Organization and Structure of Clouds and Precipitation on the Mid-Atlantic Coast of the United States. Part III: The Evolution of a Middle-Tropospheric Cold Front

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(Manuscript received 17 April 1989, in final form 26 July 1989)

ABSTRACT

The development of a complex middle-tropospheric frontal structure, the various weather associated with its progression across the United States, and its role in the production of precipitation in the eastern third of the United States are examined.

The frontal structure consisted of two features: a middle-tropospheric cold front associated with a strong 500 mb short wave that moved eastward from the Pacific Ocean, and a leeside warm front that formed in a northward sloping zone of warm-air advection associated with a trough in the lee of the Rocky Mountains. The middle-tropospheric cold front overtook the leeside warm front to produce a warm occlusion-like structure in the middle troposphere. As this system progressed eastward across the United States precipitation (from light rain to convective showers) occurred along the leading edge of the middle-tropospheric frontal zone, well ahead of a decaying surface trough.

This study highlights the importance of middle-tropospheric frontal structures in the organization and distribution of precipitation. The study also provides some insights and speculations concerning the similarities between lee troughs and drylines, the generation of squall lines by middle-tropospheric cold fronts, and the need for better conceptual models for the evolution and structure of middle-tropospheric fronts.

1. Introduction

In the first two papers in this series (Locatelli et al. 1989; Sienkiewicz et al. 1989) we showed that the Rocky Mountains can affect the mesoscale organization of precipitation as far downstream as the East Coast of the United States. In that case, an occluded-like structure on the surface formed when a surface cold front in the lee of the Rockies overtook a lee-side trough. The occluded-like structure maintained a strong surface signature as it progressed across the United States, finally resulting in the formation of rainbands over the Carolinas and the Gulf Stream.

Petterssen (1940) suggested another mechanism by which warm occlusion-like structures might form in the lee of the Rockies. He envisioned that such structures might be produced when a maritime cold front passes over the Rocky Mountains and encounters potentially denser air to the east; this would tend to force the frontal zone aloft, leaving little or no surface signature (see Fig. 145, Petterssen 1940).

The case to be described in this paper is concerned with a middle-tropospheric cold front associated with an upper-level trough, which originated over the Pacific Ocean, moved over the Rocky Mountains, and overtook a warm front that had formed in the lee of the Rockies. This produced a warm occlusion-like structure in the middle troposphere that progressed across the United States. The advance of the middle-tropospheric cold front was responsible for generating light precipitation which consistently occurred ahead of a degenerating surface trough. This surface trough began as a leeside trough east of the Rocky Mountains, maintaining some of its lee-trough characteristics (i.e., warmest air in the center of the trough, very dry air to the west of the trough axis) even after it had left the eastern slopes of the Rockies. The middle-tropospheric feature was also responsible for the generation and triggering of a convectively unstable environment in the southeastern United States which resulted in squall line-like precipitation. Finally, upon reaching the eastern seaboard, where a shallow coastal front had developed, the middle-tropospheric frontal system apparently enhanced the precipitation rate, originally associated with the coastal front alone, in a limited region stretching from New York City to Baltimore.

We begin with a description of the initial synoptic setting for this event. The structure of the frontal system is then described. Next, the formation, propagation, and maintenance of the frontal system are discussed. We also point out some similarities and differences between some aspects of the middle-tropospheric frontal system discussed in this paper and drylines, the generation of squall lines, split cold fronts, trowals, and warm occlusions.

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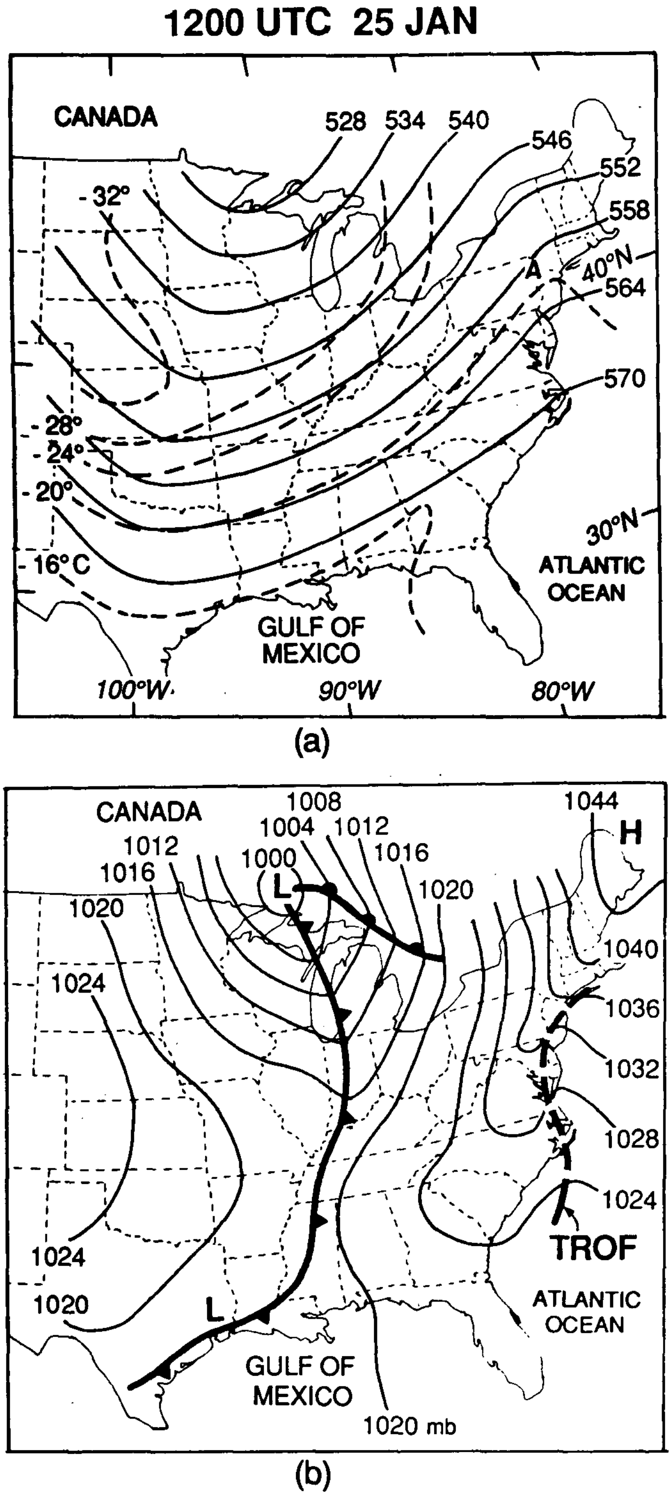

FIG. 1. (a) 500 mb geopotential heights and (b) NMC surface pressure analysis for 1200 UTC 25 January 1986. In panel (a) geopotential heights (heavier continuous lines) are labeled in tens of meters and contoured every 60 m, and isotherms (dashed lines) are labeled in °C and contoured every 4 deg. In panel (b) isobars are labeled in millibars every 4 mb.

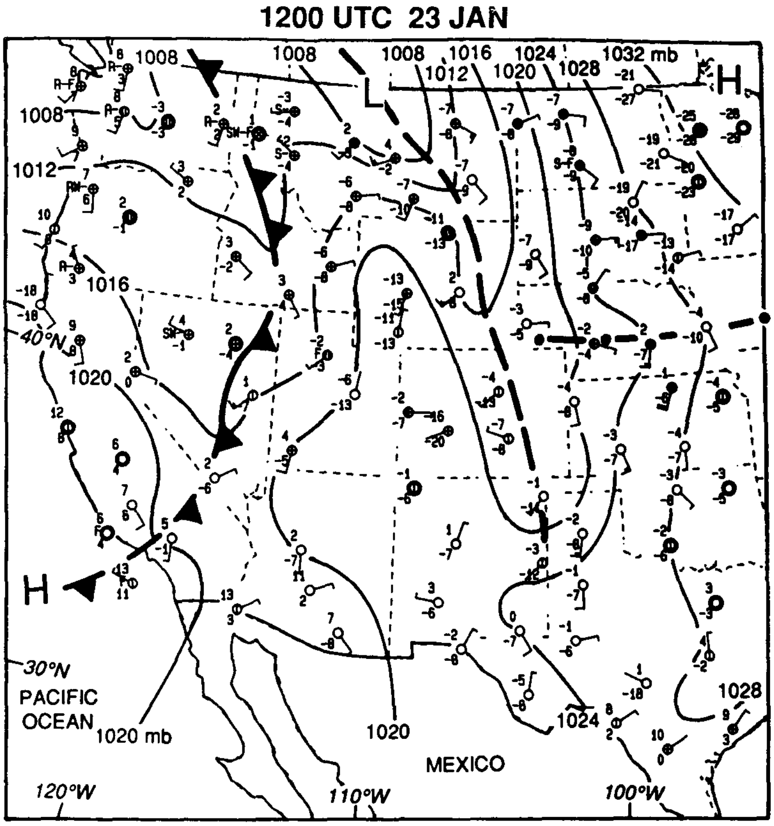

FIG. 2. Surface pressure analysis for 1200 UTC 23 January 1986. Isobars are labeled in millibars and contoured every 4 mb. Standard frontal symbols indicate the positions of surface fronts. The heavy dashed line indicates the position of the trough in the lee of the Rocky Mountains. The heavy dashed-dot line indicates the position of the arctic front. For each surface station the following data is shown: temperature (labeled in °C to the upper left of the station symbol), dewpoint temperature (labeled in °C to the lower left of the station symbol), sky cover (in center of station symbol), wind direction and speed and present weather. Sky cover is shown using the following symbols: open circle—clear, one vertical line—scattered cloud, two vertical lines—broken cloud, a cross—overcast, and an X—sky obscured. Wind speeds are indicated by: circle around a circle—calm, long barb—5 m s^{-1}, short barb—2.5 m s^{-1}, and flag—25 m s^{-1}. Present weather symbols are: R (rain), W (showers), L (drizzle), H (haze), S (snow), F (fog), ZR (freezing rain), BS (blowing snow), and K (smoke). A plus or minus sign after the precipitation type indicates heavy and light precipitation, respectively.

In a future paper in this series, we will describe the mesoscale and microscale structure of the frontal system described here as it passed over the *G*enesis of *A*tlantic *L*ows *E*xperiment (GALE) observational network on the East Coast.

2. Analysis of the structure and progression of the middle-tropospheric frontal system

Sutcliffe (1947) warned: ". . . expect the appearance of abnormal weather developments in complex thermal structures without indication from the surface observations. . . ." The system with which we are concerned here had a complex, nonclassical thermal structure, indicated by the fact that the 500 mb cold advection at 1200 UTC 25 January is ahead of the surface cold front (Fig. 1). We therefore undertook a detailed synoptic analysis to shed light on the factors responsible for the development of this system and the role it played in spreading precipitation across the eastern third of the United States. Our analysis begins in the lee of the Rocky Mountains and progresses eastward across the continent.

a. In the lee of the Rockies

Figure 2 shows our surface synoptic analysis for 1200 UTC 23 January 1986. Several features are of interest. The main features in the west are a decaying low-pressure center in the southern Gulf of Alaska (not shown) with a trailing cold front running through eastern Washington, through central Idaho, through Nevada to Los Angeles. Along the lee of the Rocky Mountains there is a stationary trough trailing from a low-pressure area in southern Alberta. There is also a slight trough in the pressure field through central Nebraska with much colder air to the north. A large area of high pressure (not shown) blankets the eastern two-thirds of the United States with cold dense air. Very low temperatures, associated with a central high of 1039 mb, are present north of the North Dakota–Canadian border.

