Observational Analysis of an Upper-Level Inverted Trough during the 2004 North American Monsoon Experiment

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ABSTRACT

Upper-level inverted troughs (IVs) associated with midlatitude breaking Rossby waves or tropical upper-troposphere troughs (TUTTs) have been identified as important contributors to the variability of rainfall in the North American monsoon (NAM) region. However, little attention has been given to the dynamics of these systems owing to the sparse observational network over the NAM region. High temporal and spatial observations taken during the 2004 North American Monsoon Experiment (NAME) are utilized to analyze a significant IV that passed over northwestern Mexico from 10 to 13 July 2004. The Colorado State University gridded dataset, which is independent of model analysis over land, is the primary data source used in this study.

Results show that the 10–13 July IV disturbance was characterized by a warm anomaly around 100 hPa and a cold anomaly that extended from 200 to 700 hPa. The strongest cyclonic circulation was in the upper levels around 200 hPa. Quasigeostrophic (QG) diagnostics indicate that the upper-level low forced weak subsidence (weak rising motion) to the west (east) of its center. Net downward motion to the west was a result of the Laplacian of thermal advection (forcing subsidence) outweighing differential vorticity advection (forcing weak upward motion). Despite the QG forcing of downward motion west of the upper-level IV, enhanced convection occurred west of the IV center along the western slopes of the Sierra Madre Occidental (SMO). This seemingly contradictory behavior can be explained by noting that the upper-level IV induced a midlevel cyclonic circulation, with northeasterly (southeasterly) midlevel flow to the west (east) of its center. Increased mesoscale organization of convection along the SMO foothills was found to be collocated with IV-enhanced northeasterly midlevel flow and anomalous northeasterly shear on the western (leading) flank of the system. It is proposed that the upper-level IV increased the SMO-perpendicular midlevel flow as well as the wind shear, thereby creating an environment favorable for convective storms to grow upscale as they moved off the high terrain.

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). Douglas et al. (1993) show that western Mexico receives 60%–70% of annual precipitation during the 3-month period from July to September. 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), which causes midlevel winds over the NAM region to shift from southwesterly during June to southeasterly in July.

Variability in the summertime convective activity over the NAM region results from complex interactions between synoptic and mesoscale processes (Adams and Comrie 1997). Local topographic effects are critical to the spatial and temporal variability in convection. The Sierra Madre Occidental (SMO) is a prominent northwest–southeast-oriented mountain range in western Mexico (Fig. 1). Convective initiation typically 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, Mexico (Fig. 1). Lang et al. (2007) used radar data to classify undisturbed periods as those days when SMO convection does not survive the trip to the Gulf of California (GOC). Disturbed
days, on the other hand, are characterized by a tendency for precipitating systems to grow upscale, organize into mesoscale convective systems (MCSs), and coherently 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).

One of the most important circulation systems to traverse the NAM region is the upper-level inverted trough (IV) associated with either midlatitude breaking Rossby waves (Thorncroft et al. 1993) or tropical upper-tropospheric troughs (TUTTs; Sadler 1967). The 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). A common genesis area for IVs in the Gulf of Mexico and Atlantic is the North Atlantic TUTT, a narrow cyclonic shear zone that tilts west-southwestward from the central North Atlantic into the Gulf of Mexico. Another source of IV disturbances is from midlatitude Rossby waves that filament, break off, and propagate westward on the southern periphery of an upper-level anticyclone (Thorncroft et al. 1993).

