Diagnosing an Operational Numerical Model Using Q-Vector and Potential Vorticity Concepts

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ABSTRACT

A quasigeostrophic (QG) diagnostic model is used to evaluate the nested grid model's (NGM) predictions for a December cyclone whose impact on northeastern Colorado was underpredicted. Although the NGM predicted deepening of the associated 500-mb low, the model was 12 h slow in the onset of deepening and moved the storm too far east too quickly. Synthetic soundings, generated from 12-h predicted data initialized 24 h before cyclogenesis became apparent, were submitted to the same QG diagnostic algorithms used to analyze verifying rawinsonde data. Comparisons reveal that the NGM apparently 1) transported too much potential vorticity, westerly momentum, and cold air into the lower troposphere along the axis of the jet stream; 2) moved the first of two short-wavelength jet streaks too far northeastward and with too much strength; 3) failed to predict the strength of the following jet maximum; and 4) failed to develop an apparent tropopause fold. It is established that these errors were not caused by obvious discrepancies in the model's initialization. Through inference, the errors could have been caused by rapid growth of subtle, undetected initialization errors or by the model's inadequate parameterization of some physical process—perhaps of turbulent dissipation over mountainous terrain. Diagnosis of the model's subsequent initialization (12 h after its first erroneous prediction) indicates that the model did not have available crucial Mexican soundings that might have prevented it from making a similar error in predicting the position and strength of the then-intensifying cyclone. The diagnostic results could have alerted forecasters not only to the presence of the complex jet stream but also to the extent and intensity of its associated tropopause fold. Furthermore, QG diagnostics can alert forecasters to model errors that are not made obvious by conventional model comparisons.

1. Introduction

Winter storms that develop in association with cutoff lows over Arizona are a familiar forecasting problem for Denver-area forecasters (Howard and Tollerud 1988). In spite of available historical knowledge concerning these storms, the wide variety of scenarios that can develop out of each case presents a dilemma to forecasters, especially when relatively small differences in numerical model guidance can mean the difference between forecasting a light snowfall or an intense blizzard. The Christmas weekend storm in 1987 was just such a case (Barnes and Colman 1993, henceforth BC93).

In BC93, descriptive and diagnostic details are presented covering more than 72 h of the storm's track across the contiguous United States. The case concerns a complex jet structure whose jet-streak circulations are diagnosed without having to infer them on the basis of the usual conceptual model. In section 2, a synopsis of the storm's influence on Colorado is presented. In section 3, the methodology for applying quasigeostrophic (QG) theory and potential vorticity (PV) concepts in diagnosing jet streak circulations is discussed. On the basis of analyses of the nested grid model's (NGM's) initial data for three synoptic times (from 1200 UTC 25 December through 1200 UTC 26 December), it will be shown in section 4 that the cyclone ended one extrusion of high PV air into the midtroposphere and began another, thus contributing to the redevelopment of the storm that struck northeastern Colorado. The diagnostic fields that identify the jet stream's transverse circulations also explain the descent of stratospheric air and the development of an upper-tropospheric frontal zone.

In section 5, 1200 UTC 26 December rawinsonde data obtained prior to the storm's redevelopment are used to determine how well the NGM's 12-h model guidance verified. Discrepancies in the forecast are noted, and both cross sections and maps of diagnostic variables are used to evaluate why the model erred. In

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section 6, factors that may have contributed to the poor quality of the NGM's subsequent model run (based on 1200 UTC 26 December data) are traced to problems in its initialization, again by comparing diagnostics based mainly on observations with those based on synthetic NGM soundings. In this regard, delayed observations from northern Mexico (analyzed after the fact) played a crucial role. In section 7, the limitations of the diagnostic methodology are discussed and concluding remarks are offered.

The diagnosis and interpretations presented here are the result of an intensive and lengthy research. The techniques by which the knowledge was gained were not available to Denver forecasters in 1987. In the discussion that follows, the authors allude to information that forecasters may and may not have known at the time. The particular facts upon which forecasters based their predictions are not known. The methodology used here is recommended as one of many tools that forecasters might use in future analyses of model gridpoint data. Certainly, a more comprehensive analysis using additional diagnostic parameters might reveal ageostrophic circulations more completely. Nonetheless, the parameters suggested in this paper have the advantage of being easily computed and are relatively easy to interpret.

The reader should keep in mind that there are limitations to what a diagnostic scheme based on rawinsonde data can determine about interactions between jet streaks, the tropopause, and their effects in the lower troposphere. Because development of upper-tropospheric fronts occurs on a scale that cannot be analyzed in detail from rawinsonde data alone, many of the authors' interpretations of the diagnostic parameters are reached through inference. Although the evidence concerning tropopause folding and the development of upper fronts is presented as "hard" evidence, the authors admit there is room for alternative interpretations.

2. Synoptic overview

On Christmas night (Friday, 0000 UTC 26 December, henceforth, 26/0000), a subtropical jet was advecting moisture northeastward over the southern Great Plains, while midlevel clouds were developing near a 500-mb low over Arizona (Fig. 1). At 300 mb (Fig. 2), a polar jet streak had merged with the subtropical jet, producing winds greater than 75 m s\(^{-1}\) (>150 kt) on the southeast flank of the intense cutoff low. A shallow polar air mass lay over the Great Plains from the Texas coast to the Dakotas (Fig. 3). Sleet and freezing rain were pelting parts of Oklahoma, Kansas, and Missouri, while "upslope" snow was falling over the Texas Panhandle and the eastern plains of New Mexico and Colorado. Only showers and light snow were associated with the upper low in Arizona.

Although the threat to Colorado made Denver forecasters wary, that evening's NGM (Phillips 1979) filled the 500-mb cyclone during the first 24 h (Fig. 4) and then deepened it significantly between 24 and 36 h. Several factors lessened prospects for a major event in Colorado: 1) deepening was to take place well to the east of Colorado in central Kansas, 2) the surface polar front was far to the southeast of Colorado (Fig. 3), and

![Fig. 1. The 500-mb heights (dam) and simulated satellite IR imagery at 0000 UTC 26 December 1987. Isohyps (solid lines) are at 60-m intervals; isotherms (dashed) are at 5°C intervals. Winds are indicated by bars (5 m s\(^{-1}\)) and flags (25 m s\(^{-1}\)). Cloud-top temperatures (°C) are indicated by shadings at bottom. DEN marks location of Denver, Colorado. Other station designators are identified in text.](image1)

![Fig. 2. National Meteorological Center analysis of 300-mb heights (dam; solid lines), temperatures (°C; thick dashed lines), and winds for 0000 UTC 26 December 1987. Isotachs (thin dashed lines) are at 20-kt (=10 m s\(^{-1}\)) intervals. Shadings indicate wind speeds between 70-110 kt (=36-57 m s\(^{-1}\)) and greater than 150 kt (greater than 77 m s\(^{-1}\)).](image2)
3) the jet stream was focusing its weather-producing energy on Oklahoma and Arkansas. It is, therefore, understandable that Denver forecasters were not expecting a significant snowstorm in northeastern Colorado. Furthermore, the predicted deepening was not to occur for another 36 h—ample time to post warnings, if needed, after evaluating Saturday morning’s model run.