In the 850 mb chart for 1200 UTC 23 January (Fig. 3a) the lee trough appears in much the same location as on the surface. It had remained stationary from 0000–1200 UTC 23 January, but the thermal field associated with it (i.e., thickness ridge in the center of the trough) had strengthened during this period. A strong core of warm, dry air was present over eastern Colorado at 1200 UTC. Fig. 3b shows the 700 mb chart for 1200 UTC 23 January. A distinct axis of warm air is situated over the Rockies and there is slight troughing in the geopotential field. A hint of the trough and cold front is also evident west of the Rockies. At 500 mb (Fig. 3c), the striking feature is the trough that had come onshore from the Pacific, with a strong vorticity maximum in northern California and southeastern Oregon. A moderate synoptic scale ridge, situated over the Rockies, provided dynamical support to the more important orographically induced subsidence at lower levels. Carlson (1961) investigated lee troughs in the Rocky Mountains and found them to remain stationary while under the influence of upper-level negative vorticity advection; this was the case for the lee-trough discussed here. Carlson refers to the lee trough as a "pseudofront."

Two cross sections through the lee trough (not shown) at 1200 UTC 23 January revealed that the cores of warmest air were centered just to the east of the Rockies in Colorado and Wyoming. These cross sections also revealed an eastward sloping stable layer embedded in the lee trough.

The lee trough remained stationary throughout the intervening 12 h to 0000 UTC 24 January. At this time, the trough began to move away from the Rockies, especially near its northern end. A cross section from Grand Junction, Colorado (GJT), to Denver, Colorado (DEN), to North Platte, Nebraska (LBF), to Omaha, Nebraska (OMA) shows the thermal structure of the trough (Fig. 4). Notice that the 312 K θ_e isentrope abruptly descends from ~600 mb over the mountains to just above the surface in the lee, indicating the mag-

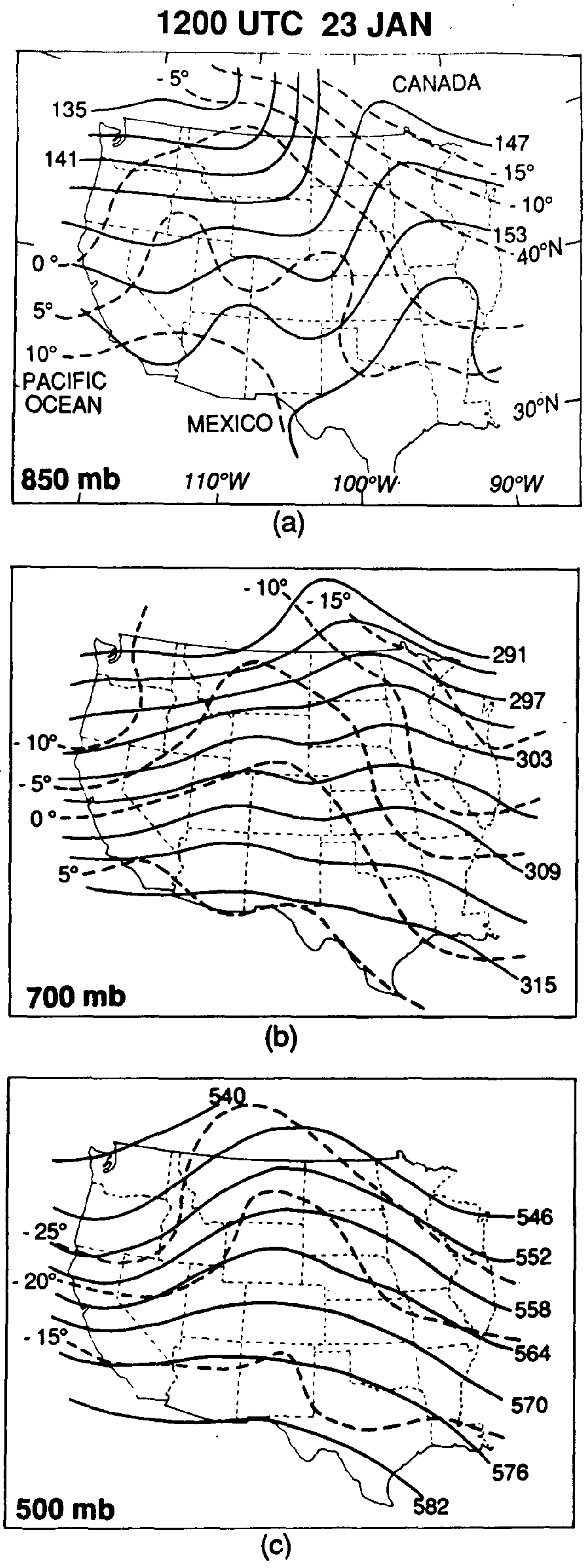

FIG. 3. (a) 850 mb, (b) 700 mb, and (c) 500 mb analyses for 1200 UTC 23 January 1986. Shown are geopotential heights (heavier continuous lines) labeled in tens of meters and contoured every 30 m [except for (c) where it is every 60 m], and temperatures (dashed lines) labeled in °C and contoured every 5 deg.

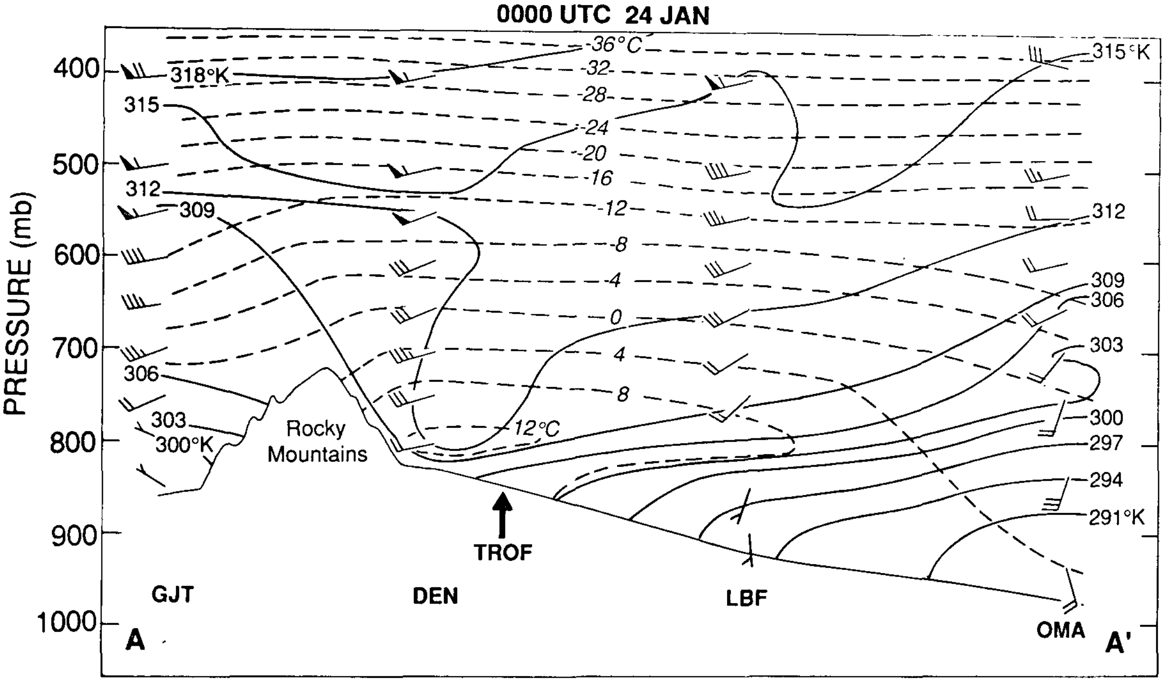

FIG. 4. Cross section (along A–A' in Fig. 6b) from Grand Junction, Colorado (GJT), to Denver, Colorado (DEN), to North Platte, Nebraska (LBF), to Omaha, Nebraska (OMA) at 0000 UTC 24 January 1986. Solid lines are values of equivalent potential temperature (θ_e) in degrees Kelvin labeled every 3 deg. Dashed lines are isotherms in degrees Centigrade labeled every 4 deg. Wind speeds are indicated by: half barb – <5 m s^{-1}, full barb – 5 m s^{-1}, flag – 25 m s^{-1}.

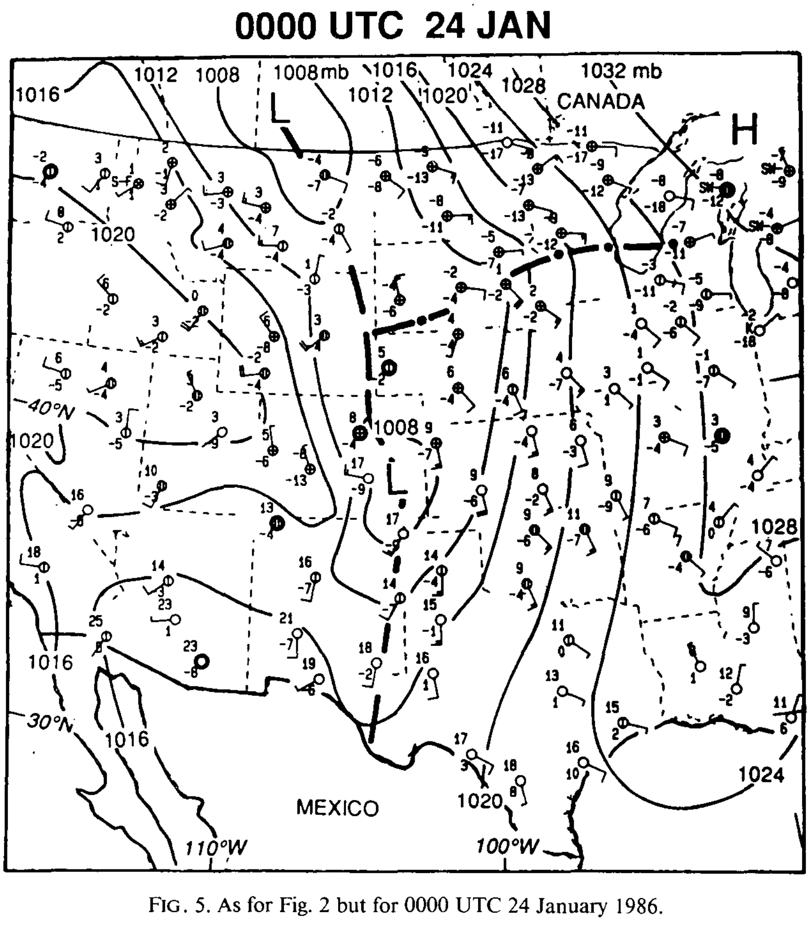

FIG. 5. As for Fig. 2 but for 0000 UTC 24 January 1986.

nitude of the orographically induced subsidence. The surface pressure field (Fig. 5) shows that the circulation associated with the trough increased on its east side as the trough deepened rapidly while the surface pressures in the Great Plains fell less quickly, resulting in an increased horizontal pressure gradient. At 850 mb (Fig. 6a), strong warm-air advection was occurring east of the trough axis, which was also the axis of the warmest air. The 700 mb trough was situated almost exactly above the 850 mb trough (Fig. 6b). Importantly, the flow at 700 mb still maintained a substantial component perpendicular to the Rockies south of the Wyoming–Colorado border, indicating that orographic forcing of the trough was still a major factor in maintaining its stationary in that region. The 500 mb flow clearly indicates that by 0000 UTC 24 January the short wave from the Pacific Ocean had advanced to just west of the Colorado Rockies (Fig. 6c). Under its influence, the lee trough began to move from its original position. The lifting associated with the short wave resulted in the development of a surface low-pressure system in western South Dakota between 0000 UTC and 0300