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). Using a diagnostic numerical model, Erickson (1971) calculated the vertical motion pattern associated with a westward-moving upper-level cold low over the Bahamas. Diagnosed vertical motion was rather small (by midlatitude standards), with a tendency for upward motion east of the 200-hPa low and downward motion to the west. Moreover, the Laplacian of thermal advection was the most important forcing function in determining the total vertical motion pattern around the low.
Kelley and Mock (1982) used rawinsonde data from western North Pacific island stations to quantitatively determine the mean characteristics of subtropical upper-level cold lows found in the summertime mid-Pacific TUTT. They found that the cold anomaly was largest near 300 hPa and extended weakly to the surface while there was a warm anomaly maximum near 125 hPa directly over the low center. The low circulation was primarily confined to the layer between 700 and 100 hPa with a vorticity maximum around 200 hPa. The southwestern quadrant of the low was characterized by subsidence and relatively little cloudiness while the southeastern quadrant was characterized by ascent and more cloudiness.

A later study by Whitfield and Lyons (1992) examined a TUTT cold low that remained quasi-stationary over Texas in 1988. The results from this study were very similar to the findings from Kelley and Mock (1982). Using global gridded analyses, the strongest cold anomaly was found near 300 hPa within the TUTT low and the cold anomaly weakened downward to 700 hPa. The TUTT low circulation was strongest at 200 hPa. Moreover, anomalous subsidence was found near the center and along with the western flank of the low. Weak anomalous rising motion was found along the eastern flank.

Owing to the sparse observational network over northwestern Mexico, studies of upper-level IVs over the NAM region are limited. Douglas and Englehart (2007) developed a summer climatology of transient synoptic systems that moved across northern Mexico, with IVs (which the authors identified at 500 hPa) being the most prevalent synoptic feature. After documenting rainfall in the proximity of numerous IVs, the authors discovered that rainfall was maximized to the west of the IV. 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. A primary objective of this research is to utilize gridded data from NAME to analyze a significant IV (hereafter referred to as IV4 since it received that designation by the operational forecasters in NAME) that passed over northwestern Mexico from 10 to 13 July 2004. The results provide an unprecedented documentation of the thermodynamic and kinematic characteristics of an upper-level IV over the NAM region. The remainder of this paper is organized as follows. Section 2 describes data and methods relevant to the present research. Section 3 presents 200-hPa plots and water vapor imagery to diagnose the synoptic conditions in the vicinity of IV4. The temperature and vorticity structure of IV4 is detailed in section 4. Section 5 analyzes the quasigeostrophic (QG) vertical motion field forced by IV4 while section 6 examines midlevel winds and vertical wind shear induced by IV4. Finally, section 7 summarizes the most significant results from the study.

2. Data and methods

a. 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. The experiment’s primary objective was to determine the “sources and limits of predictability of warm season precipitation over North America, with an emphasis on time scales ranging from seasonal to interannual” (Higgins et al. 2006). Some of the complex circulation features examined by NAME are the GOC low-level jet, gulf surges, easterly waves, upper-level IVs, MCSs, and the diurnal cycle of convection. To accomplish these multifaceted goals, a tiered (nested) structure was developed for the 2004 field campaign with three nested domains (Fig. 1). The three nested domains (in increasing spatial dimensions) are the Enhanced Budget Array (EBA), Tier I Array (T1A), and the Tier II Array (T2A). 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 (SMN)]. Many of the sounding sites within the T2A domain increased their launch frequency during the nine intensive observing periods (IOPs). Of the 23 NWS supported sites, 10 sites launched four rawinsondes per day during IOPs. The SMN supported 13 sites, 5 (2) of which launched 6 (4) rawinsondes per day during IOPs. In addition to the NWS and SMN sounding sites, there were five additional sounding sites established along the GOC at Puerto Peñasco, Bahia Kino, Los Mochis, Loreto, and the Mexican Navy vessel R/V Altair. The Department of Defense provided launch sites at Edwards Air Force Base in California and Yuma, Arizona. There were also three National Center for Atmospheric Research (NCAR) Integrated Sounding Systems (ISSs), which operated at Puerto Peñasco, Bahia Kino, and Los Mochis.