As it turned out, snow fell in northeastern Colorado for more than 40 h beginning midmorning on Saturday, 26 December and ending early on Monday, 28 December. The storm, which began as a quiet, gentle snowfall on Saturday, turned into a blizzard on Sunday. Snow accumulated to depths of 25–30 cm on the plains of eastern Colorado, and 51–107 cm at locations in and adjacent to the Denver area. Coincident with the storm center’s deepening in northeast New Mexico on Saturday evening (27/0000), the Denver forecast office began issuing the appropriate advisories and warnings (Dunn 1989, personal communication). Neither Friday evening’s (26/0000) nor Saturday morning’s (26/1200) NGM run predicted the storm’s track correctly (Hatten 1988).

3. Diagnostic methodology

Typically, forecasters interpret numerical model guidance and observations based on the magnitudes and patterns of conventional model variables: for example, pressure heights, 1000–500-mb thickness, vorticity, vertical motion, humidity distribution, and water equivalent of model-generated precipitation. Although forecasters understand that numerical models have idiosyncrasies and biases, they frequently look for consensus in predictions from two or more models. Small differences between model predictions and between model guidance and observed variables often may leave a forecaster with little more than a hunch concerning the impact that these differences might have on the evolution of a cyclone, for example. Only recently have advances been made in quantifying the effects that small differences in initial conditions have on numerical model results (Toth and Kalnay 1993). A forecaster, on the other hand, has very few tools to aid in evaluating the impact of small, but often important, differences. The techniques presented here can provide forecasters with information that is more dynamically sensitive than the conventional approaches. The methodology no longer focuses on an evaluation of conventional scalar fields or on application of qualitative conceptual models of atmospheric systems. Instead, the methodology emphasizes the visualization of atmospheric processes made possible by quantification of derived, higher-order field variables based upon quasigeostrophic theory, using the conventional aids as background information against which to view the visualized processes. Ultimately, interpretations of the diagnostic fields are necessarily qualitative but are based on a clearer impression of the atmosphere’s three-dimensional processes. The techniques employed enable a forecaster to monitor some of the dynamic processes that are simulated by numerical models and that influence observed data in significant ways.

Following a conventional approach with the impending storm in this case, forecasters may have applied the conceptual model of ageostrophic motions based upon the two-dimensional aspects of a straight, confluent–diluent wind maximum. [For a schematic of this model, see Kocin and Uccellini (1990) or Uccellini (1990).] As a general qualitative concept, this model often is useful for determining where significant upward motions occur in relation to jet streaks (Beebe and
Bates 1955). In the upper troposphere, air generally flows through an area of maximum winds, accelerating and decelerating as it does so. These accelerations induce thermally direct and indirect ageostrophic circulations transverse to the jet axis. Upstream from the jet maximum (the entrance region), a thermally direct circulation causes the cold air on the left of the jet axis to subside and the warmer air on the right side to rise. Downstream from the jet maximum (the exit region) lies an indirect circulation with rising motion on the cold left side of the axis, and descent on the right. However, as noted by those and other authors (Moore and VanKnoe 1992; Uccellini et al. 1984; Shapiro and Kennedy 1981), simple two-dimensional confluent–diffluent dynamics do not explain entirely the ageostrophic motions associated with jet streaks. Air circulates not only in planes transverse to a jet axis but along the axis as well. Newton (1954) stressed the importance of three-dimensional aspects of jet-streak ageostrophic circulations by showing that the indirect, exit-region circulation is most important in the formation of upper-level fronts. Shapiro (1981) established the importance of geostrophic shearing deformation acting on an along-stream temperature gradient in the formation of jet-front systems. Furthermore, forecasters are not always confronted with simple jet stream structures, as in the case of two jet streams merging (Hakim and Uccellini 1992), or when multiple jet streaks appear in close proximity. These complexities limit the general applicability of the conceptual jet-streak model and the correct visualization of the associated vertical motions.

Quasigeostrophic theory provides a basis for evaluating vertical motions associated with midlatitude cyclones. The Q-vector approach (Hoskins et al. 1978) has proven to be particularly adaptable to operational use (Sellers and Hoskins 1990) and is especially helpful in identifying transverse circulations associated with jet streaks, since it includes the effects of cross-front geostrophic wind shear that Shapiro (1981) found to be an important factor in the formation of upper fronts. These jet-front circulations are largely responsible for folds (downward bulges and breaks) in the tropopause and for the extrusion of stratospheric PV into the midtroposphere (Reed and Danielsen 1959). Once there, the extruded high PV air often interacts with lower-tropospheric circulations to produce deep tropospheric cyclogenesis (Gyakum 1983; Hoskins et al. 1985; Uccellini 1990). The diagnostic variable that identifies these cross-front circulations is the divergence of the Q-vector component locally perpendicular to isotherms (also isentropes) on a constant pressure surface (∇ · Qₙ; Keyser et al. 1988).¹

¹ Divergence of the Q-component along isotherms (∇ · Qₙ) reflects the movement of thermal troughs and ridges and acts to rotate isotherms without changing the magnitude of the temperature gradient.

Quasigeostrophic forcing can be represented by a pseudo-vertical-motion parameter Q₀/σ, which is 2h∇·Q divided by the net static stability in the layer for which Q has been computed. Static stability is σ = −h(∂θ/∂p), where ∂θ ≅ θ is the difference in potential temperature from the top to the bottom of the layer, and h = (R/p)(p/p₀)³ with k = R/c_p = 0.286. Tapp (1988) indicates that the distribution of this parameter provides a reasonable approximation to the actual vertical motion one obtains by solving the QG omega equation with σ varying three-dimensionally. Similarly, Q₀/σ and Q₀/σ represent the cross-isotherm and along-isotherm components of total QG vertical motion.

The diagnostic information presented next is obtained from a four-layer QG diagnostic model that uses height information from five mandatory pressure levels (850, 700, 500, 300, and 200 mb) analyzed to a 26 × 25 horizontal grid at 190.5-km intervals. Layer thicknesses are converted to layer-mean potential temperatures (θ) whose values are assigned to the mean pressure surface in each layer.²

Other Q-vector and PV diagnostics throughout the storm’s influence on Colorado are described in BC93. Their findings indicate that a tropopause fold and the potential for redevelopment of the old cutoff cyclone were evident in the observed data 12 h before the onset of significant deepening Saturday evening (27/0000). Here, cross sections through the PV extrusion and jet axis will be used to illustrate the conditions in the cyclone 24 h prior to its redevelopment. Cross-section variables are extracted along selected grid lines (constrained to be approximately north–south or west–east) and are contoured using bilinear interpolation to a finer vertical mesh. Ideally, cross sections should be selected along a perpendicular to the mean isotherms and jet axis but the software was not designed to be that versatile. The utilized cross sections approximate perpendicularity.

