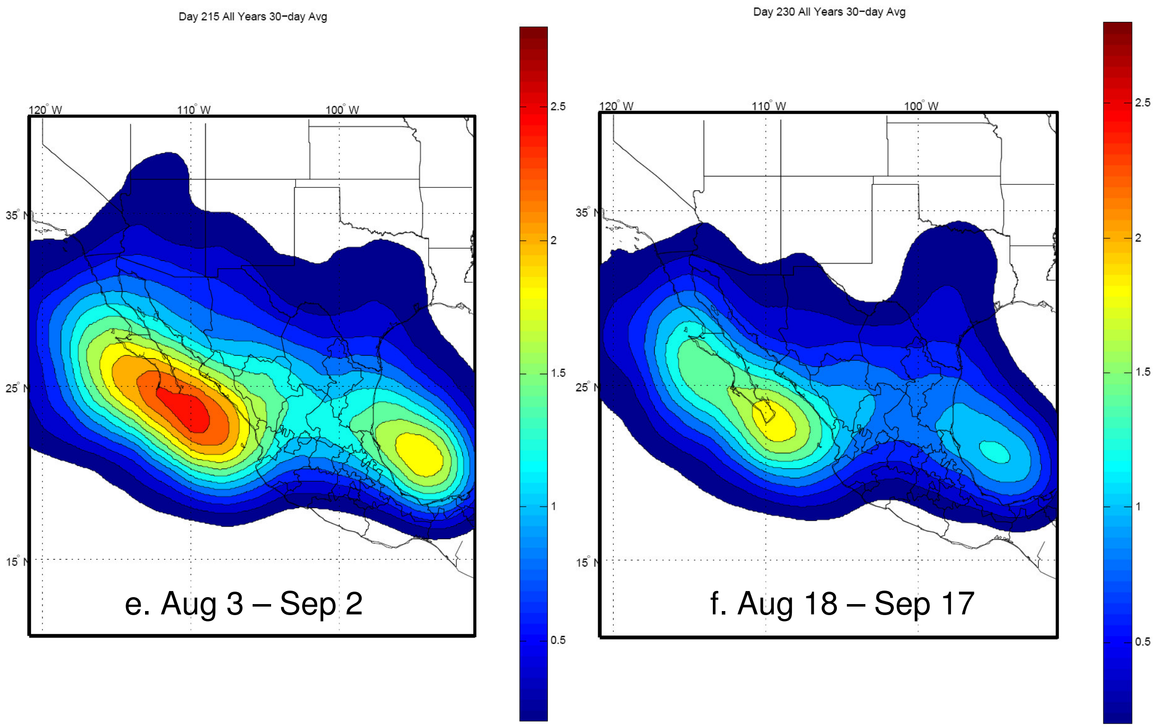
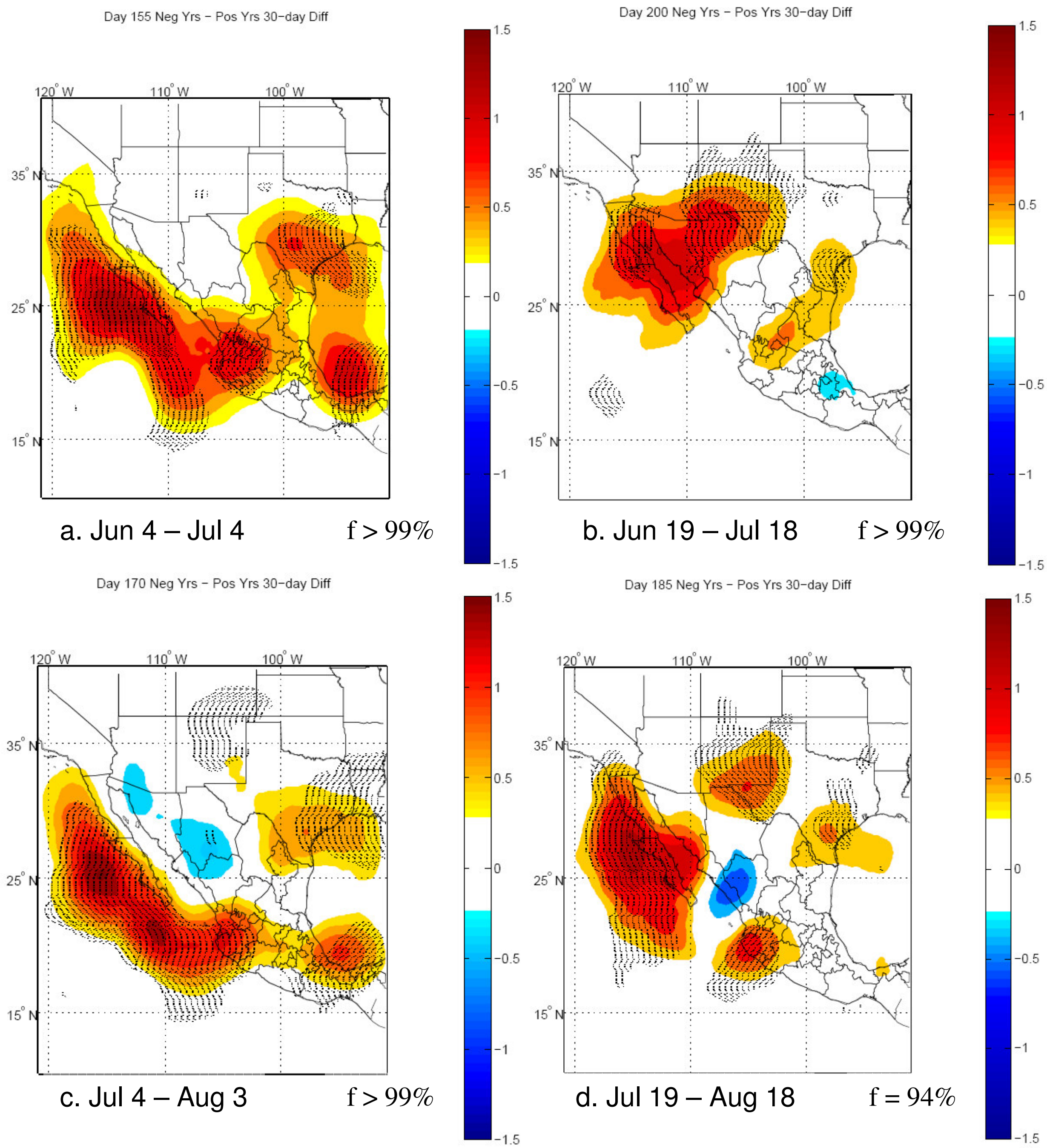


