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ANALYSIS OF AN UPPER-LEVEL INVERTED TROUGH DURING THE 2004 NORTH AMERICAN MONSOON EXPERIMENT

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1. INTRODUCTION

The North American Monsoon (NAM) is an important and complex atmospheric circulation that results in a pronounced increase in rainfall from a dry June to a rainy July over the southwestern United States and northwestern Mexico (Adams and Comrie 1997). The dramatic increase in rainfall is accompanied by a northward shift in the subtropical ridge at the end of June (Bryson and Lowry 1955, Douglas et al. 1993). Variability in the summertime convective activity over the NAM region results from complex interactions between synoptic and mesoscale processes.

One of the most important circulation systems to traverse the NAM region is the upper-level inverted trough (hereafter IV) associated with either midlatitude breaking Rossby waves or tropical upper-tropospheric troughs (TUTTs). IV disturbances have been observed to progress westward over the NAM region on the southern periphery of the subtropical ridge and impact weather over the southern United States and northern Mexico (Whitfield and Lyons 1992, Douglas and Englehart 2007).

Past studies of subtropical upper-tropospheric lows have been confined to areas outside of the NAM region (Erickson 1971, Kelley and Mock 1982, Whitfield and Lyons 1992). These studies showed that the cold anomaly extended from 200 hPa to the surface. The low circulation was primarily confined to the 700-100 mb layer with a cyclonic vorticity maximum around 200 hPa. Diagnosed vertical motion was rather small (by midlatitude standards), with a tendency for upward motion east of the low center and downward motion to the west.

Owing to the sparse observational network over northwestern Mexico, studies of upper-level IVs over the NAM region are limited. Douglas and Englehart (2007) found that IVs were the most prevalent synoptic feature over northern Mexico during the NAM season. After documenting rainfall in the proximity of numerous IVs, the authors discovered that rainfall was maximized to the west of the upper-level low. Bieda et al. (2009) indicated that lightning counts increase over the low deserts of southern Arizona and Sonora when an IV is located within their study domain. While these studies suggest that IVs are important contributors to the variability in rainfall and convection across the NAM region, there are many unanswered questions.

The 2004 North American Monsoon Experiment (NAME) field campaign provided an unprecedented observational sounding network over the NAM region. The primary objective of this study is to utilize gridded data from 2004 NAME to analyze a significant IV that passed over northwestern Mexico from 10-13 July 2004.

2. METHODS

2.1. NAME experimental network

The extended observing period (EOP) of the NAME field campaign was conducted from 1 June through 30 September 2004, although many instrumentation platforms were only operational from 1 July through 15 August. A tiered (nested) structure was developed for the 2004 field campaign with three nested domains (Fig. 1). The analyses in this study were conducted over the T2A domain (15°-40°N, 90°-120°W), which covered most of Mexico and the southwestern United States. The T2A domain consisted of rawinsonde sites operated by the U.S. National Weather Service (NWS) and the Mexico Weather Service (Servicio Meteorológico Nacional or SMN). Many of the sounding sites within the T2A domain increased their launch frequency during the nine intensive observing periods (IOPs).

2.2. NAME gridded dataset and IV identification

The quality controlled sounding data were objectively analyzed into a gridded dataset using the multiquadric interpolation scheme of Nuss and Titley (1994). The primary data source used in this study is Version 3.0 of the Colorado State

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University (CSU) - NAME gridded dataset over the T2A domain. Fields of horizontal wind components, temperature, specific humidity, and geopotential height were computed using the interpolation scheme at 1º horizontal resolution and 25 hPa vertical intervals. The T2A gridded analyses were produced at 0000 and 1200 UTC for the period 1 July to 15 August. NCEP Reanalysis data were applied to the data sparse oceanic regions of the Gulf of Mexico and Eastern Pacific. However, the reanalysis data was not applied to the interior T2A domain, where IV4 predominantly tracked (Fig. 2).