4. Initialization

On Friday evening (24 h before cyclogenesis was obvious), forecasters knew that a jet maximum had been analyzed south of Colorado in southwestern 300-mb flow (Fig. 2). They might also have noticed that the tropopause had already sagged below the 300-mb level, as was evident by the pocket of warm air over Baja California. The −30° and −35°C isotherms indicate the warm-advective and cold-advective couplet that is characteristic of a downward protruberance of the tropopause in the vicinity of an upper-level jet streak (Hirschberg and Fritsch 1991a,b). On the same chart is an indication of a secondary speed maximum

² For discussion purposes, mean pressure levels are referenced to the nearest 50 mb.
This downward motion in the left entrance quadrant of the secondary jet maximum (Fig. 2) is consistent with a thermally direct circulation (cold-air subsiding).

Readers familiar with the appearance of the total Q field in the vicinity of an upper-tropospheric cyclone (Fig. 6) will recognize the direct circulation southwest of the 700–500-mb thermal center as the vectors directed at an angle across isotherms toward warmer air. However, the locations of this circulation’s up and down branches are not exactly clear. Analysis of the \( Q_n \) components and \( F_{Q,s}/\sigma \) (Fig. 7) makes this more obvious. The downward branch (DD) is over northern Baja California, and the upward branch (DU) lies over the Pacific Ocean southwest of the DD branch. From Figs. 5 and 7, we infer that the direct downward branch has vertical continuity from the stratosphere to at least the midtroposphere. This is an important consideration in the prospects for later cyclogenesis, as discussed at the end of this section.

Downstream from the principal (150 kt) jet maximum (Fig. 2), the presence of a thermally indirect circulation (cold air rising, warm air descending) is indicated by those \( Q \) vectors (Fig. 6) that have a component across isotherms from warm to cold air, increasing then decreasing from right to left across the jet axis. The impression one gets from a cursory evaluation of the \( Q \)-vector pattern is that the two jet maxima are combining to produce a single quadrupole structure of direct- and indirect-circulation branches, according to the conceptual model of a simple jet streak. The \( Q_n \) vectors over New Mexico (Fig. 7) indicate a broad, strong indirect upward (IU) circulation, with weaker subsidence in the warm air (ID) over

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3 Some authors (e.g., Uccellini 1990) use 1 ppu = \( 10^{-5} \) K m \( \text{mb}^{-1} \) s \( ^{-1} \), which are related to the indicated units by a factor of approximately 10 m \( \text{s}^{-2} \), the acceleration due to gravity. These units may be more useful to forecasters, since they suggest the defining units of PV: static stability times absolute vorticity. The reader can easily convert the units used here to “operational” units by multiplying the former by 10.

4 Nominally, PV is a conserved tracer of air parcels for a dry adiabatic, inviscid process. Computed changes in PV magnitude may be due to the fact that the NGM initializations do not attempt to conserve PV from run to run.

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FIG. 5. Track of potential vorticity maxima on 295 K isentropic surface. Plotting model indicated at upper left includes day and hour of observed maximum and highest pressure at which stratospheric PV (\( \geq 2.0 \) ppu) was found. Potential vorticity values are based on NGM initial winds from C-grid data. Arrows show direction PV maxima moved. Lines I08, I10, and J09 refer to transects mentioned in later figures.

FIG. 6. The \( Q \) vectors for 700–500-mb layer and isotherms (K) of layer-mean potential temperature at 0000 UTC 26 December 1987, based on a mix of rawinsonde observations and synthetic soundings from NGM initial C-grid data. The \( Q \)-vector scaling shown by size of heads: small are to scale one grid length = \( 10^{-12} \) m \( \text{s}^{-1} \) \( \text{mb}^{-1} \); medium are one-half scale; large are one-sixth scale. Vectors terminate at grid points. Grid points are 190.5 km apart at 60°N. Thin lines locate transects I08, I10, and J09.
Texas. However, closer inspection of the area between the two jet maxima reveals a more complex structure of cross-isotherm circulations. Both jet maxima exhibit direct and indirect transverse circulations, just as would be expected on the basis of theory. In fact, the switch in direction of $Q_v$ along the jet axis provides information for positioning the jet maxima, which should lie at the points where the indirect circulations change to direct circulations. Thus, we have some basis (in lieu of wind observations) for locating the primary and secondary jet maxima as shown in Fig. 7. The position of $J_1$ is the same as that shown in Fig. 2, but $J_2$ is closer to Baja California than is indicated by Fig. 2.

The direct circulation associated with $J_1$ is confined to a small entrance region over northwestern Mexico. The indirect circulation associated with $J_2$ is found over the Gulf of California, the upward branch being but a spur off of the main IU center in New Mexico. Without a quantitative diagnosis (such as Fig. 7), it is improbable that forecasters could have ascertained the strengths of these circulations, or whether in fact they even existed.

The influence of $J_2$ is further illustrated in Fig. 8, which is a north-south transect through the PV maximum (along 108 in Figs. 5–7). The transect ranges horizontally 3620 km from Alberta (ALB), Canada, on the left to the Gulf of California (GOC) on the right. Vertically, it indicates the variation of mean conditions in four layers between 850 and 200 mb. The distribution of layer-mean PV is indicated by shadings that range from 1 pvu over the GOC at 600 mb to greater than 8 pvu over Arizona at 250 mb in the stratosphere. Over the GOC near 600 mb, the shape of the tropopause has been distorted downward in the descending branch of the indirect thermal circulation, shown schematically by the looping arrow. This type of circulation contributes to a strengthening of the upper front in the area between the two highlighted isentropes, although in these layer-mean depictions the exact location of the front is not obvious. At 400 mb over the GOC, part of the DD branch of the principal jet is found. This combination of direct and indirect branches is similar to the mean circulations inferred by Danielsen (1968) from a number of aircraft flights through folds in the tropopause. The combination is also similar to the circulations associated with a cold-air-advecting jet streak based on primitive equation model results described by Keyser and Pecnick (1985, p. 1279). In their model, an indirect circulation tilts the isentropes more toward the vertical, thus contributing to frontogenesis. The direct circulation decreases potential energy in the system in order to

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Footnote: Because mean values of PV are computed over rather deep layers, values greater than 1 pvu are considered arbitrarily to represent stratospheric air in this and similar figures. Layer averaging also accounts for the fact that PV on the 296 K surface in Fig. 8 is only about 2 pvu over southern Arizona, and this surface is not close to 460 mb as one would expect based on the higher-resolution information presented in Fig. 5.
maintain or increase kinetic energy of the upper-level jet associated with the developing frontal zone. They further point out that maximum subsidence is found on the warm side of the developing frontal zone, as it appears to be in Fig. 8. Horizontal separation of the upper and lower circulations is seen clearly in Fig. 7 by the different orientations of the $Q_v$ vectors in Mexico just east of the 108 transect. Both of these downward branches transport PV and westerly momentum into the midtroposphere (Shapiro 1981).