Quality control procedures modeled after those used in Tropical Ocean Global Atmosphere Coupled
Ocean–Atmosphere Response Experiment (TOGA COARE; Loehrer et al. 1996) were performed on the raw NAME sounding data. The procedure includes automated internal consistency checks and the assignment of quality flags. After the assignment of quality flags, detailed quality control checks were conducted by the Colorado State University (CSU) Mesoscale Dynamics group. This included visually inspecting thermodynamic variables and vertical profiles of the $u$ and $v$ wind components using skew $T$–log$\rho$ plots (Johnson et al. 2007).

b. 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 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 1° horizontal resolution and 25-hPa vertical intervals. The T2A gridded analyses were produced at 0000 and 1200 UTC for the period 1 July–15 August. Profiler data from the three NCAR ISS sites and pibal soundings were merged into the gridded datasets at times when rawinsonde winds were unavailable. Moreover, observations from the aviation routine weather report (METAR) stations over land and Quick Scatterometer (QuikSCAT) winds over the ocean were incorporated into surface analyses (Ciesielski and Johnson 2008).

Because of the data-sparse ocean regions in the T2A domain, grid points over the eastern Pacific and Gulf of Mexico used National Centers for Environmental Prediction (NCEP)–NCAR reanalysis data (Kalnay et al. 1996). NCEP–NCAR reanalysis data were only applied to the large-scale T2A analyses so that mean-}

In the T2A gridded dataset. The 200-hPa wind field had to be IV6 (21 July–24 July).1 The position of IV4 was identified every 12 h (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.

c. QG vertical motion

To investigate the QG vertical motion ($\omega$) that is forced by the dry dynamics of IV4, the traditional QG omega equation (Bluestein 1992),

$$\left(\nabla^2_p + \frac{f^2}{\sigma p} \frac{\partial^2}{\partial p^2}\right) \omega = \frac{\sigma}{\sigma p} [\mathbf{v}_g \cdot \nabla_p (\xi_g + f)] + \frac{R}{\sigma p} \nabla^2_p (\mathbf{v}_g \cdot \nabla_p T),$$ (1)

is used where $\mathbf{v}_g$ is geostrophic wind, $\xi_g$ is geostrophic relative vorticity, $f$ is the Coriolis parameter, $\sigma$ is static stability, and $T$ is temperature. There are two terms on the right-hand side (rhs) of (1): vertical differential vorticity advection and the horizontal Laplacian of temperature advection. Given the two “forcing functions” along with the proper boundary conditions on $\omega$, the vertical motion field can be found at any time by inverting the operator on the left-hand side of (1). The advantage of using the traditional form of the QG omega equation is that the contribution from the individual forcing terms to the total vertical velocity can be determined.

Homogeneous boundary conditions were applied ($\omega$ set to zero on the lateral and vertical boundaries of the computational domain). The lateral boundaries were chosen to be far enough from the upper-level low center (7°E–W and 7°N–S) that the IV forcing of vertical motion would be negligible at those locations. The “forcing” terms and omega values were solved for over the pressure layer between 700 and 100 hPa using an iterative relaxation scheme. Using 700 hPa as the lower boundary ensures that the lower boundary is above the SMO at all times. The relaxation scheme continued until the greatest difference in $\omega$ between successive iterations was less than $10^{-3}$ Pa s$^{-1}$ across the entire domain.

d. Vertical wind shear and GOES satellite imagery

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

\footnote{1 Because of space limitations, only the results for IV4 are presented in this study. However, the results for IV6 are similar to those of IV4.}
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.
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. Because of uncertainties in the shear depth that is most important for MCS organization along the SMO foothills, the average wind over the 3–6-km AGL layer is chosen for the midlevel wind used in the shear calculation. The wind shear vector can then be computed by subtracting the surface wind vector from the midlevel wind vector.

To diagnose convection in the vicinity of IV4, the Geostationary Operational Environmental Satellite–10 (GOES-10) infrared (IR) data were obtained from the NAME field catalog (available online at http://catalog.eol.ucar.edu/name) over the NAM region. Of particular interest were convective development and organization along the SMO foothills and GOC coastal plain. The water vapor (WV) channel gives an indication of WV along the SMO foothills and GOC coastal plain. The water vapor (WV) channel gives an indication of WV in the mid to upper troposphere. Since IVs are largely upper-level features, GOES-12 WV imagery was useful in identifying the circulation of IV4.