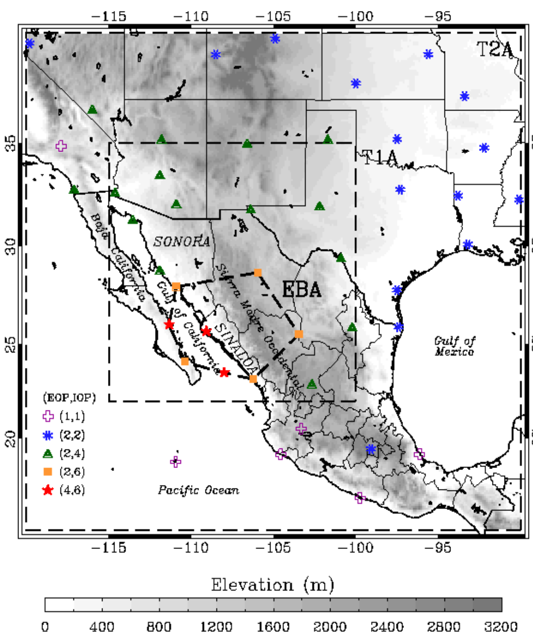

FIG 1. NAME rawinsonde sites over the T2A domain. The site symbol indicates the number of rawinsonde launches during the EOP and nine IOPs. Shaded contours represent elevation above sea level.

NAME forecasters at the Forecast Operations Center identified and numbered ten IVs from 1 July to 15 August. IV4 (10 July – 13 July) was one of two major IVs that tracked across the dense observational network in northwestern Mexico, the other being IV6 (21 July – 24 July). The position of IV4 was identified every twelve hours (0000 and 1200 UTC) by noting the location of the maximum 200-hPa relative vorticity in the T2A gridded dataset. The 200-hPa wind field had to describe a closed circulation at a synoptic time to be associated with IV4.

2.3 Quasi-geostrophic (QG) vertical motion

In order to investigate the QG vertical motion that is forced by the dry dynamics of IV4, the traditional QG omega equation (Bluestein 1992) is used. There are two terms on the right-hand side (RHS) of the omega equation: vertical differential vorticity advection and the horizontal Laplacian of temperature advection. The advantage of using the traditional form of the QG equation is that the contribution from the individual forcing terms to the total vertical velocity can be determined.

Homogeneous boundary conditions were applied (ω set to zero on the lateral and vertical boundaries of the computational domain). The "forcing" terms and omega values were solved for over the pressure layer between 700 and 100 hPa using an iterative relaxation scheme. The relaxation scheme continued until the greatest difference in ω between successive iterations was less than 10^{-3} Pa s^{-1} across the entire domain.

2.4. Vertical wind shear

In order to examine the influence of IV4 on vertical wind shear and convective organization, a shear algorithm was developed. For each grid point where the shear is calculated, the shear algorithm uses the surface pressure as the bottom pressure level. The mean winds at the lowest three pressure levels (i.e., surface, 25 hPa AGL, and 50 hPa AGL) are used to compute the surface wind conditions. Next, the algorithm calculates the average wind in the 3-6 km AGL layer. The wind shear vector can then be computed by subtracting the surface wind vector from the midlevel wind vector.

3. SYNOPTIC SETTING

Figure 2 illustrates the 200-hPa heights, wind vectors, and absolute vorticity at 1200 UTC 8 July – 13 July over the T2A domain. The time period encompasses 12 h before IV4 forms to the synoptic time at which IV4 dissipates. The two important synoptic features over this time period are IV4 and the subtropical high. At 1200 UTC 8 July, a kink in the height field, caused by a shortwave trough in the westerlies, develops over the Texas-Louisiana area to the east of the subtropical ridge over central Mexico (Fig. 2a). The 200-hPa circulation becomes better defined by 1200 UTC 9 July and the subtropical ridge axis builds northward to the west of the low (Fig. 2b). By 1200 UTC 10 July, the 200-hPa low circulation has become better defined with closed height contours over the western Gulf of Mexico (Fig. 2c). IV4 closes off in a manner similar to that suggested by Thorncroft et al. (1993), in which a closed low can form at the base of a thinning trough over the southern United States.