In summary then, the analyses presented in Figs. 5–8 indicate that stratospheric PV extends into the midtroposphere well below 400 mb over Arizona and Mexico. The principal thermally indirect upward motion center is found over New Mexico but its extension into Mexico is interpreted as a redevelopment of the upper front caused by the secondary jet maximum. With regard to the possibility of cyclogenesis, the authors attribute the following significance to the evidence. When a jet stream advects colder air along its axis, stratospheric air descends along the upper frontal zone into the midtroposphere. Some of that air then moves along cyclonically curved horizontal trajectories that eventually ascend east of the cyclone (Muller and Fuelberg 1990). There, the air mass marked by high PV can be stretched to increase relative vorticity, which augments deepening of a cyclone, especially when a low-level diabatic source of PV is present in the same area. These concepts have been described in detail in Gyakum (1983), Hoskins et al. (1985), and Uccellini (1990), and they are consistent with details of the storm's evolution as described in BC93. Conceivably, this is the process by which the NGM is attempting to deepen the 500-mb low after 36 h. Next, we consider evidence that the NGM forecast is off track after only 12 h.

5. NGM 12-h prediction versus observed conditions

While forecasters in Colorado waited for the numerical guidance based on Saturday morning's observations, they might have looked at the 26/1200 observations and the previous night's 12-h prediction from a different perspective. First, an analysis of observed PV would have indicated that the maximum they had been tracking on the 295 K surface continued to descend to 475 mb (Fig. 5) and a new 2.6-pv u center had appeared over the Arizona–New Mexico border at a higher altitude (at 425 mb; Fig. 5). This new extrusion of stratospheric PV is found in the same location that the main IUU branch was found 12 h earlier (Fig. 7). The previously inferred upper-frontogenesis along 108 (Fig. 8) supports this evidence of a new tropopause fold.

a. Comparison of 850-mb data

Saturday morning's rawinsonde observations (26/1200) provided the first opportunity to check quantitatively whether the previous night's NGM prediction was on track. Predicted 850-mb data for the area southeast of Colorado are shown in Fig. 9a. A low height center is predicted northwest of Stephenville (72260, SEP), Texas, but observations (Fig. 9b) indicate that the low is centered southwest rather than northwest of SEP, and extrapolating from the three nearby reports, the observed central height is 10–25 m higher than predicted. The NGM has pushed a cold
front to the east of SEP (west wind 10 m s\(^{-1}\) and 9°C temperature difference between central and eastern Texas), but SEP reports a southeast wind of 10 m s\(^{-1}\) and the temperature is 5.5°C warmer than predicted. The 850-mb cold front is only just east of Del Rio (72261; DRT), Texas. The predicted 850-mb frontal position is just west of an inverted trough in sea level pressure (BC93; Fig. 7a), which suggests the front is overrunning the shallow surface polar air mass and is more vertically oriented (more baroclinic) than the observations indicate. This NGM run brings the low-level system northeastward too fast and too deep. At the same time, the 500-mb central height was predicted to rise 21 m (see Fig. 4).

b. Comparison along cross sections

Figure 10 reveals that the NGM-predicted 600-mb temperature is 3 K too cold over the Texas Panhandle (at “C”). In general, observed 850–500-mb thicknesses increased over New Mexico and the Texas Panhandle (reflected also in the +90-m height rise observed over Arizona; see “12” position in Fig. 4). The NGM heights did not rise as much; its prediction of the 500-mb cyclone’s central height is 69 m too low. Comparisons of predicted synthetic soundings with two observations in the Texas Panhandle also indicate errors of −36 and −55 m. This is consistent with the NGM’s known cold bias in 1000–500-mb thickness in this region (Smith and Mullen 1993), but the magnitude is considerably larger than the mean error over cyclone centers that Smith and Mullen found (their Table 5, −28 m at 24 h). This suggests that something other than model bias is involved in the errors.

Figure 10 also shows that the NGM has too much PV over New Mexico below 400 mb (differences > 0.4 ppu). The combination of excessive midtropospheric PV with predicted low-level PV in excess of 1 ppu in west Texas (not shown) may account for the NGM’s deepening of the 850-mb low (Fig. 9a). The low-level PV (also observed) was associated with a north–south baroclinic zone in the surface polar air mass along the western edge of the Great Plains.

The indication in Fig. 9a that the NGM placed the 850-mb cold front in eastern Texas is corroborated in the layer-mean \(\theta\) differences in Fig. 10. At 800 mb (850–700-mb layer), the NGM has too strong a \(\theta\) gradient between Oklahoma and Arkansas (J08 cuts along the southern Oklahoma border on into southern Arkansas; see Fig. 6). With warmer air to the east, this too indicates a cold front in this layer. With regard to the potential for cyclogenesis in Kansas, the NGM is too warm at 800 mb over Arkansas and Mississippi, which suggests that the model is bringing warm, moist air from the Gulf of Mexico northward too fast (see also Fig. 9).

Along a north–south cross section (Fig. 11) through the new PV maximum (110 in Figs. 5 and 6) and across the jet-stream axis (but not perpendicular to the isotherms of layer-mean \(\theta\)), the morning rawinonde observations indicate that the spur of the 1U branch no longer exists. Instead, there is now a DD branch at 600 mb over northern Mexico (lower half of inset figure, central portion). The location of this DD branch appears to be in the exit region of the 300-mb jet maximum, according to its location on the NMC’s Limited Fine-Mesh two-dot (LFM · ·) analysis (shaded “J”). However, this location is not in accord with the conceptual jet-stream model and implies an error in the LFM · · analysis. The NMC’s Northern Hemisphere optimal interpolation analysis (not shown) places the 300-mb jet maximum more correctly near Midland (72265; MAF in Fig. 1), Texas. On the basis of the diagnosed transverse circulations, the authors believe that a jet maximum (“J”) lies over the Big Bend area of Texas where the jet axis crosses the interface between the direct and indirect circulations—that is, where \(Q_p\) reverses direction from the cold side of the jet axis to the warm side. Transect 110 does not extend far enough south to see the associated upward branch of the thermally direct circulation but that branch is just visible in the southeast and southwest corners of the inset figure. The authors believe (for reasons to be explained later) that this jet maximum \((J)\) probably is the \(J_2\) jet maximum noted earlier off Baja California (Fig. 7) and that the \(J_1\) jet maximum has moved northeastward toward Oklahoma.