3. Synoptic conditions

a. Upper-level flow

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, with a northwesterly 200-hPa jet on the trough’s west side (Fig. 2b). The subtropical ridge axis builds northward to the west of the low. 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. However, IV4 develops from a shortwave trough, which is different from the longwave northeast–southwest thinning trough considered in that study. 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 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, at 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$^{-1}$.

b. Convective conditions

The evolution of the convective conditions and upper-level moisture around IV4 can be seen from the WV images in Fig. 3. The WV images were selected to depict times when the convection appeared to have its greatest extent or intensity. Therefore, the times associated with the WV images do not necessarily match those in Fig. 2. During the initial formative stage of IV4 at 1209 UTC 9 July, the upper-level low center is characterized by relatively dry conditions (Fig. 3a). The MCS over the coastline of Louisiana is likely caused by the developing IV4. Two days later (1209 UTC 11 July) the low is located over east-central Mexico. The deepest convection, along with a developing MCS, occurs over the western Gulf of Mexico and along the Mexican Gulf coast to the east of IV4 (Fig. 3b). Extremely dry conditions in the upper troposphere are evident in the western part of the domain (Baja Peninsula and adjacent eastern Pacific) where strong southwesterly upper-level flow is advecting drier into that region.

By 0308 UTC 12 July, SMO convection organizes into a large MCS over the southern GOC coastal plain in Sinaloa (Fig. 3c). This marks the first time since the formation of IV4 on 9 July that deep convection reaches the GOC, as convection had largely been limited to higher elevations of the SMO before this date. Other important features include the large area of cloudiness and high moisture content to the southwest of IV4, which is associated with a developing tropical depression that later becomes Tropical Storm Blas. Convection appears to be suppressed in the low center with a relative minimum in moisture.

Deep convection on 13 July follows the northwestward progression of IV4. At 0609 UTC 13 July there is a developing MCS in northwest Sonora (Fig. 3d). The convective environment over the Sonora region must have become more favorable on this day to support organized convection. The initiation of a significant gulf surge that moved through Yuma at 1200 UTC 13 July is likely tied to this convective development over the GOC.
coastal plain (Rogers and Johnson 2007). Deep convection decreases to the east of IV4, although upper-level moisture and clouds encircle the low along its periphery. MCS development and propagation to the GOC coastal plain was more pronounced on 12 and 13 July. It is important to examine how the approach of IV4 may have modified the large-scale convective environment on these days (section 6b).
4. Vertical structure

a. Temperature

Figure 4 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. Pressure levels above 750 hPa are shown since this level is above the SMO at all times in the composite. There is a warm anomaly maximum of 4°C at 100 hPa slightly east of the low center. The warm anomaly is confined above 150 hPa and changes to a cold anomaly below this pressure level. An upper-level cold anomaly maximum is centered near 400 hPa over the composite low center. An additional cold anomaly maximum at 650 hPa is 1–3°C east of the center. 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).

The temperature anomaly time series for IV4 is shown in Fig. 5. 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 −3°C 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. The mechanism(s) for this weakening are uncertain.

b. Vorticity

To examine the vertical circulation of IV4, the relative vorticity through the composite 200-hPa low center is plotted in Fig. 6. The strongest relative vorticity of $14 \times 10^{-5}$ 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 $4 \times 10^{-5}$ 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. Figure 6 also suggests a slight eastward tilt in the system with height.