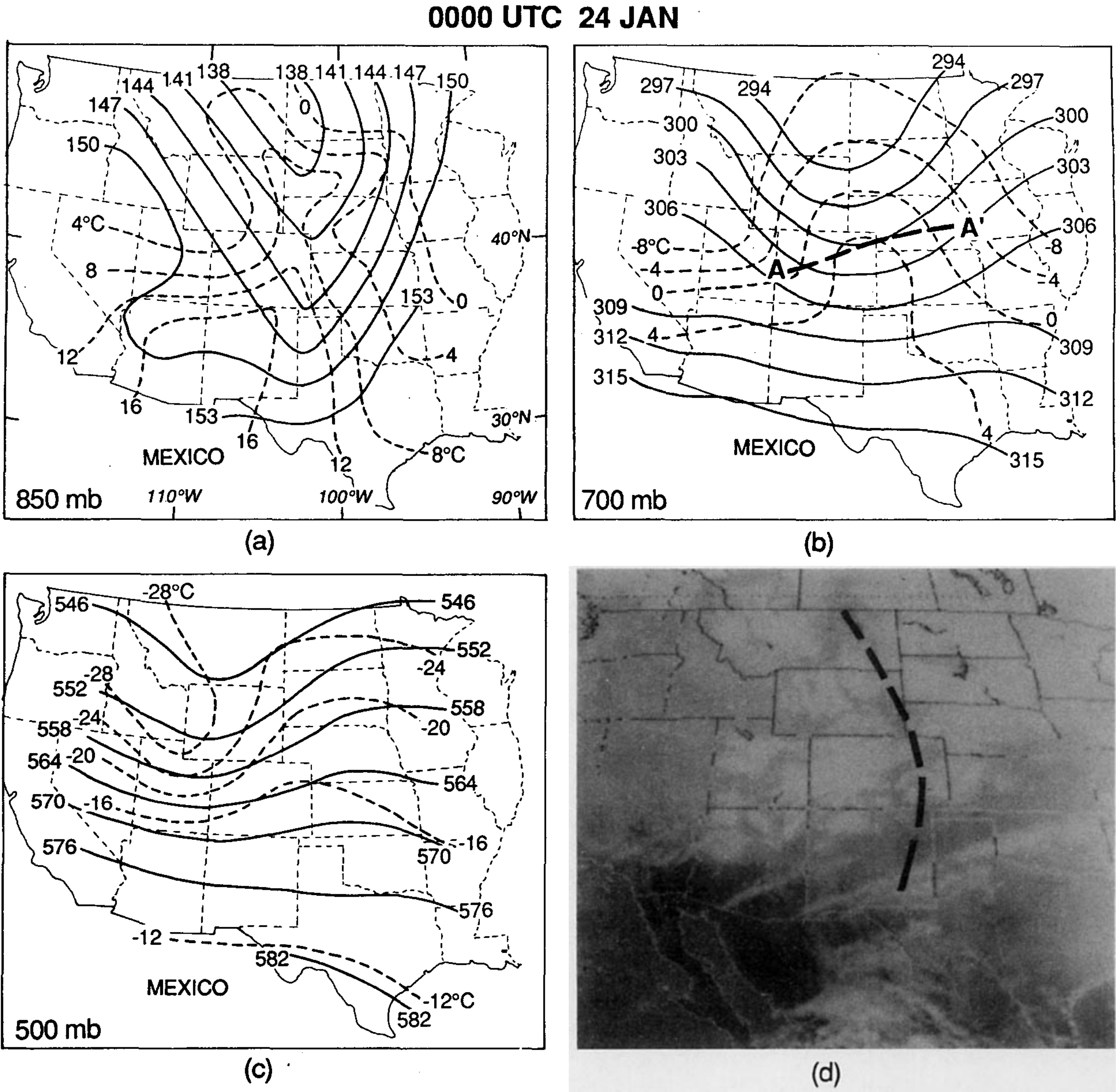

FIG. 6. Panels (a), (b), and (c) are like Fig. 3 but for 0000 UTC 24 January 1986. A vertical cross section along the dashed line A–A' in (b) is shown in Fig. 4. (d) Infrared satellite image for 0000 UTC 24 January 1986. The dashed line indicates the position of the leeside trough.

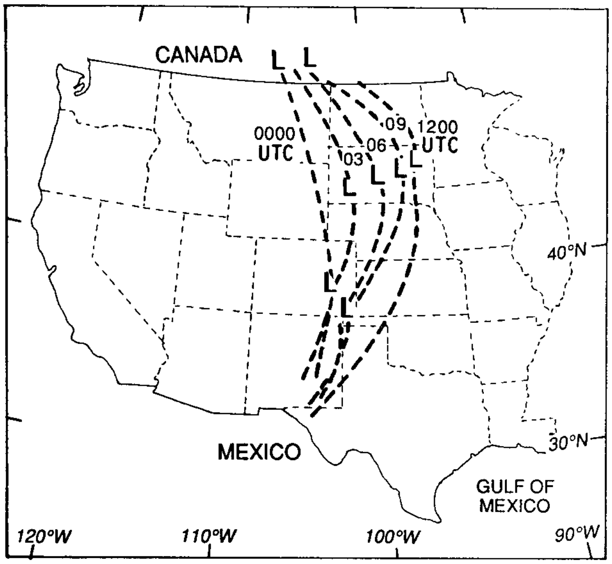

FIG. 7. Positions of low centers (L) and leeside trough (dashed lines) at 3 h intervals from 0000 to 1200 UTC 24 January 1986.

UTC 24 January. This feature progressed to the northeast and deepened somewhat in the next 15 h. Accompanying the passage of the upper-level trough was a gradual change in middle-tropospheric flow relative to the orientation of the Rockies. The cloudiness exhibited in the satellite imagery at this time lacked coherent structure (Fig. 6d).

b. Progression across the midwestern United States

Figure 7 shows the progression of the lee trough from 0000 to 1200 UTC 24 January 1986. By 0600 UTC the NMC analyzed surface cold front was nearing the lee trough and by 0900 UTC the cold front was analyzed to occupy the trough axis. By 1200 UTC the surface chart (Fig. 8) indicates that the lee trough had moved further eastward from the mountains under the combined influence of an increased flow parallel to the mountains at 700 mb (indicating the fact that orographic subsidence was no longer occurring) and the broad, eastward moving region of synoptic lifting associated with the passage of the 500 mb short wave (Fig. 9a).

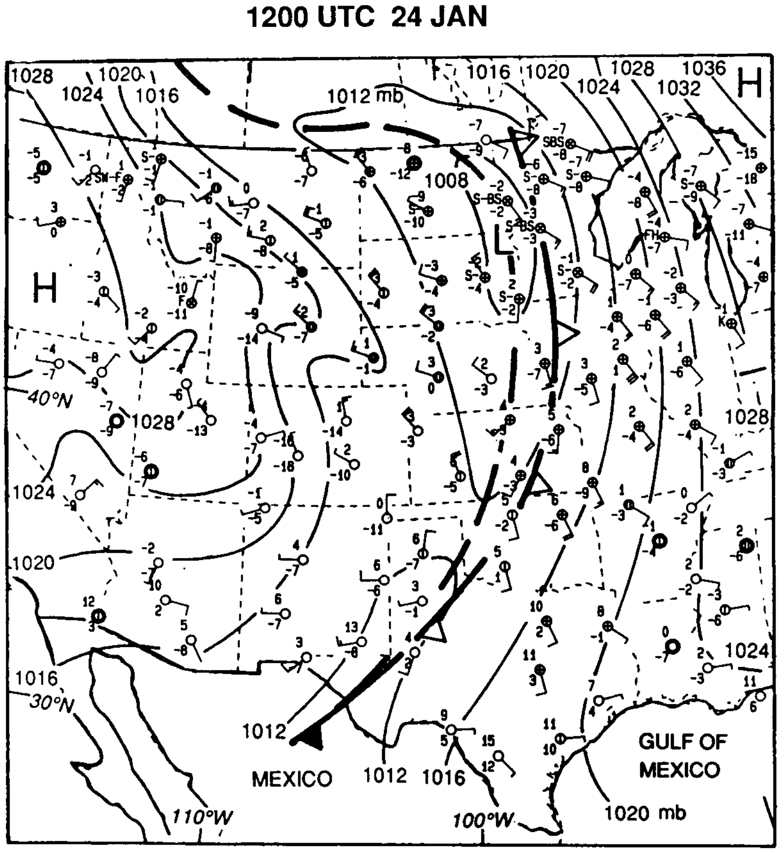
1200 UTC 24 JAN

FIG. 8. As for Fig. 2 but for 1200 UTC 24 January 1986. The heavy dashed line indicates the position of the leeside trough and the open cold-frontal symbols indicate the position of the cold front in the middle troposphere.

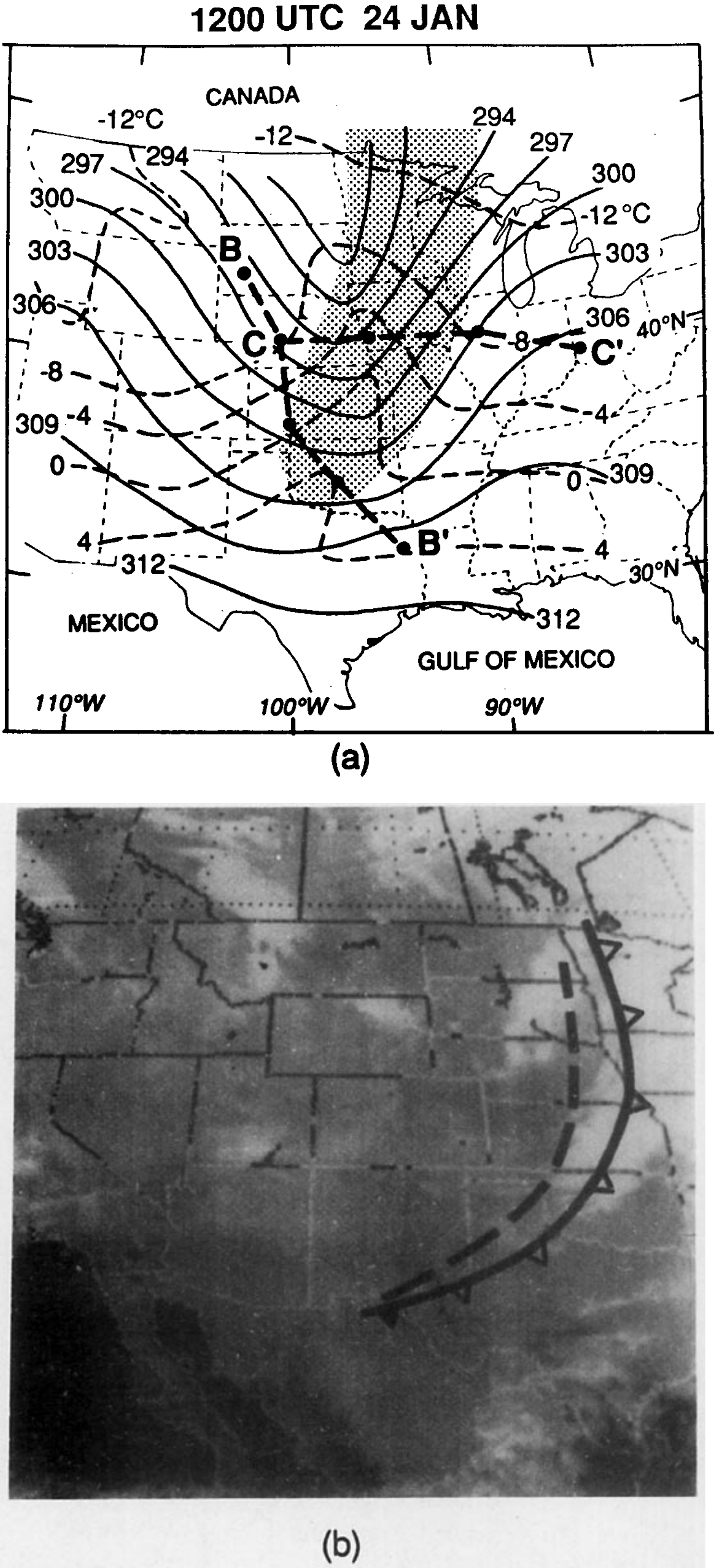

FIG. 9. (a) 700 mb analysis for 1200 UTC 24 January 1986. See caption to Fig. 3 for key to isolines. Stippled area represents region of positive advection of 500 mb vorticity by the 1000–500 mb thermal wind. Vertical cross sections along the dashed lines *B–B′* and *C–C′* are shown in Figs. 10a and 10b, respectively. (b) Infrared satellite imagery for 1200 UTC 24 January 1986. The location of the cold front in the middle troposphere is indicated by open cold-frontal symbols and the location of the lee trough at the surface by the dashed line.