In Fig. 11, the observed PV anomaly no longer protrudes below 600 mb and the DD branch fills the entire troposphere, maximum descent being near 400 mb. The NGM 12-h forecast along the same transect (Fig. 12) also has a direct circulation over Mexico but places the center of this circulation (zero isolach) two grid points farther to the north at 400 mb and has maximum descent at 600 mb. This difference is not due to the noted phase error in the prediction. Inspection of north–south cross sections to the east and west of 110 show that the NGM simply has too much PV at and below 600 mb all along the north side of the jet axis.

In summary, considering the diagnostics presented in Figs. 10–12, the NGM prediction has not developed the thermally direct circulation correctly. According to its scenario, the DD branch has extruded too much PV and cold air into the lower and middle troposphere, and the maximum descent is placed too low, which the authors infer to mean that the evolution of this branch has progressed too fast (assuming that when the tropopause folds the region of maximum downward motion propagates downward with time). According to Shapiro (1981), the DD branch also transports high values of absolute momentum, which in this case means too much westerly momentum in the middle and lower troposphere. This might account for the NGM’s pushing the 850-mb cold front into eastern Texas (Fig. 9a).
c. Comparison of lapse rates

Support for the just-described interpretations of the NGM prediction is provided from analyses of data that are independent of the QG diagnostic computations—predicted and observed temperature lapse rate. Forecasters usually rely on rawinsonde data plotted on a thermodynamic chart to assess the descent of stratospheric air and the strength of the associated upper front. The typical signature of this process is the lowering of a strong, dry inversion near the tropopause to the midtropospheric over the period between soundings (12 h). While such charts may give a forecaster an impression of what is happening in the vicinity of a few stations, it is not easy to visualize how these disparate pieces of information fit into the overall structure of a storm. In this regard, the authors have found that a more useful chart is obtained by mapping lapse rates computed from reported temperatures at 700 and 500 mb, for example, divided by the thickness of the layer. From the authors’ experience in evaluating such lapse rate maps, different airstreams often can be identified as centers of greater and lesser static stability. In the lower troposphere (near 850 mb), fronts are generally found at the “less stable” edge of a zone of lapse-rate gradient. In the midtroposphere, fronts typically lie along an axis (ridge) of maximum stability. In both layers, the front’s baroclinicity is characterized by the strength of the lapse-rate gradient on the cold-air side of the front. Lapse rates in the cold air are more stable in the lower layer and less stable in the middle layer.

In Fig. 13, lapse rates for the layers 700–500 mb \((a,b)\) and 300–200 mb \((c,d)\) are mapped. In the observed 700–500-mb distribution (Fig. 13b), the cold cyclone is indicated as the less stable air over Arizona. Over the GOC lies “more stable” air near the position of the midtropospheric front inferred from Fig. 11. The mean position of this front (in the layer) is denoted by the line B–B’. This position is consistent with (on the cold air side of) the position of the front at 700 mb (not shown). The prediction (Fig. 13a) indicates greater stability in both the cyclone and in the de-
Fig. 11. Verifying analysis along transect 110 at 1200 UTC 26 December 1987. Layer-mean PV is indicated by shaded areas (legend at bottom; $10^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$); layer-mean $\theta$ is indicated by dotted lines at 4 K intervals (296 and 304 K are highlighted by dashed stippling and oblique hatching, respectively); $F_{Q\alpha}$ is indicated by the more vertical solid and dashed lines at intervals of $8 \times 10^{-15}$ mb s$^{-1}$ m$^{-2}$. Thermally direct circulation centered near 400 mb over Mexico (MEX) is shown schematically by the shaded, looping arrow. Two-letter abbreviations represent states; "ALB" is Alberta, Canada; "NM" lies at the intersection of 110 and 109 in the inset figure. Inset figure: $F_{Q\alpha}$ is indicated at 600 mb (same time) over the southwestern United States and Mexico. Vector scaling as in Fig. 6. The heavy curved arrow is jet axis at 300 mb; shaded "J" denotes jet maximum according to NMC's LFM analysis. Solid "J" denotes the jet maximum according to the change from indirect to direct transverse circulations. Types of branches are indicated by two-letter designations in shaded boxes: "DD" is direct downward branch, "IU" is indirect upward branch, etc. Transect 110 cuts the jet axis along the column of vectors identified as H10.

scended stratospheric air associated with the upper front (A–A'), suggesting in both areas that the model atmosphere has subsided (reduced potential energy) more than observed. Consequently, the gradient of lapse rate between the upper front and the cyclone is larger in the prediction than is observed. Furthermore, the predicted zone of largest lapse-rate gradient extends farther northeastward (toward MAF in Fig. 1) than it does in the observed distribution, suggesting that the model has produced excess frontogenesis consistent with its rapid advance of the dominant jet maximum into that area. The observations, on the other hand, seem to indicate a split in the strength of the upper front, with the old front in Mexico hanging back south of the cyclone and a new front developing in New Mexico. This too is consistent with the observed lowering of a new PV maximum in western New Mexico at this time (Fig. 5).

There is support for this interpretation from the lapse-rate structure in the layer containing the tropopause—in this case, the 300–200-mb layer (Fig. 13d). The more stable lapse rates over Arizona are an indication of stratospheric air. The less stable lapse rates over Oklahoma and Arkansas indicate tropospheric air. Between the two areas lies a gradient of lapse rate that is indicative of the general position of the tropopause in this layer. The orientation of this gradient suggests that the intersection of the tropopause with this layer is along a north-northeast to south-southwest line near the New Mexico–Texas border. The wavellike shape of
the lapse-rate isopleths in this area is indicative of a perturbation (folding?) of the tropopause.

The NGM prediction (Fig. 13c) fails to capture the correct orientation and strength of the near-tropopause lapse-rate gradient. This same discrepancy is seen in a comparison of predicted and observed geostrophic potential vorticity (Figs. 14a,b, generated in conjunction with the QG diagnostic algorithms rather than from the high-resolution NGM gridpoint data). These two fields show the distribution of stratospheric values of PV. Figure 14b also indicates that, in this layer, the tropopause intersects 250 mb over western Texas (most likely, between the 1- and 2-pv isopleths), and again the orientation is observed to be more north–south than the NGM has it. Note that the observed PV (Fig. 14b) also indicates the wavelike perturbation in the height of the tropopause mentioned in regard to Fig. 13d, suggesting that lapse rates less than about 6.5°C km⁻¹ in this layer may be a reasonable surrogate for a PV analysis near the tropopause.