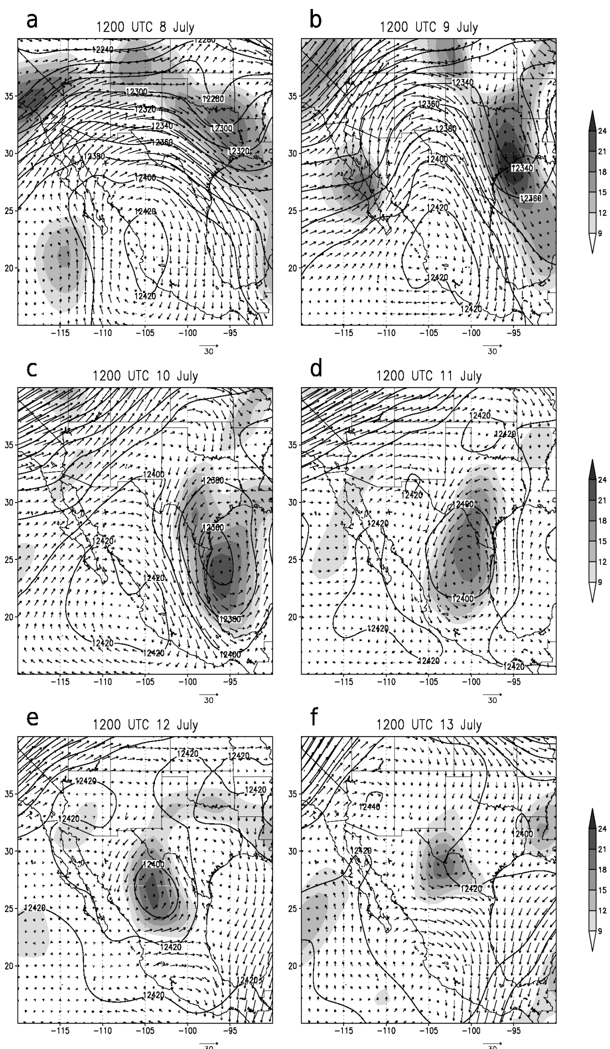

FIG 2. 200-hPa heights (m, solid contours), wind (m s^{-1}, vectors), and absolute vorticity (10^{-5} s^{-1}, shaded contours) at 1200 UTC 8-13 Jul 2004.

IV4 begins moving westward to a position over central Mexico at 1200 UTC 11 July (Fig. 2d). The upper-low's movement is likely linked to the northwest shifting of the subtropical ridge center to a position near Sonora. By 1200 UTC 12 July, IV4 is located just east of the SMO axis and the 200-hPa circulation remains strong (Fig. 2e). Heights continue to increase on the northwest flank of IV4 associated with the northward-moving subtropical ridge center. IV4 then moves northward to a position near Big Bend, Texas on 1200 UTC 13 July (Fig. 2f). The 200-hPa circulation has become ill-defined and there are no longer closed height contours at this level. This indicates a significantly weakened system and IV4 dissipated shortly thereafter. The average translational speed of IV4 over its lifetime is approximately 7 m s^{-1}.

4. RESULTS

4.1 Temperature

Figure 3 depicts the composite temperature anomaly in a west-east vertical cross section through the 200-hPa low center of IV4. The composite was computed by averaging over individual synoptic times in the period from 0000 UTC 9 July to 1200 UTC 13 July. The warm anomaly is confined above 150 hPa with a maximum of 4°C at 100 hPa. The cold anomaly associated with IV4 is not just an upper-level feature, as it extends into the midlevels. The vertical temperature structure of IV4 is in general agreement with the previous studies of subtropical upper-level lows over non-NAM regions (Erickson 1971, Kelley and Mock 1982, Whitfield and Lyons 1992).