Two cross sections constructed from the 1200 UTC 24 January sounding data are shown in Fig. 10. The first runs from Rapid City, South Dakota (RAP), to North Platte, Nebraska (LBF), to Dodge City, Kansas (DDC), to Oklahoma City, Oklahoma (OKC), to Longview, Texas (GGG) (Fig. 10a). This cross section illustrates the vertical structure of the middle-tropospheric cold front associated with the upper-level trough. The second cross section runs from North Platte, Nebraska (LBF), to Omaha, Nebraska (OMA), to Peoria, Illinois (PIA), to Dayton, Ohio (DAY) (Fig. 10b). It illustrates the occluded-like structure that developed as the 500 mb trough and its associated cold front overtook the lee-side trough and the warm-frontal feature which had developed east of the trough axis. Unlike a "classical" warm-occlusion, this feature lacked a maximum θ_e tongue extending from the intersection of the fronts aloft to the surface. The warm occlusion-like structure discussed by Locatelli et al. (1989) developed when a surface cold front in the lee of the

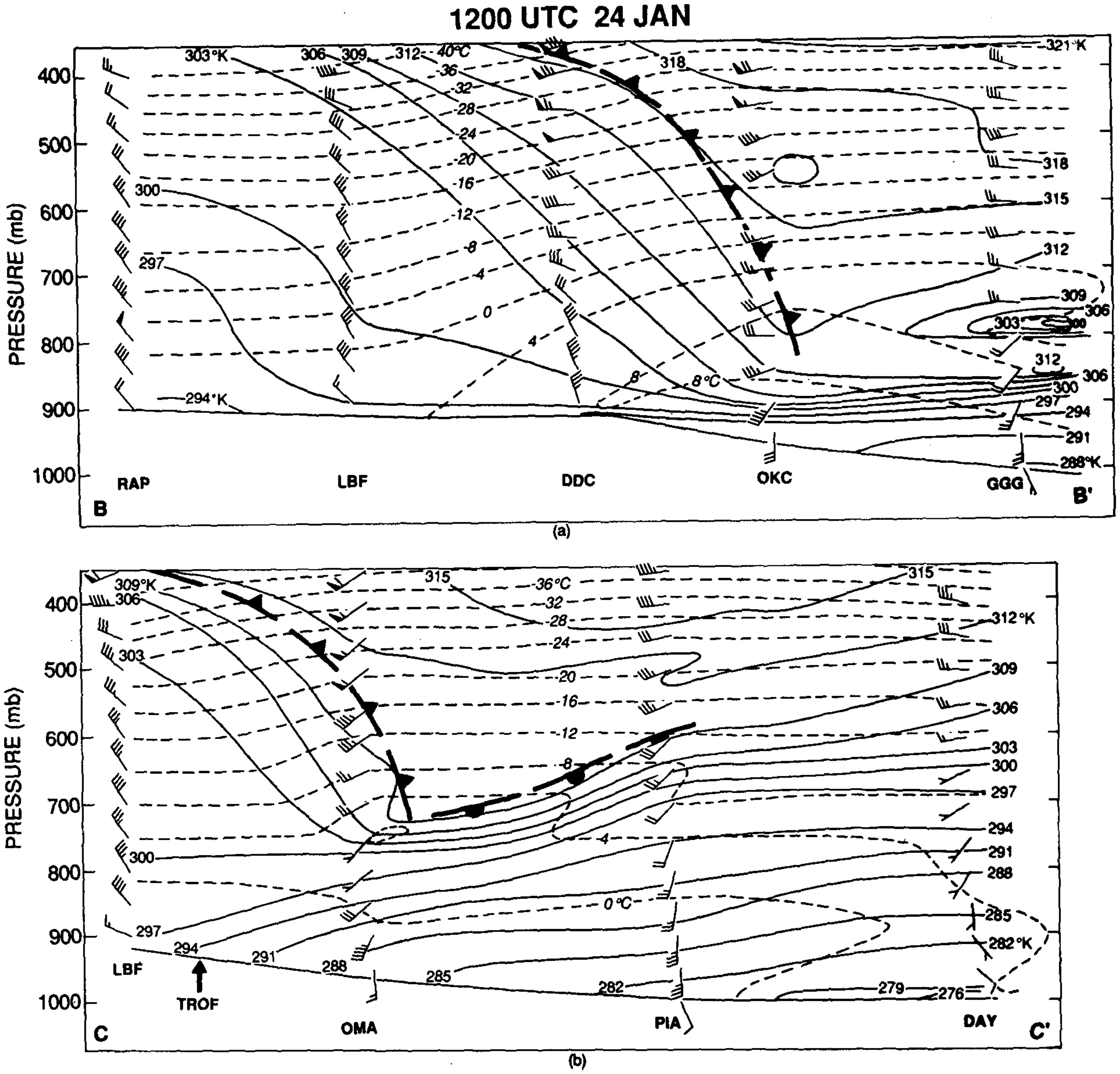

FIG. 10. (a) Cross section (along *B–B'* in Fig. 9a) from Rapid City, South Dakota (RAP), to North Platte, Nebraska (LBF), to Dodge City, Kansas (DDC), to Oklahoma City, Oklahoma (OKC), to Longview, Texas (GGG) at 1200 UTC 24 January 1986. (b) Cross section (along *C–C'* in Fig. 9a) from North Platte, Nebraska (LBF), to Omaha, Nebraska (OMA), to Peoria, Illinois (PIA), to Dayton, Ohio (DAY) at 1200 UTC 24 January 1986. See Fig. 4 caption for key to lines and symbols. Dashed frontal symbols indicate position of fronts in the middle troposphere.

Rockies moved quickly southeastward out of central Canada to overtake a lee-side trough. Since there was cold air down to the ground in that case, the superposition of the two features resulted in a more classical warm occlusion-like structure. In the present case, the cold front from the Pacific Ocean was characterized by relatively mild maritime air at the lowest levels. Since the lower portion of the cold-frontal zone was largely destroyed by adiabatic warming in the lee of the Rockies, the formation of the occluded-like structure occurred at mid-levels.

To further illustrate the three-dimensional structure of the evolving frontal system, we show in Fig. 11 the 306 K θ_e surface at 1200 UTC 24 January (this surface was situated in the middle of both the cold- and warm-frontal zones). This θ_e surface accurately indicates the leading edge of the cold-frontal zone in the middle troposphere. Note the strong discontinuity in height gradient (marked by a dashed line in Fig. 11), the high value of $\partial v/\partial x$ associated with it, and the pronounced tendency for up-gradient flow ahead of the discontinuity and down-gradient to parallel flow behind it. The satellite imagery (Fig. 9b) shows a distinct edge to the cloud shield coincident with the dashed line in Fig. 11. Thus, the dashed line in Fig. 11 represents the leading edge of the cold front aloft. Also, the 500 mb vorticity in this case was ~10 times stronger than the 1000 mb vorticity. Thus, the thermal vorticity, which is a reflection of the Laplacian of the vertically averaged temperature field, was approximately equal to the 500 mb vorticity which has a maximum close to the dashed line (Fig. 12). As stated earlier, the 500 mb trough at this time was well east of the Rockies, so the lee trough was also moving eastward. By 1200 UTC 24 January, the leading edge of the middle-tropospheric cold front almost coincided with the lee trough through Texas and central Oklahoma. The cold front was slightly ahead of the lee trough north of central Oklahoma, where the occlusion-like structure was present.

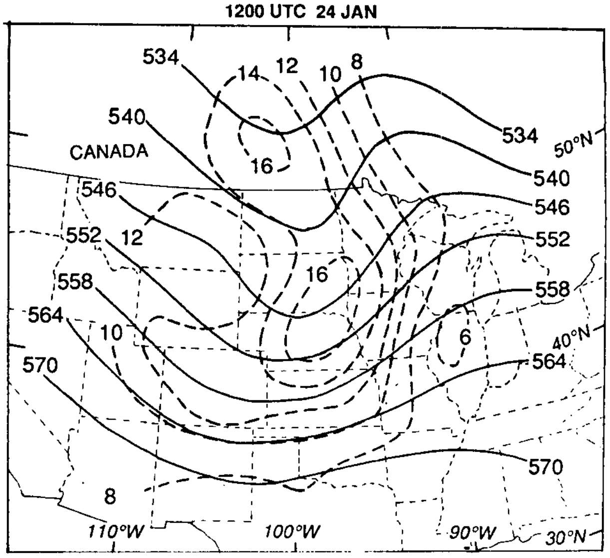

FIG. 12. National Meteorological Center geopotential height analysis for the 500 mb pressure surface at 1200 UTC 24 January 1986. Geopotential heights (solid lines) are labeled in tens of meters and contoured every 60 m. Absolute vorticity (dashed lines) are labeled in units of 10^{-5} s^{-1}..

By 1800 UTC 24 January, the NMC analysis had placed a cold front in the center of the eastward-moving lee trough (Fig. 13). Also, the high pressure center, which was originally in central Manitoba, had progressed to central Quebec and induced a ridge of high pressure east of the Appalachians. This process, known as cold-air damming, has been documented by Rich-

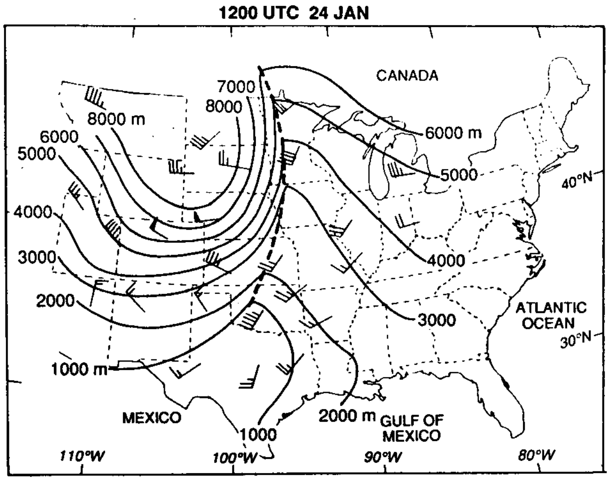

FIG. 11. Height (in meters and contoured every 1000 m) of the θ_e = 306 K surface at 1200 UTC 24 January 1986. Wind convection as for Fig. 4. The dashed line indicates the leading edge of the cold front in the middle troposphere.

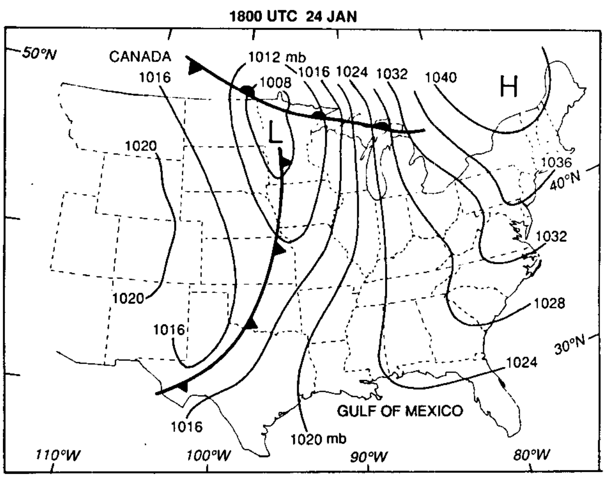

FIG. 13. National Meteorological Center surface pressure analysis for 1800 UTC 24 January 1986. Isobars are labeled in millibars at intervals of 4 mb.

wein (1980), Forbes et al. (1987), and Bell and Bosart (1988). The cold-air damming was to play an important role in the subsequent development of a coastal front.