The same characteristics of tropopause orientation and position are seen also in the pattern of the thermally indirect circulation at 250 mb (Fig. 14d). The central value of the NGM’s IU branch (Fig. 14c) is considerably weaker than observed. Also, the predicted gradient between the upward and downward (ID) branches is weaker over western Kansas, the Texas Panhandle, and New Mexico, and the observed isopleths are oriented in a more northerly direction.

Finally, there are additional clues in Figs. 13a,b that suggest that the Kansas cyclogenesis may not take place as predicted. Lapse rates have not increased over Kansas (5.5°C km⁻¹ versus predicted values greater than 6.5°C km⁻¹), and at 700 mb, 6 g kg⁻¹ air has not been transported (or upwelled) as far north as predicted (stippled areas). Rather, moisture maximizes over northeast Texas, just north of a zone where, at 850 mb (Fig. 9b), there appears to be a warm front. Apparently, the NGM has not handled the retreat of the polar air mass correctly either.

d. Comparison of total QG forcing and its along-isotherm component

Analyses of the total QG forcing and its $F_{Q}/\sigma$ com-
Fig. 13. Predicted (left) and observed (right) lapse rate and mixing ratio in the midtroposphere and near tropopause for 1200 UTC 26 December 1987. In (a) and (b), solid lines indicate 700-500-mb lapse rate at intervals of 0.5°C km⁻¹, and dashed lines are 700-mb mixing ratio (g kg⁻¹); stippling indicates values greater than 6 g kg⁻¹. Broad lines A-A' and B-B' indicate mean position of upper front in the layer. (Dashing indicates less confidence in analyzed position.) In (c) and (d), solid lines indicate 300-200-mb lapse rate at intervals of 1°C km⁻¹ and dashed lines are 500-mb mixing ratio at intervals of 0.5 g kg⁻¹.

ponent help us to understand what the NGM has done in this case. Figure 15a shows the NGM's QG vertical motion parameter $F_\varphi/\sigma$ in the 700-500-mb layer for Saturday morning's prediction (26/1200). The model indicates two areas of upward motion, one over north-central Mexico and a stronger one where the borders of Colorado, New Mexico, and Oklahoma meet. These upward motion centers indicate that the NGM has two short-wavelength, midtropospheric disturbances in its solution, with the more northerly of the two having more energy. This interpretation is confirmed by the analysis of $F_\varphi/\sigma$ for the same layer (Fig. 15c), which more clearly identifies the locations and strengths of the two waves. The NGM has taken the principal jet maximum ($J_1$ in Fig. 7) too far into Oklahoma and has swung the weaker secondary jet ($J_2$) into northwestern Mexico. In fact, forecasters could have learned from Saturday morning's diagnoses based on the observations (Figs. 15b,d) that the disturbance caused by $J_1$ had not quite reached Oklahoma, and $J_2$ had become the stronger of the two and moved into north-central Mexico approaching the Texas border. These results support placement of the (new) principal jet maximum over the Big Bend area of Texas as was done in Fig. 11 (inset).

The NGM 12-h guidance also misplaces the downward branch of the direct circulation (DD) that trails the new jet maximum (see Figs. 14c,d and Figs. 15a,b). As mentioned before, this branch is the main conduit for descending stratospheric air. Certainly, the observed location of this high momentum, high-PV air beneath the axis of the jet (Fig. 14d and Fig. 15b) is more favorable for advecting PV into the developing cyclone than is the predicted position of this branch (which is in northwesterly flow southwest of the cyclone center; Figs. 14c and 15a).

6. NGM initialization, 26/1200

All of the information just discussed could have been available to forecasters on that Saturday morning be-
fore the current model run was available. When guidance did become available, it indicated a similar scenario for the cyclone's development in Kansas. What might forecasters have learned from a QG diagnosis of the NGM initial (26/1200) data? Unfortunately, the conclusion reached here—that the initialization was faulty—could not have been reached by forecasters due to missing observations from Mexico.

The NMC's message appended to the 1435 UTC radar summary chart did not indicate that Mexican observations were missing from the initialization for 26/1200 but only two Mexican observations appeared on the Northern Hemisphere analysis (not shown)—Empalme (76256; GYM) and Mazatlan (76458). On the other hand, the analyses of observed data presented in Fig. 11 and Figs. 13–15 are based on five (of six) Mexican rawinsonde observations obtained after the fact from the National Climatic Data Center (NCDC) archive (only Chihuahua, Mexico, remained missing).

Comparison of these analyses with analyses based on NGM initial 26/1200 data indicated that the NGM's geopotential heights in Mexico were different by greater than 20 m at 700 mb and greater than 60 m at 200 mb. Comparison of rawinsonde observations with synthetic soundings for stations south of the missing Chihuahua data revealed similar errors. At the same time, the NGM's 500-mb heights at GYM were 50 m lower than observed, which resulted in the placement of a trough over the GOC. These errors appear to have entered the NGM's initialization because of its dependence, in lieu of the delayed observations, on the NMC's regional optimal interpolation analysis (as depicted on NCDC's Northern Hemisphere charts). A QG diagnosis of the NGM initial 26/1200 mandatory height data indicates that the storm's upper-tropospheric energy was divided between two short waves—one just east of GYM (ahead of its 300-mb trough) and one over the Texas Panhandle. Both of these cen-
Fig. 15. (a) Predicted and (b) observed total QG vertical motion ($F_{QG}/\sigma$; $10^{-3}$ mb s$^{-1}$ m$^{-2}$) at 600 mb for 1200 UTC 26 December 1987 and its (c) predicted and (d) observed along-isotherm component ($F_{QG}/\sigma$). Scaling of $Q_{c}$ vectors is given in Fig. 6.

Hinders (identified in the $F_{QG}/\sigma$ fields; not shown) were 20%-30% weaker than the observed waves (Fig. 15d). Furthermore, the wave over Mexico was located southwest of El Paso (72270; ELP in Fig. 1), Texas, rather than southeast as observed. The NGM initial PV distribution over Mexico at 400 mb was similarly in error, indicating a lobe of stratospheric PV along the GOC trough when in fact (Fig. 14b) it should have been in the vicinity of Chihuahua (MCV in Fig. 1). Thus, this NGM run started with too little energy and vorticity in the vicinity of ELP.

As for the misplaced jet maximum in the LFM analysis mentioned in section 5, (over the GOC; shaded "J" in Fig. 11 inset), comparison of observations near the jet axis with synthetic soundings generated from the NGM initial 26/1200 data indicates that its 300-mb winds were too slow by 5–6 m s$^{-1}$ (10–12 kt) at El Paso and Midland and too fast by 7 m s$^{-1}$ (14 kt) at Empalme. The Midland observation reported a speed of 74 m s$^{-1}$ (144 kt), while Empalme reported only 56 m s$^{-1}$ (109 kt). This misplacement of the jet maximum is consistent with the NGM's poor height initialization in the vicinity of Chihuahua.