A time series of relative vorticity for IV4 is portrayed in Fig. 7. The plot 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 $8 \times 10^{-5}$ s$^{-1}$, but it decreases to $4 \times 10^{-5}$ s$^{-1}$ one day later. It is interesting that 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 (Fig. 2). This suggests that topographic effects may play a role in the weakening, a notion proposed by Bieda et al. (2009). Midlevel relative vorticity remains relatively constant with time. The time series of relative vorticity and temperature anomaly (Figs. 5 and 7) for IV4 are consistent with each other, indicating that IV4 became progressively weaker, especially at upper levels, as it moved across northwestern Mexico.

5. QG forcing of vertical motion

The composite total QG vertical motion ($\omega$) for the 700–300-hPa layer associated with IV4 is shown in Fig. 8a. The general spatial pattern of $\omega$ indicates weak subsidence (very weak rising motion) to the west (east) of the low center. Subsidence is maximized 4°W of the low while the rising motion maximum is located 2°E of the low. An analysis of the composite vertical motion at individual pressure levels reveals that $\omega$ is maximized in the upper levels around 300 hPa (not shown). The absolute magnitudes of the $\omega$ values in Fig. 8a are relatively small (an order of magnitude smaller than the mean $\omega$ inside the EBA; Johnson et al. 2007, see their Fig. 19). In his numerical analysis, Erickson (1971) found similar magnitudes for vertical motion around a subtropical upper-level cold low over the Bahamas. The small (by midlatitude standards) values of $\omega$ 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. 8d).

Figure 8b 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 $\omega$ in Fig. 8b are approximately 3 times smaller than the total QG $\omega$. The spatial pattern of $\omega$ in Fig. 8b is as expected with positive vorticity advection on the forward (west) flank of IV4 and negative vorticity advection on the trailing (east) flank of the low. However, the very small magnitudes of vertical motion in Fig. 8b indicate that the vertical derivative of vorticity advection is minimal over the layer examined in the vicinity of IV4.

The QG $\omega$ associated with the Laplacian of temperature advection term is plotted in Fig. 8c. The spatial pattern of $\omega$ in Fig. 8c looks very similar to the total QG $\omega$. A vertical profile of $\omega$ rms amplitude associated with the two rhs forcing terms was calculated (not shown). It was found that throughout the 700–300-hPa layer, the $\omega$ rms amplitude associated with the thermal advection term was 3–4 times larger than the vorticity advection term. We can conclude that thermal advection forcing is the dominant factor in the calculated total QG $\omega$ 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 $\omega$ pattern.

The spatial pattern of vertical motion in Fig. 8c implies cold (warm) air advection in the 700–300-hPa layer to the west (east) of the low (Fig. 8d). Cold air advection (CAA) is strongest 4°W of the low and warm air advection (WAA) is strongest 3°SE of the low. 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 a 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 embedded in an environment of very weak horizontal temperature gradients.

The general spatial pattern in total QG $\omega$ is in agreement with previous studies of subtropical upper-level lows over non-NAM regions (Erickson 1971; Kelley and Mock 1982; Whitfield and Lyons 1992) that showed subsidence (rising motion) to the west (east) of the low. Yet, it is seemingly contradictory to more recent NAM-related studies (Pytlak et al. 2005; Douglas and Englehart 2007) that indicate an increase in convective organization and rainfall to the west of an IV. Moreover, the total QG $\omega$ spatial pattern at 0000 UTC 12 and 13 July (Fig. 9) shows IV-forced subsidence in the areas of MCS activity over the SMO foothills and GOC coastal plain (Figs. 3c,d). From a dynamics standpoint, IV4 induces an unfavorable condition (subsidence) for convection to the west of its center. One has to conclude that IV4 modifies the connective environment in some other way that supports increased convective development and organization to the west of the low center.