The surface analysis at 0000 UTC 25 January is shown in Fig. 14. Cold air damming along the Appalachians continued, as did the progression of the frontal system aloft and the lee trough at the surface. An arctic front extended through Minnesota and western Iowa. Meager precipitation had broken out in central Illinois and central Arkansas. There is some hint of a surface warm front in coastal Texas. Figure 15a is the 700 mb chart for the same time; this clearly indicates that the leading edge of cold air advection at that level was well ahead of the surface trough. The same is true, but to a lesser extent, at 500 mb where there was a strong vorticity gradient ahead of the surface trough (Fig. 15b). This situation is characteristic of an occluded-like system.

Two cross sections, at 0000 UTC 25 January, are shown in Fig. 16. One extends from Victoria, Texas (VTC), to Longview, Texas (GGG), to Little Rock, Arkansas (LIT), to Salem, Illinois (SLO), to Flint, Michigan (FNT) (Fig. 16a). This cross section illustrates a feature that has all of the characteristics of a warm-frontal zone: high stability, veering and speed shearing of the winds with height, and a strong horizontal temperature gradient. Note also the high θ_e air, capped by low θ_e air.

Shown in Fig. 16b is a cross section from Topeka, Kansas (TOP), to Monett, Missouri (UMN), to Little Rock, Arkansas, to Jackson, Mississippi (JAN), to Boothville, Louisiana (BVE). It shows the leading edge of the middle-tropospheric cold front to be between Little Rock and Monett, well ahead of the surface trough. The convectively unstable region just ahead of the cold front consists of a dry cap of low θ_e air above a region of higher θ_e air. Trajectory analysis was performed using Nested Grid Model (NGM) C-grid grid-point data. Trajectories were calculated using a 24- or 36-hour sequence of 6- and 12-hour forecasts of 3D velocity data from the NGM which were saved for the GALE period. Parcels were traced backward from an ending point. Interpolation in time was based on the cubic spline technique and the spatial interpolation was linear. This was motivated by the fact that the available time resolution was coarse (6 h) whereas the horizontal spacing (80 km) was smaller than the density of

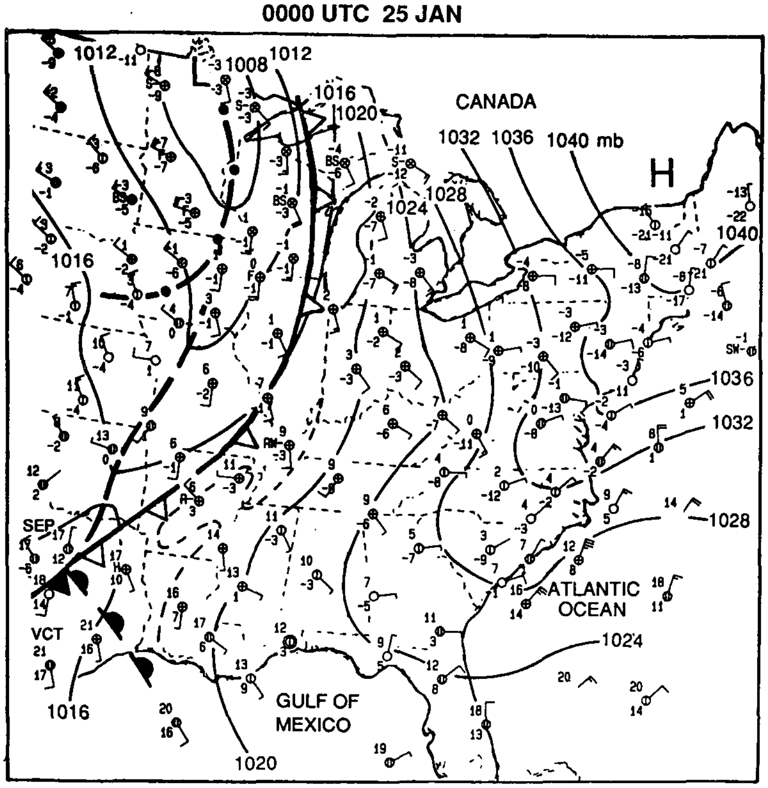

FIG. 14. As for Fig. 2 but for 0000 UTC 25 January 1986. The dashed-dot line indicates the position of the arctic front. The open cold-frontal symbols indicate the location of the cold front in the middle troposphere. The dashed warm-frontal symbols indicate the position of the surface warm front. The dashed line indicates the location of the surface leeside trough.

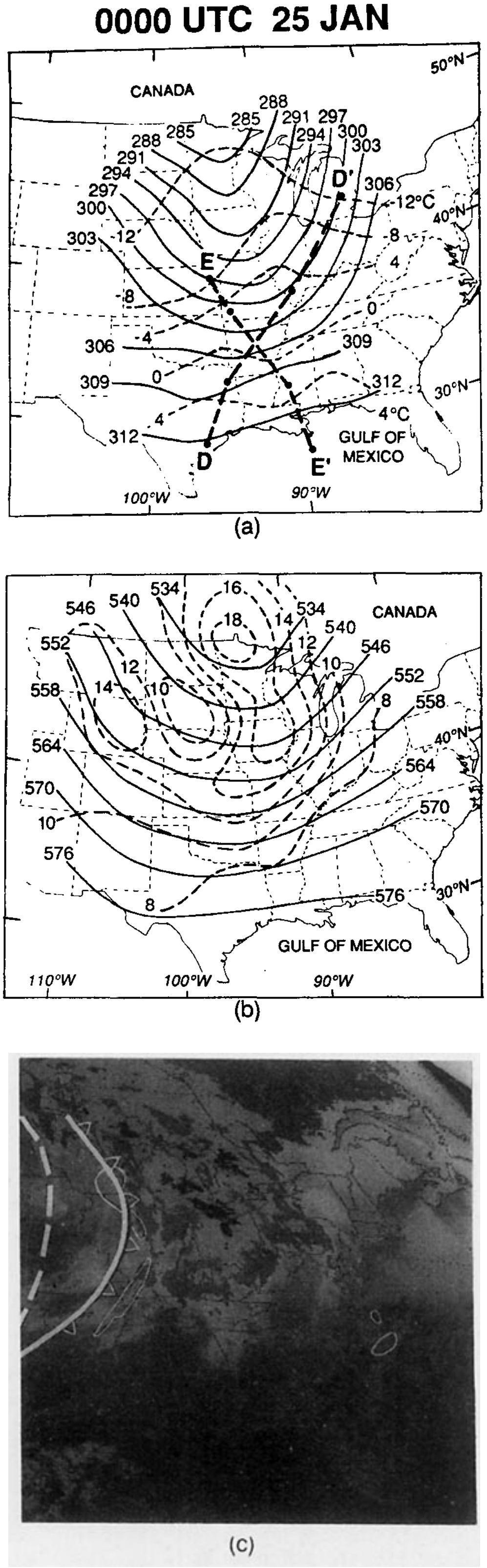

FIG. 15. (a) As for Fig. 3b but for 0000 UTC 25 January 1986. Vertical cross sections along the dashed lines *D–D′* and *E–E′* are shown in Figs. 16a and 16b, respectively. (b) As for Fig. 12 but for 0000 UTC 25 January 1986. (c) Infrared satellite imagery for 0000 UTC 25 January 1986. The open cold-frontal symbols indicate the position of the cold front in the middle troposphere. The dashed line indicates the position of the surface leeside trough. The thinner continuous lines outline the radar echo regions determined from composite NWS radar data.

soundings really allows. The time step used was 5 minutes. This analysis indicates that the dry air cap originated over the Mexico–New Mexico plateau. After being subjected to this elevated diabatic heating source, the dry air subsided to low levels over western Texas. Then, caught in the developing frontal circulation, it gradually rose to cap the high θ_e air that originated in the Gulf of Mexico. By 0300 UTC 25 January, strong thunderstorms had broken out from eastern Arkansas into central Mississippi, as the advancing middle-tropospheric cold front provided the lifting necessary to release the instability.

The 306 K θ_e surface was analyzed for 0000 UTC 25 January (Fig. 17). It illustrates the progression of the middle-tropospheric frontal zone eastward to a position where convergence along its leading edge (not shown) resulted in precipitation at the surface and the maintenance of vorticity along its length (Fig. 15b). As seen in Fig. 15c, the scattered, light precipitation at this time coincided with the analyzed position of the leading edge of the middle-tropospheric cold front. Even the nonprecipitating clouds appeared linked to this feature. Also, the cold front had an obvious extension to the ground in central Texas, as evidenced by the 306 K θ_e analysis and the strong temperature and dewpoint gradients between stations such as Victoria and Stephenville, Texas (SEP) (Fig. 14).

The 1200 UTC 25 January surface analysis is shown in Fig. 18. By this time, the lee side trough had begun to weaken considerably and the warmer air which had earlier defined the trough, had undergone mixing and radiative cooling. Cross section analysis (not shown here) indicates that the warm-frontal structure originally associated with the lee trough was still quite vigorous at 1200 UTC 25 January. The arctic front was wheeling through Michigan and Indiana, causing moderate snowfall to break out in these areas. In fact, by this time the arctic front had incorporated itself into the northern portion of the trough. The coastal front had strengthened as the low-level convergence and deformation responsible for it was nearing its maximum intensity. Also, in a region of generally weak middle-tropospheric stability in the wake of strong thunderstorms, a low-pressure region was forming on the surface in western Louisiana and coastal Texas. This feature apparently fed on the low-level baroclinicity of the groundward extension of the middle-tropospheric cold front, and also the synoptic lifting associated with a strong vorticity maximum at 500 mb that entered the