Missing data were not the source of the NGM's initialization problem from Kansas to Mississippi. There, at 700 mb, the NGM initial data for 26/1200 had heights about 10 m too high and temperatures 1°–2°C too warm, producing a more intense height gradient (stronger winds) over east Texas and Arkansas than observed. The 1200 UTC initial NGM synthetic sounding at SEP (Fig. 9) had a temperature that was 4.4°C too cold, which produced a significant temperature gradient between SEP and the stations immediately to the east. The suggestion is, of course, that the initial NGM analysis had the cold front too far to the east in Texas, a representation that is curiously similar to the NGM 12-h predicted data for that time (see Fig. 9a). Figure 16, illustrating the total QG vertical motion...
Fig. 16. Total 600-mb QG vertical motion $F_{Q}/\sigma \times 10^{-5}$ mb s$^{-1}$ m$^{-2}$ computed from NGM's initial C-grid data for 1200 UTC 26 December 1987 (compare Fig. 15a).

$F_{Q}/\sigma$ at 600 mb, was computed from the NGM initial data at 26/1200. Compare this figure with the 12-h predicted field for the same time (Fig. 15a). Neither figure bears much resemblance to the observed pattern (Fig. 15b). Had these discrepancies in initial conditions been known to forecasters, the new guidance certainly would have been viewed with a large degree of skepticism.

7. Discussion and concluding remarks

Some aspects of the NGM's performance on 26/0000 are typical of its behavior in dealing with "lee of the Rockies" cyclones. At 12 h into the model run, cold thickness bias and excessive propagation velocity were evident and are well-known errors (Smith and Mullen 1993). However, the 48-h displacement error was not typical for the region, being more easterly and larger than expected [compare Fig. 4 and, in Smith and Mullen (1993), Fig. 3]. The NGM's handling of the dual jet maxima was typical of what is observed in this type of cyclone. The first jet, already on the southeast flank of the cyclone, was predicted to carry most of the storm's energy rapidly northeastward and, in association with rapid advection of moisture northwest, develop a lower-tropospheric cyclone over Kansas in 36 h. The trailing jet was predicted to lag far behind and have little weather-producing potential. But in this case, the evolution of the jet stream was not typical. Obviously, the simple conceptual model of jet-streak vertical motions did not help forecasters anticipate when and where this storm's development would occur.

Dunn (1991) reviewed the development of current qualitative diagnosis of large-scale vertical motions and suggested that, as gridded data become available (this is currently happening in the NWS), forecasters finally will be able to assess quasigeostrophic forcing qualitatively and eventually will discard application of conceptual models (e.g., the classic jet-streak model, and the vorticity- and thermal-advection models of the QG omega equation). The demonstrated QG-based diagnostic technique proved to be useful for identifying and tracking important ageostrophic circulations in this developing storm. The general utility of the scheme has not been tested rigorously, but in the lead author's experience, mapping and tracking jet-streak circulations, static stability, and moisture always provides a meaningful context in which to view conventional analyses and data.

Interpreting diagnostics, either from observations or model gridded fields, is not straightforward. For example, the significance that the ageostrophic circulations were to have on the ensuing developments in the Christmas 1987 cyclone cannot be determined precisely. The diagnostic fields depict only gross (layer-averaged) structure and are available only at 12-h intervals. Detailed understanding of the effects that the tandem jet maxima had on the cyclone would require analyzing a properly initialized, primitive equation numerical model, which is beyond the scope of this research. Furthermore, the scale of the interactions between these two jet maxima is near the minimum resolvable horizontal wavelength of the NGM (350 km, Hoke et al. 1989). Newer versions of the NGM, with its "regional data assimilation system" (RDAS, Petersen et al. 1991; Dimego et al. 1992), may be more successful in depicting the complex physical processes leading to tropopause folding and cyclogenesis.

While the diagnostics presented here would not have indicated to forecasters exactly what the storm was going to do during the day Saturday, they certainly would have indicated the possibility that a new tropopause fold (upper frontogenesis) had developed on Friday evening (Fig. 8), and by Saturday morning, that the storm had developed a new PV center farther to the north than the old one (Fig. 5). Also by Saturday morning, forecasters would have known that the NGM prediction was off track and too early in its development of the cyclone at 850 mb (Fig. 9). The numerical guidance also failed to predict what appears in Fig. 13 to be a significant midtropospheric front in the Texas Panhandle, and instead moved the 850-mb front (and apparently, the midtropospheric front) too far to the east. Finally, analysis of observed geostrophic PV in a layer intersecting the lowered tropopause (Fig. 14a) indicates that the NGM failed to predict a perturbation (apparent fold) of the tropopause in the same area that the midtropospheric front was observed.

Insofar as can be determined, the NGM initialization on Friday evening (26/0000) was not at fault in producing the first erroneous 12-h prediction (see Appendix). The diagnostic fields, computed as they were from
a mix of observations and synthetic soundings, indicated only subtle differences whose impacts on the forecast cannot be determined. This is much the same limitation that forecasters would face if they were using these diagnostics in an operational mode; they could not reinitialize the model.

As for the subsequent erroneous guidance (initialized at 26/1200), it is disconcerting that the critical information about the jet streak's dynamical structure had to be generated almost entirely by the NMC's data assimilation process in the absence of Mexican rawinsonde observations. Currently, with soundings only once per day from Mexico, this data deficiency is more than the exception. Very often (e.g., Anthes et al. 1982) the lack of information from Mexico has affected the quality of short-term guidance about disturbances that affect the southern Rocky Mountain and southern Great Plains states. In this case, the delayed Mexican observations for Saturday morning (26/1200) were crucial for determining the strength and position of the second jet maximum. Certainly, the misplaced jet maximum in the LFM analysis did not help forecasters assess the situation correctly. Using diagnostic capabilities such as those demonstrated here, forecasters that morning easily could have determined the inconsistencies between the initial model fields and the observed fields if the Mexican observations had been available. But then, the NGM probably would not have erred in its initial conditions had those observations been available.

It is important that forecasters know why a particular weather system is, or is not, behaving in the manner predicted by an operational model. Our research has not determined why the NGM predicted excessive PV and westerly momentum in the midtroposphere—only that it did. Unfortunately, we did not think to determine whether or not the NGM predicted the new PV extrusion along the 295 K surface at 26/1200, and the required computer resources are no longer available. Since we do not have the capability to rerun the NGM with different parameterizations or initial conditions, we can only guess at the reasons for its behavior. Plausibly, one reason may have been that the 1987 version of the NGM did not have a parameterization of a turbulent dissipation process that was adequate for mountainous terrain. The evidence also suggests that moisture transport over the “mountain” of polar air overlying the southern Great Plains was incorrectly handled. Each of these factors (PV, momentum transport, and moisture availability) is known to influence the timing and location of cyclogenesis.