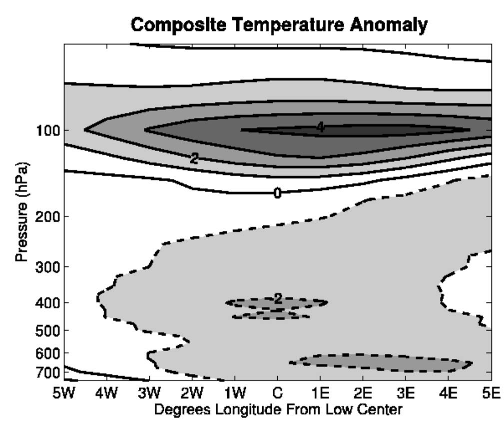

FIG 3. West-east vertical cross section of temperature anomaly (ºC) through the 200-hPa composite low center. Solid (dashed) contours represent positive (negative) anomalies. Longitudinal degrees are west (W) and east (E) of the 200-hPa low center (C).

The temperature anomaly time series for IV4 was also analyzed (not shown) The magnitude of the warm anomaly centered near 100 hPa remains relatively constant over the lifetime of IV4. However, the underlying cold anomaly exhibits a very different evolution. The cold anomaly is strongest at the beginning of the period, but weakens considerably with time. At 1200 UTC 10 July the cold anomaly near 400 hPa is -3ºC and extends weakly into the midtroposphere. As the low progresses westward across Mexico, the cold anomaly amplitude decreases steadily, becoming a neutral temperature anomaly by IV4 dissipation on 1200 UTC 13 July. The weakening of the cold anomaly is a feature of the upper and midtroposphere, at all pressure levels between 700 and 200 hPa.

4.2 Vorticity

In order to examine the vertical circulation of IV4, the relative vorticity through the composite 200-hPa low center is plotted in Fig. 4. The strongest relative vorticity of 14×10^{-5} s^{-1} is located over the low center at 200 hPa. This circulation maximum around 200 hPa was also found in Kelley and Mock (1982) and Whitfield and Lyons (1992). The circulation of IV4 decreases rapidly into the midlevels, with a relative vorticity less than 4×10^{-5} s^{-1} below 500 hPa. While there is a midlevel manifestation of IV4, the strongest circulation of the system is largely confined to upper levels.

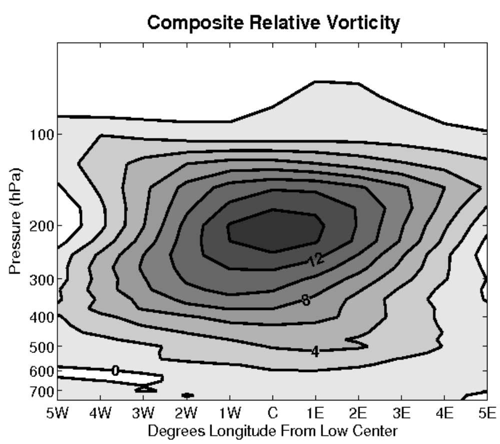

FIG 4. West-east vertical cross section of relative vorticity (10^{-5} s^{-1}) through the 200-hPa composite low center. Only positive (cyclonic) values are shaded. Longitudinal degrees are west (W) and east (E) of the 200-hPa low center (C).

A time series plot of relative vorticity (not shown) indicates that IV4's circulation weakens with time, especially at upper levels during the last day (13 July). At 1200 UTC 12 July the 200-hPa relative vorticity is greater than 8×10^{-5} s^{-1}, but decreases to 4×10^{-5} s^{-1} one day later. The upper-level circulation shows the most pronounced weakening starting at 0000 UTC 13 July, which corresponds to the time when IV4 reached the SMO axis and began moving northward. This suggests that topographic effects may play a role in the weakening, a notion proposed by Bieda et al. (2009). The time series of relative vorticity and temperature anomaly for IV4 are consistent with each other, indicating that IV4 became progressively weaker, especially at upper levels, as it moved across northwestern Mexico.