Figure 6a-f: Track density climatology for all years within the NAME Tier II Region using a 30-day average in units of total IVs/1°x1° grid cell. A data density equation was used where 1 was the center and a radius of 1 degree from the center was considered 0. One degree is equal to approximately 4 times the grid spacing of NARR, which was near the limit of physically resolved wavelengths in the dataset (Pielke, 1992). Dates are noted within each figure caption.


Day 155 Neg Yrs - Pos Yrs 30-day Diff
120° W
110° W
100° W
35° N
25° N
15° N
1.5
1
0.5
0
−0.5
−1
−1.5
a. Jun 4 – Jul 4
f > 99%
Day 200 Neg Yrs - Pos Yrs 30-day Diff
b. Jun 19 – Jul 18
f > 99%
Day 170 Neg Yrs - Pos Yrs 30-day Diff
c. Jul 4 – Aug 3
f > 99%
Day 185 Neg Yrs - Pos Yrs 30-day Diff
d. Jul 19 – Aug 18
f = 94%

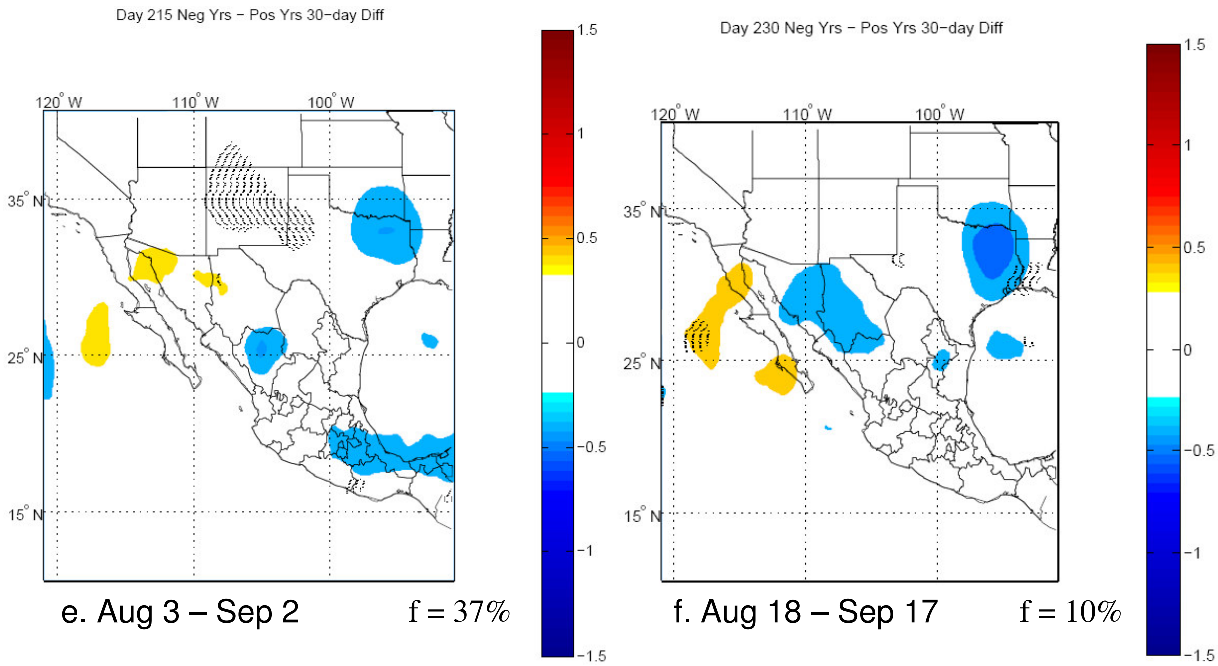


Figure 7a-f: Climatological track density difference for CPVM negative years minus CPVM positive years within the NAME Tier II Region using a 30-day average. Dates and field significance are noted within each figure caption, with stippling indicating 90% local significance.