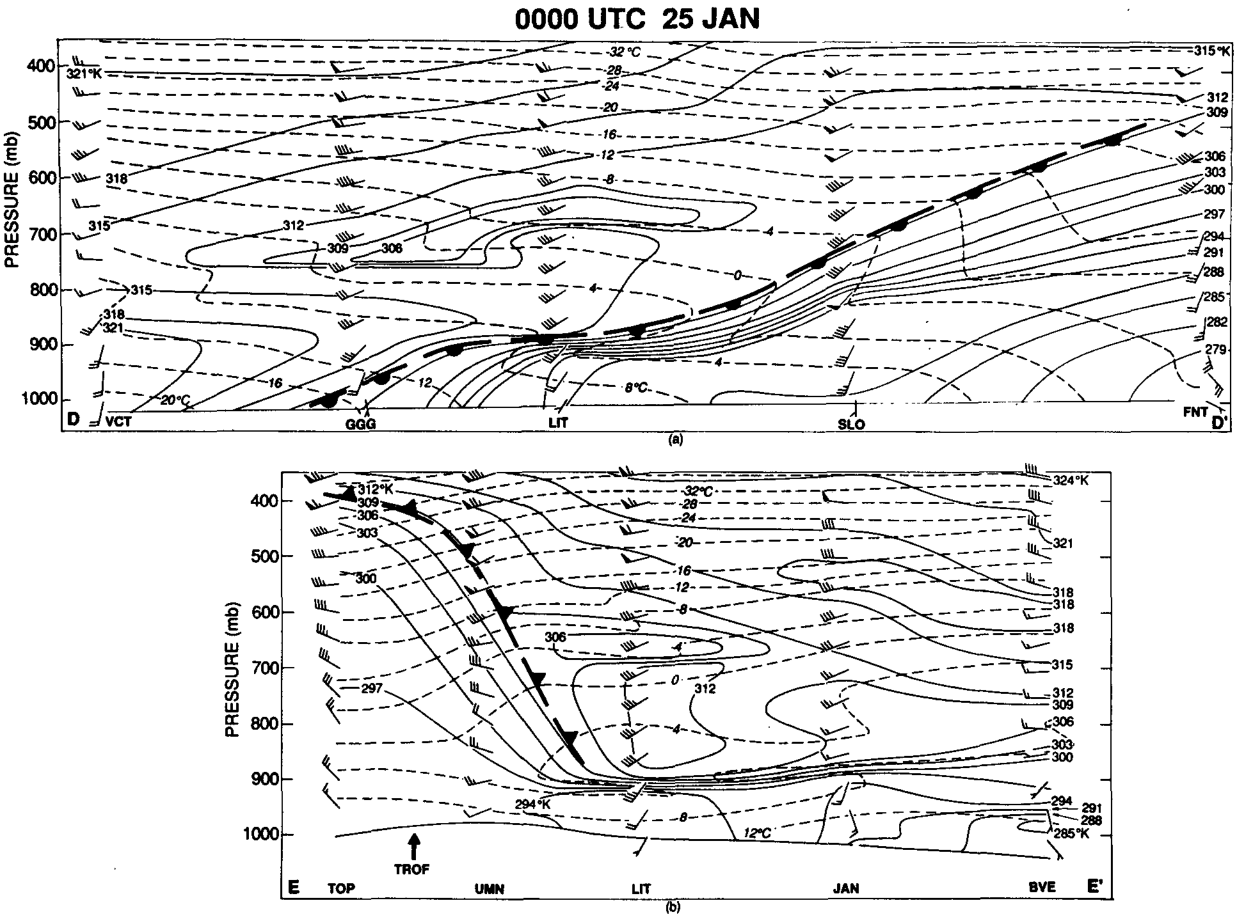

Fig. 16. (a) Cross section (along *D–D'* in Fig. 15a) from Victoria, Texas (VCT), to Longview, Texas (GGG), to Little Rock, Arkansas (LIT), to Salem, Illinois (SLO), to Flint, Michigan (FNT) at 0000 UTC 25 January 1986. (b) Cross section (along *E–E'* in Fig. 15a) from Topeka, Kansas (TOP), to Monett, Missouri (UMN), to Little Rock, Arkansas (LIT), to Jackson, Mississippi (JAN), to Boothville, Louisiana (BVE) at 0000 UTC 25 January 1986. See caption to Fig. 4 for key to lines and symbols. The dashed frontal symbols in panels (a) and (b) indicate the positions of the frontal surfaces in the middle troposphere.

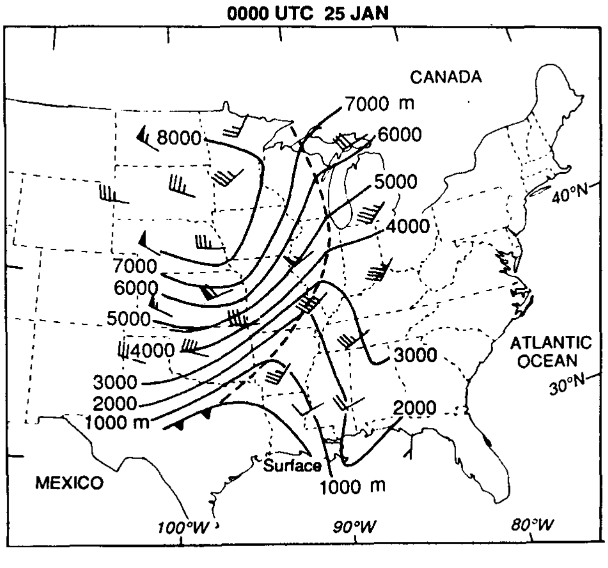

Fig. 17. As for Fig. 11 but for 0000 UTC 25 January 1986.

region from the Great Plains (Fig. 19a). It was this system that was eagerly anticipated by the GALE field researchers. (In fact, the cold air outbreak that resulted from its passage over the southeastern United States provided the record low temperatures in Florida on the day that the *Challenger* shuttle exploded just after lift off.)

Other cross sections (not shown here) illustrated the progression of the frontal system to the east. Much of the information in these cross sections is seen in the 306 K θ_e surface shown in Fig. 20. At 1200 UTC 25 January, the middle-tropospheric front was still well ahead of the surface trough, and advancing steadily towards the New York City–Baltimore corridor. Once again, the radar precipitation echoes were coincident with the analyzed position of the middle-tropospheric cold front (Fig. 19b). The cloudiness seen behind the front in the satellite imagery was determined from soundings and surface hourly reports to be high, nonprecipitating cloud. By 1800 UTC 25 January, the

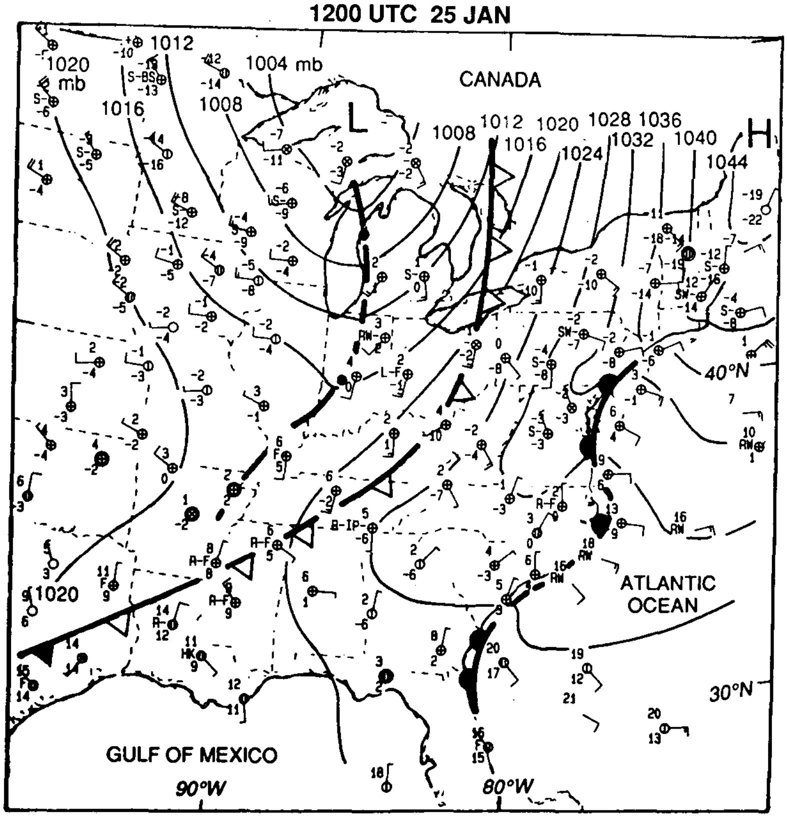

FIG. 18. As for Fig. 2 but for 1200 UTC 25 January 1986. For key to symbols see caption to Fig. 14. Solid warm-frontal symbol represents the coastal front.

coastal front had reached its maximum intensity, especially in the Middle Atlantic states, and the precipitation had begun to move towards the coast.

c. Interactions with the coastal front along the East Coast

The 0000 UTC 26 January surface analysis is shown in Fig. 21. The cyclogenesis in the Gulf of Mexico was still the beneficiary of strong synoptic support, as the southern vorticity maximum intensified (Fig. 22a). The circulation associated with the coastal front had pushed it inland all along the coast. A cross section from Flint, Michigan to Pittsburgh, Pennsylvania (PIT), to Washington, D.C. (IAD), to Wallops Island, Virginia (WAL) (Fig. 23) shows the superposition of the middle-tropospheric front and the low-level coastal front.

The 306 K θ_e surface for this time is shown in Fig. 24. It shows that the leading edge of the middle-tropospheric frontal zone coincided with the coastal front only over the New York City–Baltimore corridor. Radar echoes (Fig. 22b) were aligned along the leading edge of the middle-tropospheric cold front. The cloudiness evident on the satellite picture appears well behind the middle-tropospheric cold front. As the front progressed across the United States, its nose apparently flattened, producing a much wider region of lifting along it. This progressive flattening, which resulted in the elongated nonprecipitating cloud shield behind the analyzed position of the front, can be seen in Figs. 17, 20, and 25, and especially in Figs. 26, 27 and 29.

The distribution of precipitation along the East Coast was documented using 3-hourly raingauge data collected during GALE. This data network consisted of mostly standard reporting sites and some special sites. Data were analyzed in a block everywhere north of 32°N and everywhere east of 83°W (the entire coastal front domain). Certain regions in this block, most notably the state of Virginia, were void of precipitation reports, making it appear as though no precipitation fell there. This was not the case, as evidenced by the composite radar data shown in Fig. 22b. In fact, light precipitation was falling along much of the coastal front between 1200 UTC 25 January and 0000 UTC 26 January. Similarly light amounts occurred west of the New Jersey–Pennsylvania border between 1200 UTC and 1500 UTC 25 January (Fig. 25a). By 1800 UTC the precipitation rate had increased over that region (Fig. 25b) and continued to increase consistently there through 0000 UTC 26 January (Figs. 25c and 25d). Precipitation totals elsewhere along the East Coast,

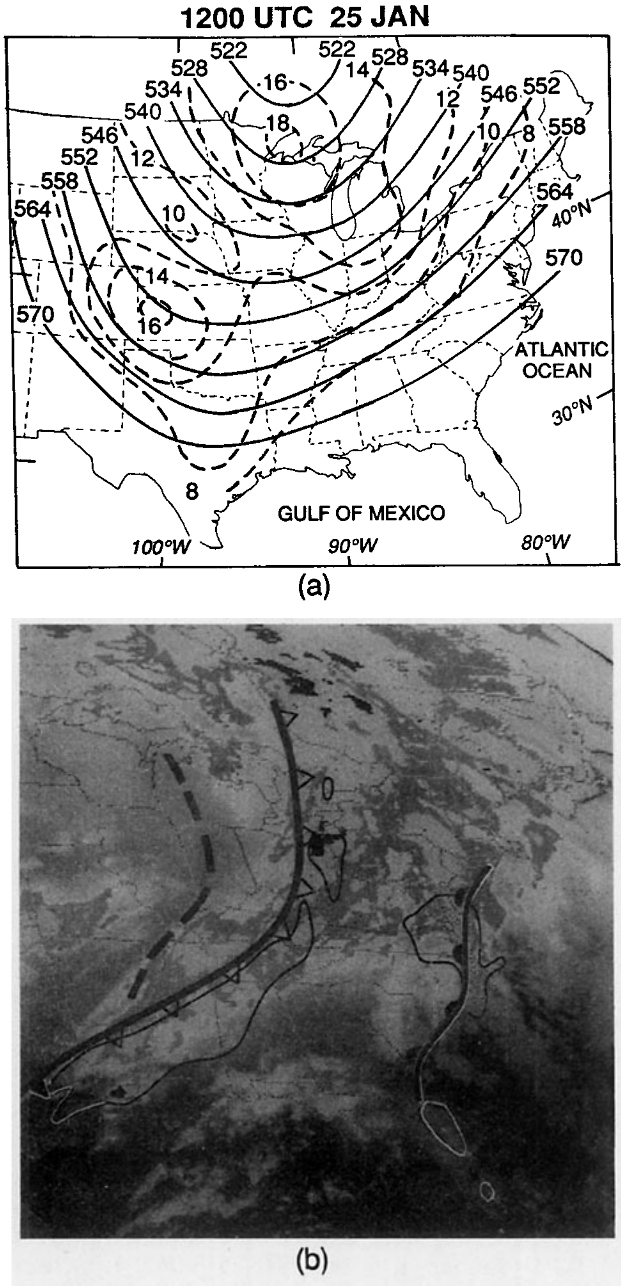

FIG. 19. (a) As for Fig. 12 but for 1200 UTC 25 January 1986. (b) Infrared satellite image for 1200 UTC 25 January 1986. Conventions as for Fig. 15c, except the solid warm-frontal symbols represent the coastal front.

however, remained very light during the same time period.