4.3 QG Vertical Motion

The composite total QG vertical motion (ω) for the 700-300 hPa layer associated with IV4 is shown in Fig. 5a. The general spatial pattern of ω indicates weak subsidence (weak rising motion) to the west (east) of the low center. The absolute magnitude of the ω values in Fig. 5a are relatively small. In his numerical analysis, Erickson (1971) found similar magnitudes for vertical motion around a subtopical upper-level cold low over the Bahamas. The small (by midlatitude standards) values of ω in the present study are not unrealistic for IV4 owing to the very weak temperature gradients in the vicinity of this synoptic scale subtropical disturbance (shown in Fig. 5d).

Figure 5b shows the calculated vertical motion associated with the differential vorticity advection term of the omega equation. Very weak rising motion occurs to the west of the low center with very weak subsidence to the east. The absolute magnitudes of ω in Fig. 8b are approximately three times smaller than the total QG ω. The QG ω associated with the Laplacian of temperature advection term is plotted in Fig. 5c. The spatial pattern of ω in Fig. 5c looks very similar to the total QG ω. A vertical profile of ω rms amplitude associated with the two RHS forcing terms was calculated (not shown). It was found that throughout the 700-300 hPa layer, the ω rms amplitude associated with the thermal advection term was three to four times larger than the vorticity advection term. We can conclude that thermal advection forcing is the dominant factor in the calculated total QG ω pattern for IV4. The results of this study are consistent with Erickson (1971), who found that the Laplacian of thermal advection was the single most important forcing function in the ω pattern.

The spatial pattern of vertical motion in Fig. 5c implies cold (warm) air advection in the 700-300 hPa layer to the west (east) of the low (Fig. 5d). The lowest temperatures are located at the low center (-8.8°C). Also evident in Fig. 8d is the weak temperature gradient in the vicinity of IV4, with slightly over 1°C rise in mean temperature from the low center to the outer fringes of the low. Hence, unlike baroclinic midlatitude systems, IV4 is a rather barotropic system.

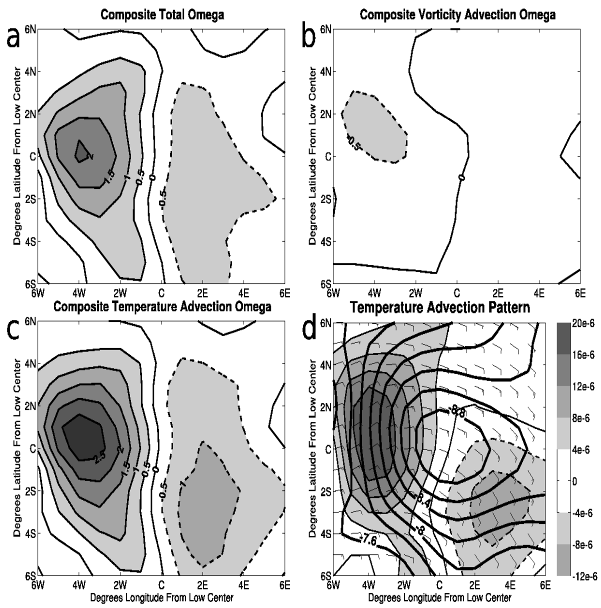

FIG 5. Plan view of vertically averaged (700-300 hPa) composite (a), total QG ω (b), QG ω from the vorticity advection term (c), QG ω from the temperature advection term, and (d) temperature (°C, thick solid contours), geostrophic wind (m s^{-1}, vectors), and geostrophic temperature advection (°C s^{-1}, thin contours shaded). QG ω fields have units 10^{-2} Pa s^{-1}. Solid (dashed) contours represent subsidence (rising motion) and cold (warm) air advection. Longitudinal degrees are west (W) and east (E), and latitudinal degrees are south (S) and north (N) of the 200-hPa low center (C).

From a dynamics standpoint, IV4 induces an unfavorable condition (subsidence) for convection to the west of its center. However, observations of infrared imagery indicate an increase in MCS activity over the SMO foothills and GOC coastal plain to the west of IV4. One has to conclude that IV4 modifies the convective environment in some other way that supports increased convective development and organization to the west of the low center.