6. Midlevel winds and shear impact on convection

a. Composite and anomalous midlevel flow

Figure 10a illustrates the composite midlevel (700–400 hPa) winds for IV4. In section 4 it was shown that the cyclonic vorticity (circulation) of IV4 was maximized near 200 hPa. Although vorticity is largest in the upper levels, Fig. 10a clearly indicates there is a midlevel cyclonic circulation associated with the upper-level potential vorticity (PV) anomaly. This is in agreement with Hoskins et al. (1985), who showed that a cyclonic upper-level PV anomaly induces a cyclonic circulation below. 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 east-northeast.
To highlight how the passing IV modifies the midlevel flow from mean monsoon conditions, Fig. 10b shows the composite anomalous midlevel winds. Average NAME midlevel flow over the latitudinal belt where IV4 passes is easterly to southeasterly. The anomalous midlevel cyclonic circulation induced by IV4 is apparent in Fig. 10b. On the trailing flank of IV4 there is a dramatic increase (6.25 m s\(^{-1}\)) in the southerly component of the midlevel flow. There is a slight increase (2.5 m s\(^{-1}\)) in the northerly and easterly component of the midlevel wind on the leading flank of the low center. Figure 10b also illustrates the horizontal scale of midlevel flow modification. IV4 modifies the midlevel flow extending 8\(^\circ\) E–W and 8\(^\circ\) N–S of the low center. It should be emphasized that IV4 does not act alone in determining the midlevel flow pattern. Rather, it is the interaction of IV4 and the subtropical ridge to the northwest (Fig. 2) that ultimately determines the midlevel flow in the vicinity of IV4. This modification of the midlevel flow pattern can affect the convective environment near the SMO.

Fig. 10. 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 composite period is 0000 UTC 11 Jul–1200 UTC 13 Jul 2004. Longitudinal degrees are west (W) and east (E), and latitudinal degrees are south (S) and north (N) of the 200-hPa low center (C).
b. Midlevel winds and shear at individual synoptic times

This section examines the midlevel (700–400 hPa) winds, vertical wind shear, and convective development near the SMO foothills at particular synoptic times associated with IV4 passage. By overlaying the average midlevel flow and average shear vectors, deviations from the average monsoonal conditions are readily apparent. Surface pressure contours are overlaid and serve as a proxy for elevation so that the midlevel wind and shear vector orientations with respect to the topographic gradient can be seen. 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 11a shows the mean (1 July–15 August 2004) midlevel winds and actual midlevel winds on 0000 UTC 10 July. The mean midlevel winds are east-southeasterly to southeasterly over the western slopes of the SMO. At 0000 UTC 10 July, IV4 is located well east (23°N, 94°W) of the domain. The midlevel wind pattern is dominated by the subtropical ridge centered over west Texas. This flow regime produces strong southerly midlevel winds over Sonora. Southerly and southeasterly midlevel flow is not conducive for steering storms, which initiate along the SMO peaks, off the Sonoran high terrain. Because of the southerly midlevel flow, the shear vectors at 0000 UTC 10 July along the Sonoran foothills are largely parallel to the topographic gradient (Fig. 11b). The IR image from 0200 UTC 10 July (Fig. 11c) is consistent with the southerly midlevel flow. Thunderstorms initiate along the SMO peaks in Sonora, but the anomalous southerly southerly 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. 11d). IV4, now located at 24°N, 98°W (center position designation with “L”), 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 very weak and not deviating from the average monsoonal conditions. In accordance with the stronger northeasterly midlevel flow over Sinaloa, the shear vector increases in magnitude and becomes oriented more normal to the topographic gradient in that locale (Fig. 11e). An MCS develops along the SMO foothills south of 28°N by 0300 UTC 11 July (Fig. 11f). 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. 12a). The cyclonic turning of the midlevel wind field in Fig. 12a is the midlevel cyclonic manifestation of IV4. Similar to the previous day, strong midlevel northeasterly flow is confined to the SMO foothills south of 28°N. The shear vectors south of 28°N are approximately the same magnitude as the previous day and oriented normal to the SMO axis (Fig. 12b). With anomalous northeasterly steering flow and shear south of 28°N, convective organization might be expected to occur in the same region. Indeed, a quite large MCS develops along the SMO foothills and GOC coastal plain by 0245 UTC 12 July (Fig. 12c). In the region of anomalous northeasterly shear, the MCS organizes and propagates southwestward all the way to the GOC coastline. There is a lack of significant convective organization north of 28°N where the shear is much weaker.