3. Discussion

a. Formation and maintenance of the warm-frontal surface

The dynamical distinctions between cold and warm fronts have been discussed by Hoskins and West (1979) and Hoskins and Heckley (1981) in the context of quasi-geostrophic theory. Harrold (1973) introduced the idea of the warm "conveyor belt" but did not discuss the possible frontogenetic nature of this feature. Locatelli et al. (1989) did not discuss, in any detail, the nature of formation of the warm-frontal feature described in their case, although they did relate it to the lee-side trough. Here we will discuss some of the frontogenetic processes that may have played a role in the formation and maintenance of the warm-frontal feature discussed in this paper.

After strengthening over a 24 h period beginning at 0000 UTC 23 January, the lee-side trough began to move eastward between 0000–0600 UTC 24 January 1986. The deepening, accompanied by slow, moderate falls in the pressures to the east of the trough, greatly increased the horizontal pressure gradient between the trough and the high-pressure region to the east. This resulted in a core of strong warm-air advection, extending upward to 700 mb over the Great Plains (see Fig. 3). At this time, the temperature fields at both 850 and 700 mb were subjected to frontogenetical diffluence east of the lee-side trough. By 0000 UTC 24 January, continued strengthening of the trough circulation had given rise to stronger flow at both 850 and 700 mb. The 700 mb temperature at Omaha, Nebraska, had risen 8°C between 1200 UTC 23 January and 0000 UTC 24 January and moderate diffluence still persisted just downstream of Omaha. At 850 mb, strong flow off the Mexican plateau increased the temperature at

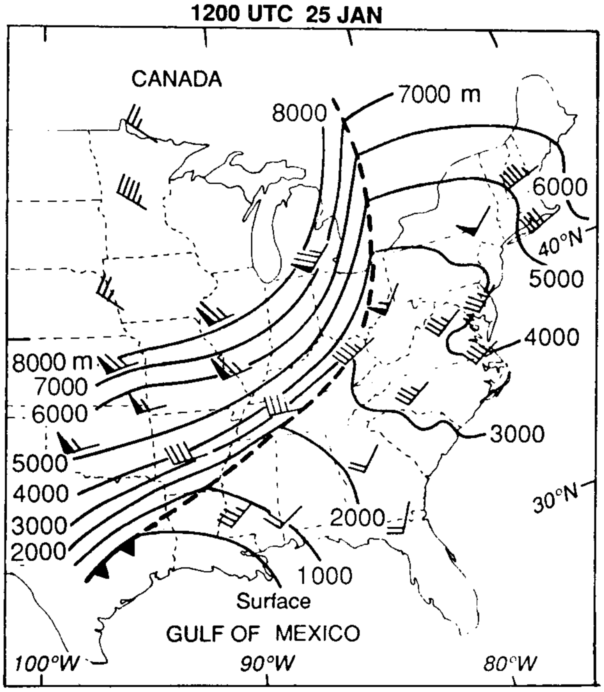

FIG. 20. As for Fig. 11 but for 1200 UTC 25 January 1986.

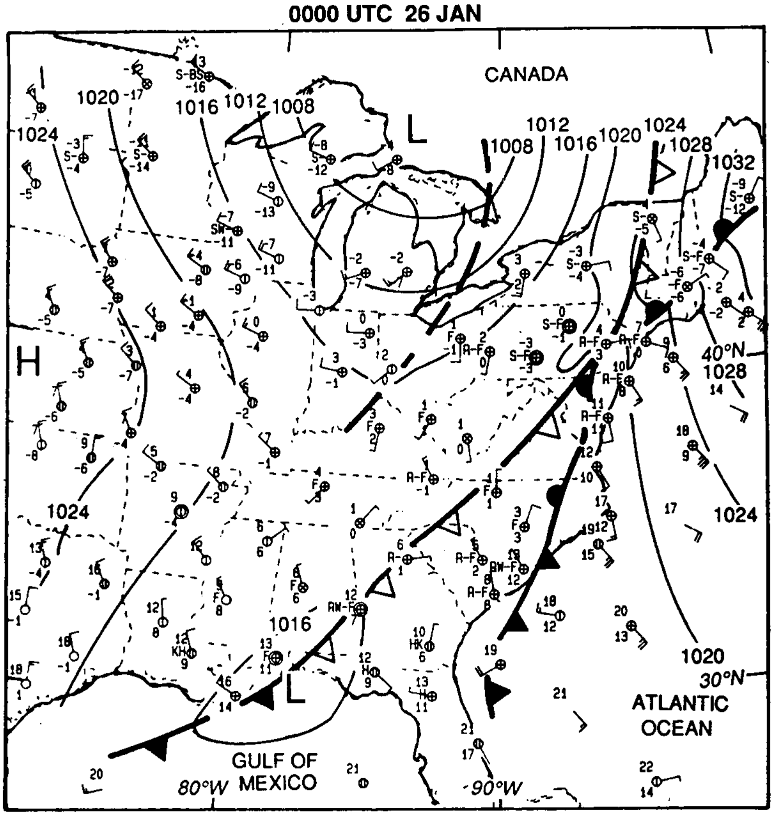

FIG. 21. As for Fig. 2 but for 0000 UTC 26 January 1986. Symbols as for Fig. 14.

Amarillo, Texas, by 8°C by 0000 UTC 24 January (Figs. 6a, 6b). At 850 mb frontogenesis was occurring everywhere north of Oklahoma City and Amarillo.

Frontogenetic values (F) (not shown here) were calculated using NGM grid point data at 50 mb intervals using Miller's (1948) 2-D formulation:

$$F = \frac{1}{|\nabla\theta|}\left\{\frac{\partial\theta}{\partial x}\left[-\frac{\partial u}{\partial x}\frac{\partial\theta}{\partial x}-\frac{\partial v}{\partial x}\frac{\partial\theta}{\partial y}\right]+\frac{\partial\theta}{\partial y}\left[-\frac{\partial u}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial v}{\partial y}\frac{\partial\theta}{\partial y}\right]+\frac{\partial\theta}{\partial p}\left[-\frac{\partial w}{\partial x}\frac{\partial\theta}{\partial x}-\frac{\partial w}{\partial y}\frac{\partial\theta}{\partial y}\right]\right\}. \quad (1)$$

This formulation for frontogenesis was chosen over quasi-geostrophic formulations because of the availability of the 3D, gridded, total wind data from the NGM. For this case, typical values of F at low levels (900–750 mb) were 3°–4°C/100 km per day in a region stretching from south-central Texas northward to Nebraska. At higher levels, these values were between 1°–2°C/100 km per day. This weakly frontogenetic flow produced a moderately intense, warm-frontal zone.

After 0000 UTC 24 January, the lee trough and the zone of strong warm-air advection moved away from the mountains. At 1200 UTC 24 January, the strongest warm-advection was over central and northern Texas at 850 mb. A deformation zone between Stephenville, Texas, and Little Rock, Arkansas, at 850 mb produced frontogenesis at lower latitudes than had previously been observed. At the same time, diffluent frontogenesis was occurring at 700 mb from southwest Missouri to Lake Michigan. This suggests that a sloping layer of frontogenesis was produced from northeastern Texas northward to Lake Michigan and that it moved eastward ahead of the advancing lee trough. This configuration was no doubt responsible for the generation and progression of the warm-frontal surface from 1200 UTC 24 January to 1200 UTC 25 January described in this paper.

Some understanding of the manner in which the northward sloping deformation/warm advection zone was produced can be obtained by considering the thermal structure of the trough in the lee of the Rockies. The warmest air at the surface, at 850 mb, and at 700 mb was along the trough axis at both 1200 UTC 23 January and 0000 UTC 24 January. Also, the lee trough was vertically stacked up to 700 mb. Thus, a thickness ridge existed in the middle of the trough. Accordingly, the sharpness of the trough decreased with height and the zone of strongest warm-air advection and deformation occurred increasingly farther north with height. We conclude that the warm-frontal surface observed

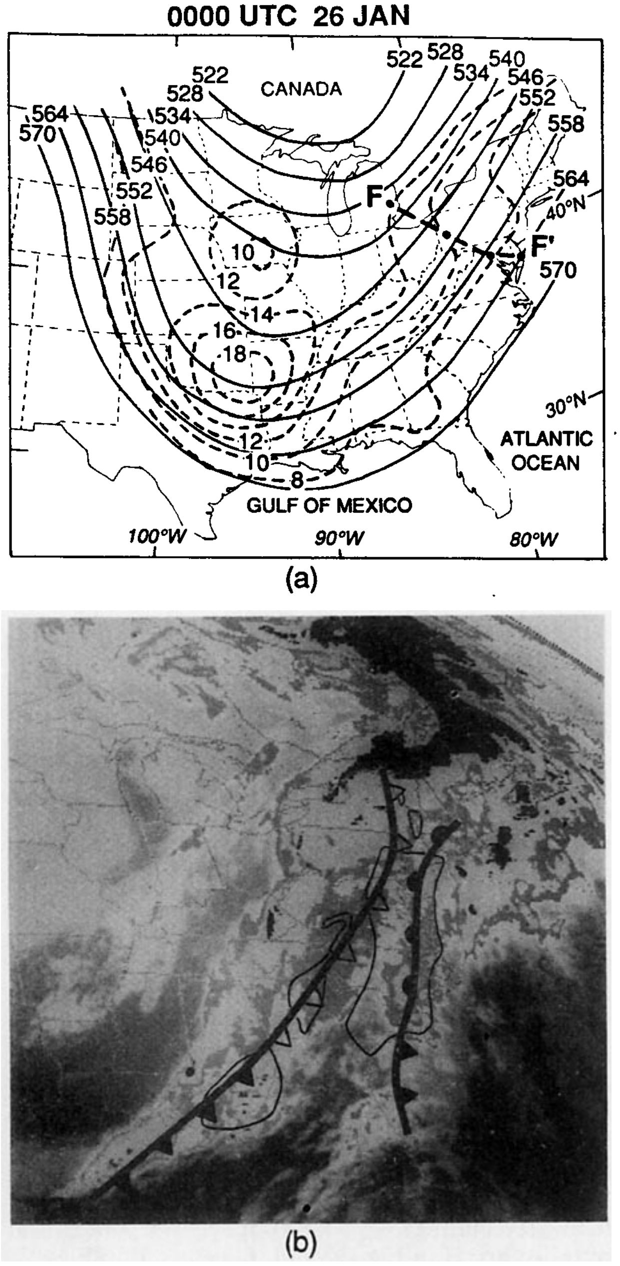

FIG. 22. (a) As for Fig. 12 but for 0000 UTC 26 January 1986. The solid line *F–F'* indicates the position of the cross section shown in Fig. 23. (b) Infrared satellite image for 0000 UTC 26 January 1986. Conventions as for Fig. 15c, except the solid warm-frontal symbols represent the coastal front.

in this case study was generated by the sloping zone of strong warm-air advection induced by the 3-D circulation associated with the trough in the lee of the Rocky Mountains.

The maintenance of this warm-frontal surface as it moved away from the Rockies was probably dependent on the circulation associated with the middle-tropospheric cold front; Fig. 10b illustrates this point. In this cross section, the warm-frontal surface loses much of its character below the point where it intersects with the middle-tropospheric cold front. Ahead of this front there is strong southerly flow and warm-air advection, especially at 0000 and 1200 UTC 25 January, as seen in the vorticity fields (Figs. 15b and 19a) and in the 306 K θ_e analyses (Figs. 17 and 11). This advection, though only modestly frontogenetic, probably helped to maintain the warm-frontal surface that had been previously generated. Below the point of intersection of the middle-tropospheric cold front and the warm front, however, strong southerly flow was not present since the cold-frontal circulation was aloft. Thus, below the point of intersection, the warm-frontal feature deteriorated rapidly.