4.4 Midlevel Winds and Shear

The Sierra Madre Occidental (SMO) is a prominent northwest-southeast oriented mountain range in western Mexico (Fig. 1). Convective initiation occurs during the afternoon over the SMO in northwestern Mexico. Although heating of the SMO triggers convection almost every afternoon during the NAM, not all days are characterized by precipitating features reaching the coastal lowlands of Sinaloa and Sonora (Fig. 1). However, some days are characterized by a tendency for precipitating systems to grow upscale, organize into mesoscale convective systems (MCSs), and propagate toward the coastal lowlands. Past studies indicate that increases in midlevel easterlies and vertical wind shear can promote MCS development over the NAM region (Smith and Gall 1989, Farfán and Zehnder 1994, Lang et al. 2007).

The composite midlevel (700-400 hPa) winds for IV4 are shown in Fig. 6a. Although vorticity is largest in the upper levels, Fig. 6a clearly indicates there is a midlevel cyclonic circulation associated with the upper-level potential vorticity (PV) anomaly. Midlevel winds are strong southeasterly (6.25 m s^{-1}) on the east side of IV4. The winds are weaker and turn more easterly near the center of the low. On the west (leading) flank of IV4, midlevel winds are primarily 5 m s^{-1} from the northeast.

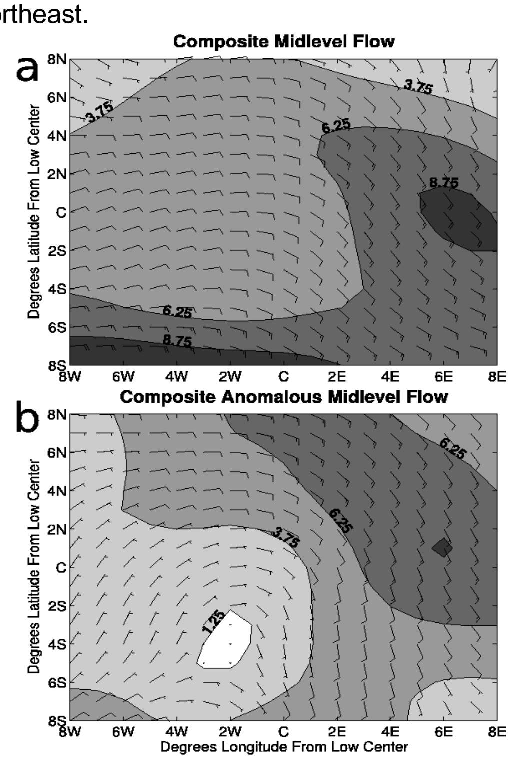

FIG 6. Plan view of vertically averaged (700-400 hPa) composite (a) midlevel winds, and (b) anomalous midlevel winds with wind speed (m s^{-1}, shaded) and wind vectors (full barb is 5 m s^{-1}, half barb is 2.5 m s^{-1}).

The remainder of this section examines the midlevel winds, vertical wind shear, and convective development near the SMO foothills at particular synoptic times associated with the IV passage. The analysis will focus on the western slopes of the SMO since that is where convective organization takes place during the NAM. Refer to Fig. 1 for the location of the two Mexican states of Sonora and Sinaloa.

Figure 7a shows the mean (1 July – 15 August 2004) midlevel winds and actual midlevel winds on 0000 UTC 10 July. IV4 is located well east (23°N, 94°W) of the domain and the midlevel wind pattern is dominated by the subtropical ridge centered over west Texas. This flow regime produces strong southerly midlevel winds over Sonora, not conducive for steering storms off the Sonoran high terrain. Due to the southerly midlevel flow, the shear vectors on 0000 UTC 10 July along the Sonoran foothills are largely parallel to the topographic gradient (Fig. 7b). The IR image from 0200 UTC 10 July (Fig. 7c) is consistent with the southerly midlevel flow. Thunderstorms initiate along the SMO peaks in Sonora, but the anomalous southwesterly midlevel winds and shear vectors in Sonora prevent significant propagation of the storms toward the west off the higher terrain.