The midlevel wind environment over the SMO foothills north of 28°N undergoes a significant change by 0000 UTC 13 July (Fig. 12d). IV4 has moved northward to 27°N, 106°W, inducing strong east-northeasterly midlevel flow over Sonora. The midlevel wind speeds over Sonora are approximately 9 m s⁻¹ stronger than the previous day, which represents a substantial increase. 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. 12e). Also, note the corresponding 2 m s⁻¹ decrease in shear over the Sinaloan coastal plain. 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. 12f). South of 27°N, the convective cloud tops are much warmer, and convective organization is not as pronounced.

c. Mechanisms for convective organization on leading flank of IV4

To address the potential impact of IV4 on convective instability, several parameters were calculated at 0000 UTC 10–13 July from sounding data at Los Mochis and Bahia Kino and are shown in Tables 1 and 2, respectively. Significant convective development occurred over the GOC coastal plain near Los Mochis on 12 July (Fig. 12c) and there is a significant increase in convective available potential energy (CAPE) over previous days (Table 1). Moreover, Table 1 indicates that the increase in instability on 12 July is the result of an appreciable
FIG. 11. Mean midlevel (700–400 hPa) 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 of m s\(^{-1}\). Mean values are calculated over the period 1 Jul–15 Aug 2004. Yellow dots (Los Mochis, southernmost and Bahia Kino, northernmost) are locations in Tables 1 and 2, respectively.
FIG. 12. As in Fig. 11, but for 0000 UTC 12 Jul and 13 Jul 2004. The GOES-10 IR image is at (c) 0245 UTC 12 Jul and (f) 0645 UTC 13 Jul 2004.
surface moisture increase. The approach of IV4 does not significantly affect midlevel temperatures (and thus midlevel instability) throughout the period, which is consistent with the very weak temperature gradients surrounding IV4 (Fig. 8d). Table 2 illustrates a similar scenario for Bahia Kino on 13 July, the only day over the 10–13 July period that significant convective development occurred near that location (Fig. 12f). There is a substantial increase in CAPE on 13 July, which is again attributable to a surface moisture increase. Slight midlevel cooling (cf. 11–12 July) does not significantly increase midlevel instability (not shown). The northward-moving gulf surge (Rogers and Johnson 2007) likely contributed to the observed increases in low-level moisture at the two locations. Hence, while convective development along the GOC coastal plain is more pronounced on the days with increased instability, the midtropospheric thermodynamic influence of IV4 on this convection is minimal.

The increase in convective development on the western flank of IV4 is in agreement with previous NAM studies (Pytlak et al. 2005; Douglas and Englehart 2007). The present study does not attempt to explain all factors influencing convective development and evolution. Nevertheless, the connection between anomalous midlevel flow and shear and subsequent convective organization is readily apparent from the period considered. In general, areas of enhanced northeasterly midlevel flow and anomalous northeasterly shear correspond to regions of enhanced MCS development along the SMO foothills and GOC coastal plain. Significant 24-h changes in the midlevel wind field and shear vectors (most notably from 12 to 13 July over Sonora and Sinaloa) are accompanied by significant shifts in the location of MCS activity. These results support the positive relationship between shear and MCS activity over the NAM region found in other studies (Smith and Gall 1989; Farfán and Zehnder 1994; Lang et al. 2007).

Table 1. Summary of instability parameters at selected synoptic times at Los Mochis. Version 3.1 of the quality controlled sonde data at Los Mochis is used for the analysis. Both \( \theta_e \) and \( q \) are surface values; CAPE is surface-based. Midlevel mean (over the 700–300-hPa layer) temperature is also shown.