We have seen only a sampling of the type of diagnostic information that could assist a forecaster’s evaluation of numerical model guidance, both with regard to initialization data and predicted data. Depicting predicted data in the form of synthetic observations allows one to make comparisons with real observations in terms a forecaster can easily grasp—the placement of fronts, the movement of moisture, etc. Comparisons of QG diagnostic information provides forecasters the chance to investigate the development of the model's prediction in terms that directly relate to the basic physical processes that influence storm development. Of course, the diagnostics suggested in these examples are not the only ones capable of depicting the information a forecaster needs, nor can they serve in lieu of other tools and aids. For example, independent observations of tropopause folding (e.g., Velden 1992) and should be used to augment (verify) what these diagnostics only suggest.

Currently, forecasters spend too much effort analyzing subtle, difficult-to-interpret versions of the nationally disseminated numerical guidance, all of which are received well after synoptic observations times. To judge how a model’s prediction is performing in a given situation, it would be more efficient to compare current rawinsonde observations with synthetic soundings and with dynamically sensitive fields derived from 12-hold model guidance. To do this, forecasters need to be able to analyze current rawinsonde data in real time and to compute the required information from model gridpoint data. This capability would allow forecasters to make more timely adjustments in the forecast products they disseminate.

Potential weaknesses in this suggestion include the absence of a first-guess field for the objective analysis scheme employed. This weakness is particularly troublesome when forecasters have to deal with significant meteorological features in or near a data-sparse area. Another weakness in the analysis scheme used here is that the data must be free from large errors. Often, this requires editing prior to computing the diagnostics in order to eliminate or replace troublesome information with other, more reasonable, data. The skills required to resolve these difficulties and the knowledge required to ensure that forecasters are cognizant of the pertinent physics driving the “forecast problem of the day” will require an ongoing field training program. Programs such as the Cooperative Program for Meteorological Education and Training (Spangler et al. 1991) can foster an efficient and successful transition to this new approach.

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6 Through experience, it has been found that many of the diagnostic fields are useful for identifying stations with erroneous data. Typically, a “bull's eye” of isophths is found centered on, or near, the irregular information. Generally, no physical basis (e.g., QG theory basis) can be found to support the feature, which also lacks temporal continuity.
tems Laboratory scientists) provided many questions and suggestions that helped measurably to improve the presentation of these unfamiliar diagnostic fields so they might be more understandable to field forecasters. The comments and suggestions of the editor and his reviewers also were very helpful.

APPENDIX

Analysis Problems Due to Missing Data

The NGM C-grid data (spaced 91.45 km at 60°N) for the initialization time 26/0000 were analyzed to determine if the model did in fact start with the conditions discussed in section 4. To eliminate the possibility of different results arising from different analysis schemes (as between the National Meteorological Center's analysis and the "Barnes" scheme used in this research), the initial data for Friday evening's NGM run were subjected to the same diagnostic algorithms used to analyze the actual observations. This was accomplished by creating synthetic soundings from the NGM's gridpoint data (bilinearly interpolated to station locations from four surrounding grid points). Synthetic data also were generated for eight bogus stations in the Pacific Ocean along the west coast of North America and two sites in the Gulf of Mexico as well. This tactic helps to control errors that would be induced by a lack of soundings near the analysis domain's boundary.

Diagnostic results using the NGM's initial data exclusively at all sounding sites were essentially the same as those presented in Figs. 6–8. Over the well-sampled continental United States, the diagnostic fields varied only in very minor ways. Unfortunately, that was not quite the case over northern Mexico where two crucial Mexican soundings were not available in time for the 26/0000 operational analysis cycle—Guadalupe Island (76151; IGP) and Chihuahua (76225; MCV). Of the available observations, height and temperature data at 500 mb and above for Empalme were rejected from the NGM initial data. Since these northern Mexico observations are crucial to the events unfolding, four analysis tests were designed to determine the impact of the missing Mexican data on the diagnostic results.

For the first test, mandatory-level height and temperature data for the Mexican stations were interpolated from the National Meteorological Center's (NMC) LFM ⋅ ⋅ analyses obtained on microfiche from the NCDC, Asheville, North Carolina. Data at four of the bogus sites in the Pacific Ocean near Baja California were interpolated from the same source. Data at all other stations were from actual rawinsonde observations or, if missing, were from NGM initial synthetic soundings. Since no other stations in the vicinity of northern Mexico were missing, test results in this area of the analysis domain are virtually independent of the NGM initial data.

For the second and third tests, Mexican rawinsonde data obtained after the fact from NCDC were checked for hydrostatic consistency and inspected on thermodynamic charts. The sounding for Guadalupe Island failed the hydrostatic check and was not used. All of the other soundings passed inspection, even the Empalme sounding rejected by NMC's quality control. The latter sounding also was compared visually with the Empalme soundings 12 h either side of 26/0000, and no obvious discrepancies could be found. For these tests then, the observed Mexican data have greatest impact on the crucial northern Mexico results. In both of these tests, NGM synthetic initial data were used for the 10 bogus sites over water. The second test also used NGM initial data for Guadalupe Island and the missing Chihuahua sounding. The third test did not and thus left rather significant information gaps near Guadalupe Island and Chihuahua. The fourth test ignored all of the Mexican observations and instead used the NGM's initial data at those sites, including Guadalupe Island and Chihuahua.

Results from each of the four tests showed similar transverse circulation features, the differences being mainly in the positions of the features and their magnitudes. The second test (using a mix of Mexican observations and NGM data) was the least satisfactory with regard to the scale of the features represented. Typically, when NGM synthetic observations and the actual observations are at odds, extraordinarily intense bull's-eyes appear in the diagnostic fields in the vicinity of the mismatched data. Although this was not the case in the second test results, there was enough small-scale variability in them to make the authors suspect the data were incompatible. The LFM-based results and the results based on only observations were similar in their placement of the transverse circulations but both suffered from the absence of data at Guadalupe Island and Chihuahua. As is typical with distance-weighted, interpolation-type objective analyses, features expand to fill the gaps between stations, thus making ambiguous their true location. Therefore, it was decided to use NGM data instead of Mexican observations (the fourth test) as the most reliable dataset upon which to base the diagnostic analyses. The NGM results in Mexico blended nicely with the results supported by rawinsonde observations in Arizona, New Mexico, and Texas. Obviously, if the NGM data are not representative, then the diagnostics are not correct. However, the authors could find no evidence that the NGM initial data are seriously in error.

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