The midlevel flow regime changes considerably by 0000 UTC 11 July compared to the previous day (Fig. 7d). IV4 (24°N,98°W) has moved closer to the SMO. Midlevel northeasterly winds, on the western flank of IV4, are impinging on Sinaloa. Over Sonora, the midlevel flow is much weaker. In accordance with the stronger northeasterly midlevel flow over Sinaloa, the shear vector increases in magnitude and becomes oriented off the SMO (Fig. 7e). An MCS develops along the SMO foothills south of 28°N by 0300 UTC 11 July (Fig. 7f). With the anomalous northeasterly steering flow and shear, the convection propagates farther southwest toward the GOC coastal plain compared to the previous day. Convection fails to organize over the SMO foothills of Sonora north of 28°N, in the area of substantially weaker midlevel flow and shear.

IV4 moves closer to the SMO foothills by 0000 UTC 12 July and is located at 25°N,103°W (Fig. 8a). The midlevel cyclonic manifestation of IV4 is clearly evident. Similar to the previous day, strong midlevel northeasterly flow is confined to the SMO foothills south of 28°N. With anomalous northeasterly steering flow and shear south of 28°N (Fig. 8b), convective organization occurs along the SMO foothills and GOC coastal plain by 0245 UTC 12 July (Fig. 8c). There is a lack of significant convective organization north of 28°N where the shear is much weaker.

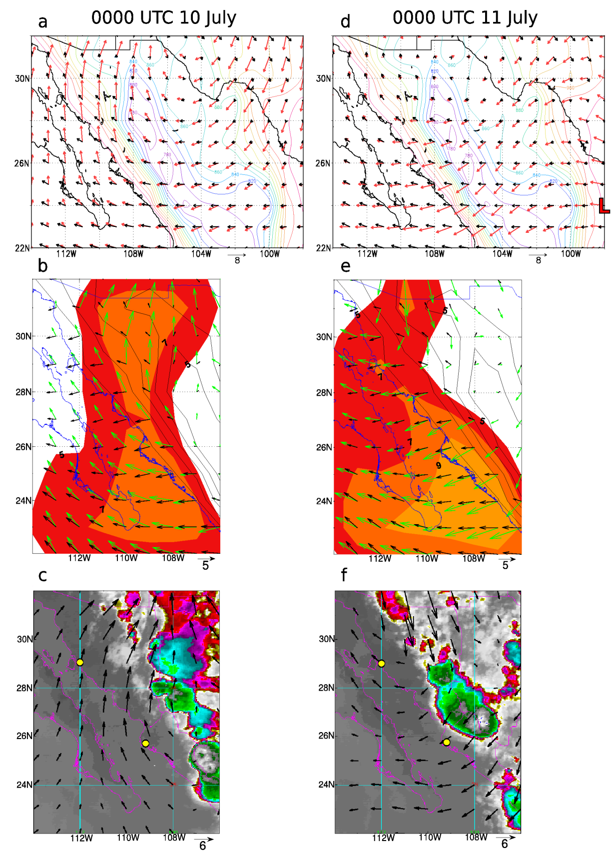

FIG 7. Mean midlevel winds (black vectors) and actual midlevel winds (orange vectors) at 0000 UTC (a) 10 Jul and (d) 11 Jul. The 200-hPa IV center is denoted by "L" and surface pressure is contoured. Mean shear (black vectors), actual shear (green vectors), and actual shear magnitude (shaded) at 0000 UTC (b) 10 Jul and (e) 11 Jul. Surface pressure (black contours) are plotted. GOES-10 IR image with anomalous shear vectors at (c) 0200 UTC 10 Jul and (f) 0300 UTC 11 Jul. Midlevel wind and shear have units m s^{-1}.