<table>
<thead>
<tr>
<th>Time UTC + day month</th>
<th>( \theta_e ) (K)</th>
<th>( q ) (g kg(^{-1}))</th>
<th>Midlevel mean ( T ) (°C)</th>
<th>CAPE (J kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 UTC 10 Jul</td>
<td>351</td>
<td>15</td>
<td>-6.2</td>
<td>964</td>
</tr>
<tr>
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<td>352</td>
<td>15.5</td>
<td>-6.2</td>
<td>1066</td>
</tr>
<tr>
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<td>-5.5</td>
<td>2438</td>
</tr>
<tr>
<td>0000 UTC 13 Jul</td>
<td>356</td>
<td>17.5</td>
<td>-6.7</td>
<td>1652</td>
</tr>
</tbody>
</table>

The interaction between IV4 and the subtropical ridge, along with the induction of a trough at midlevels by an upper-level PV anomaly (Hoskins et al. 1985), creates anomalous northeasterly midlevel flow on the western flank of IV4. This causes the steering flow vector and shear vector to become oriented more normal to the SMO axis. The northeasterly midlevel wind vector is an ideal orientation, above a southwesterly surface wind along the SMO slopes (Ciesielski and Johnson 2008), to maximize shear potential in the SMO foothills and GOC coastal plain. Thus, it is proposed that IV4, through this mechanism, creates an environment (on its leading flank) that is favorable for convective storms to grow upscale as they move off the high terrain of the SMO.

Previous studies (Hales 1972; Rogers and Johnson 2007) have suggested that gulf surge initiation is tied to the presence of large convective systems that reach the GOC coastline. The IVs could play an indirect role in surge initiation by creating a more favorable environment for such propagating convective systems on their western flank. A significant gulf surge did pass through Yuma on 1200 UTC 13 July. The surge occurred after significant MCS activity, and when IV4 was located to the east of the SMO foothills (Rogers and Johnson 2007).

Table 2. As in Table 1, but at Bahia Kino.

<table>
<thead>
<tr>
<th>Time UTC + day month</th>
<th>( \theta_e ) (K)</th>
<th>( q ) (g kg(^{-1}))</th>
<th>Midlevel mean ( T ) (°C)</th>
<th>CAPE (J kg(^{-1}))</th>
</tr>
</thead>
<tbody>
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<td>-6.8</td>
<td>3157</td>
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</tbody>
</table>

7. Summary and conclusions

The upper-level inverted trough (IV) is an important component of the NAM system that can modulate rainfall and convective activity over northwestern Mexico. Past detailed studies of subtropical upper-level lows have been confined to areas outside the North American monsoon (NAM) region. The spatial and temporal resolution of the 2004 North American Monsoon Experiment (NAME) observational network was sufficient to explore several aspects of an IV over the NAM region. Using the CSU–NAME grid dataset, this study presented a detailed observational analysis of IV4, a significant IV that passed over northwestern Mexico from 10 to 13 July 2004.

IV4 developed at the base of a thinning shortwave trough over the south Texas Gulf Coast region. The system then moved westward across northwestern Mexico with a strengthening subtropical ridge to the northwest of IV4. 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. While much weaker than the upper-level circulation, there was also an associated midlevel cyclonic circulation. IV4 showed a steady weakening trend over its lifetime with more pronounced weakening as the system reached the SMO axis.

The spatial pattern of total quasigeostrophic (QG) omega forced by IV4 indicated weak subsidence (weak rising motion) to the west (east) of the low center. Magnitudes of vertical motion in the vicinity of IV4 were smaller than midlatitude baroclinic systems owing to weak temperature gradients within the system. 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 vertical motion couplet. The midlevel cyclonic circulation of IV4 induced northeasterly (southeastern) 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.

This paper presents results for one IV during the 2004 NAME. It is uncertain the extent to which these conclusions hold for other IVs over the NAM region. However, the study is unprecedented in examining several midlevel IVs. Future studies of IVs should help to clarify the effects that these important systems have on the variability of the NAM system.

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