The midlevel wind environment over Sonora undergoes a significant change by 0000 UTC 13 July (Fig. 8d). IV4 has moved northwestward to 27°N,106°W inducing strong east-northeasterly midlevel flow over Sonora. There is a 2-4 m s^{-1} increase in shear along with a significant change (from southeasterly to northeasterly) in the direction of the shear vector over the Sonoran coastal plain (Fig. 8e). With the anomalous northeasterly shear now located over Sonora, a northerly shift in MCS development over the previous day is expected. By 0645 UTC 13 July, a significant MCS has organized over the Sonoran foothills in the region of anomalous northeasterly shear (Fig. 8f).

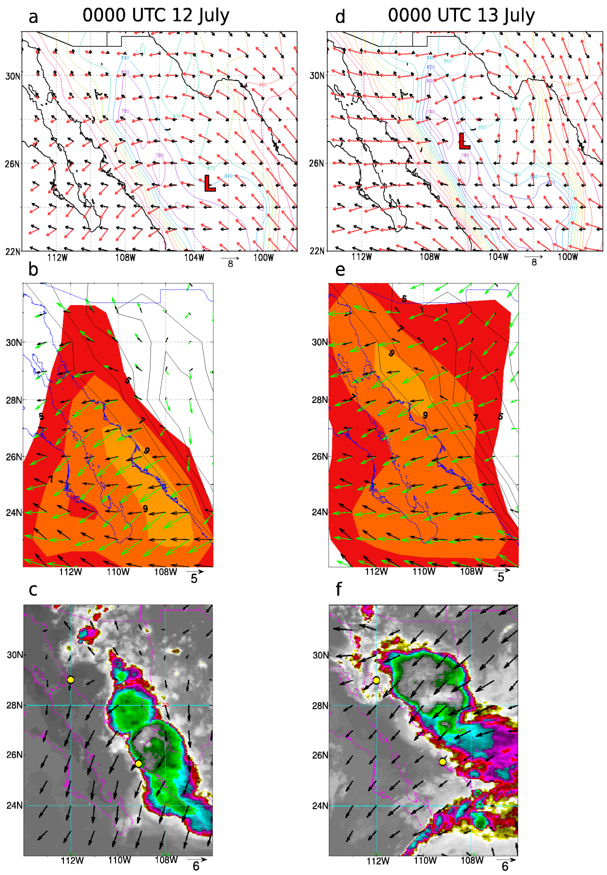

FIG 8. Same as Fig. 7, except for 0000 UTC 12 Jul and 13 Jul. The GOES-10 IR image is at (c) 0245 UTC 12 Jul and (f) 0645 UTC 13 Jul.

5. CONCLUSIONS

The upper-level IV is an important component of the NAM system that can modulate rainfall and convective activity over northwestern Mexico. Using the CSU-NAME gridded dataset, this study presented a detailed observational analysis of IV4, a significant IV that passed over northwestern Mexico from 10 – 13 July 2004.

IV4 developed at the base of a thinning shortwave trough over the south Texas Gulf coast region. The vertical temperature structure of IV4, with a warm anomaly maximum around 100 hPa and a cold anomaly that extended from 200 hPa into the midlevels, is in general agreement with previous subtropical upper-level low studies. The strongest circulation of the system was in the upper levels around 200 hPa, with a much weaker midlevel cyclonic circulation.

The spatial pattern of total QG omega forced by IV4 indicated weak subsidence (weak rising motion) to the west (east) of the low center. A partitioned analysis of vertical motion showed that the Laplacian of thermal advection overwhelmed the vorticity advection forcing term in the traditional QG omega equation. Cold (warm) air advection to the west (east) of IV4 produced the subsidence (rising motion) couplet. The midlevel cyclonic circulation of IV4 induced northeasterly (southeasterly) midlevel flow to the west (east) of IV4. Analysis of individual synoptic times revealed that IV4 affected the midlevel wind regime and environmental wind shear over the SMO foothills. Significant MCS activity along the SMO foothills was collocated with regions of northeasterly midlevel flow and anomalous northeasterly shear. In the presence of persistent diurnal forcing of convection over the SMO, midlevel northeasterly winds induced by the approaching IV4 provide a favorable environmental condition for convective organization to the west of the low, which overwhelms the effects of weak QG-forced subsidence.

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