By 0000 UTC 26 January, the lack of significant frontogenesis along the warm-frontal surface resulted in a weakening of the front. The circulation associated with the middle-tropospheric cold front had also weakened somewhat, as seen in the 500 mb vorticity field for 0000 UTC 26 January (Fig. 22a), and this may also have been a factor in the weakening of the warm-frontal surface.

b. Precipitation from the middle-tropospheric cold front and the coastal front

Figures 26 and 27 are 3-D schematic representations of the frontal system described in this paper at 1200 UTC 25 January at 0000 UTC 26 January, respectively. The arrows represent 11 h trajectories of air parcels ending at 1200 UTC 25 January (Fig. 26) and 0000 UTC 26 January (Fig. 27). Trajectory E in Fig. 26 shows that considerable lifting occurred ahead of the middle-tropospheric cold front in the 11 h leading up to 1200 UTC 25 January. This lifting resulted in the light precipitation that fell over the shaded area in Fig. 26. Trajectory G and H show the circulation of the low-level coastal front and its associated precipitation region.

Trajectory I in Fig. 27 indicates that subsidence in the cold air occurred behind the middle-tropospheric cold front in the 11 h ending at 0000 UTC 26 January. Trajectory J shows strong lifting just ahead of the mid-level feature during this same period. Trajectory L indicates the veering in the surface winds that contributed to the demise of the coastal front by weakening the low-level convergence and deformation fields which are important to frontogenesis.

The maximum 3 h averaged precipitation rate due to the middle-tropospheric cold front upstream of and just prior to its superposition with the coastal front was 0.8 mm h^{-1}. The maximum 3 h averaged precipitation rate due to the coastal front prior to the superposition of the middle-tropospheric cold front was 1.6 mm h^{-1}, but the maximum 3 h averaged precipitation rate after the two fronts were superimposed was 5.3 mm h^{-1}. Thus, the combination of the middle-tropospheric cold

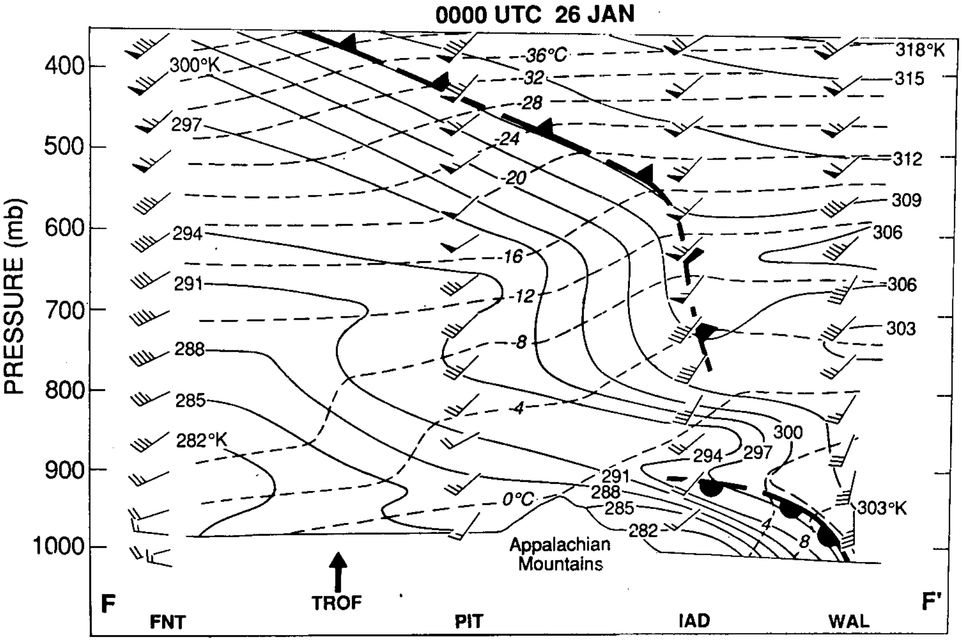

FIG. 23. Cross section (along the line *F–F′* in Fig. 22a) from Flint, Michigan (FNT), to Pittsburgh, Pennsylvania (PIT), to Washington, D.C./Dulles (IAD), to Wallops Island, Virginia (WAL) at 0000 UTC 26 January 1986. See Fig. 4 caption for key to lines and symbols. The dashed cold-frontal symbols represent the cold front in the middle troposphere. The solid warm-frontal symbols represents the coastal front.

front and the coastal front produced a precipitation rate that was more than twice the sum of the two individual precipitation rates. Marks and Austin (1979) suggested that low-level clouds associated with a coastal front could enhance synoptic scale precipitation through a "seeder–feeder" process. This was likely in the present system; however, another process also appears possible. A comparison of the vertical air velocities before and during the superposition of the two fronts indicates that the low-level vertical velocity associated with the coastal front increased when superposition occurred. This increase in vertical velocity could have been responsible for the enhanced precipitation rate, in which case the superposition of the two fronts produced dynamical as well as microphysical effects.

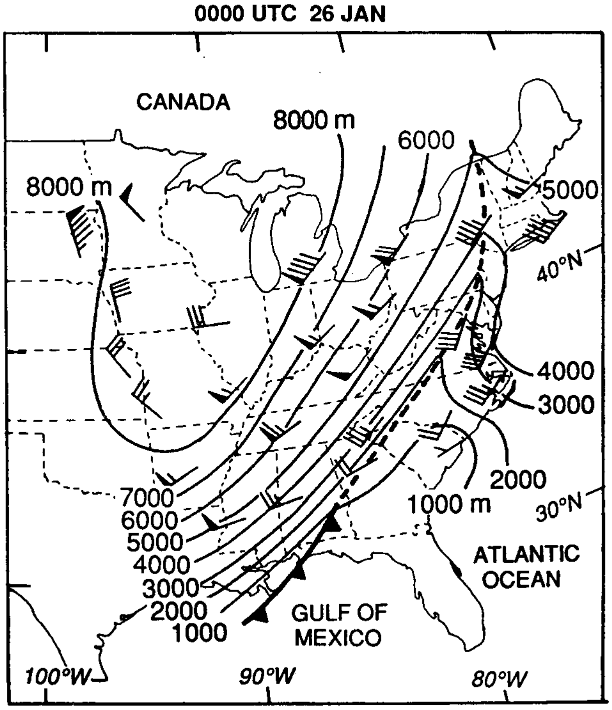

FIG. 24. As for Fig. 11 but for 0000 UTC 26 January 1986.

To illustrate this latter point we compare the change in low-level lifting (~1.5 km) implied by a comparison of trajectory H in Fig. 26 and trajectory L in Fig. 27. Trajectory H in Fig. 26 shows that relatively little lifting occurred near 1.5 km as oceanic air was advected inland during the initial coastal frontogenesis. The substantial low-level lifting resulting from the superposition of two features is indicated by trajectory L in Fig. 27. The increase in low-level lifting was presumably a result of the combined circulation of the middle-tropospheric cold front and the coastal front.

c. Some possible connections with drylines and squall lines

Some similarities exist between aspects of the middle tropospheric frontal system described in this paper and

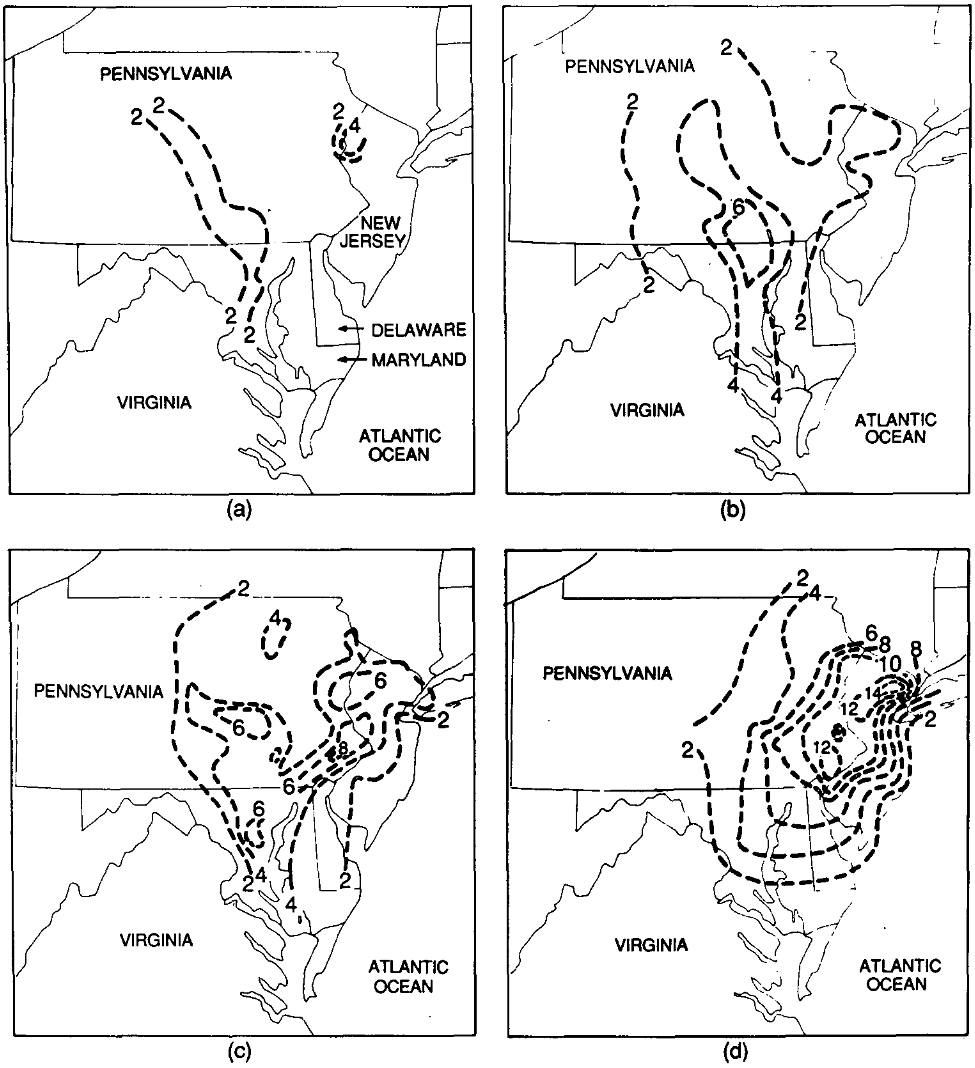

Fig. 25. Precipitation totals (dashed lines, labeled in millimeters of liquid water equivalent) over 3 h ending at (a) 1500, (b) 1800, and (c) 2100 UTC on 25 January 1986, and at (d) 0000 UTC 26 January 1986.

features commonly associated with drylines and squall lines in the south-central United States. In this section we point out some of these similarities, and we suggest that middle-tropospheric cold fronts may trigger squall lines.

The structure of the dryline, an intense low-level moisture gradient separating moist air originating in the Gulf of Mexico from dry air originating in the desert southwest and in the lee of the Rockies, has been described by McCarthy and Koch (1982) and Schaefer (1974).

The dryline is most commonly observed in Texas and Oklahoma from May through July as hot air, that subsides from the Mexican plateau and/or the Rockies, meets extremely humid summertime air from off the Gulf Coast of Texas and the lower Mississippi River Valley. We believe that drylines are characterized by moderate troughs in the surface pressure field (for example, see Fig. 4b of McCarthy and Koch).

In the case described in this paper, which occurred in winter, there was a substantial gradient in mixing ratio across the lee trough (Fig. 28), and this produced a structure that resembled a dryline. In the present case, however, the moisture signal was much weaker than the pressure signal, whereas the reverse was true for the dryline described by McCarthy and Koch.

In spring and summer (the dryline season), the mean flow perpendicular to the Mexican Plateau and the Rockies is considerably weaker than during winter. Also, in spring and summer the air temperature is higher and the mixing ratio gradient between the Gulf of Mexico and western Texas is higher than in winter.

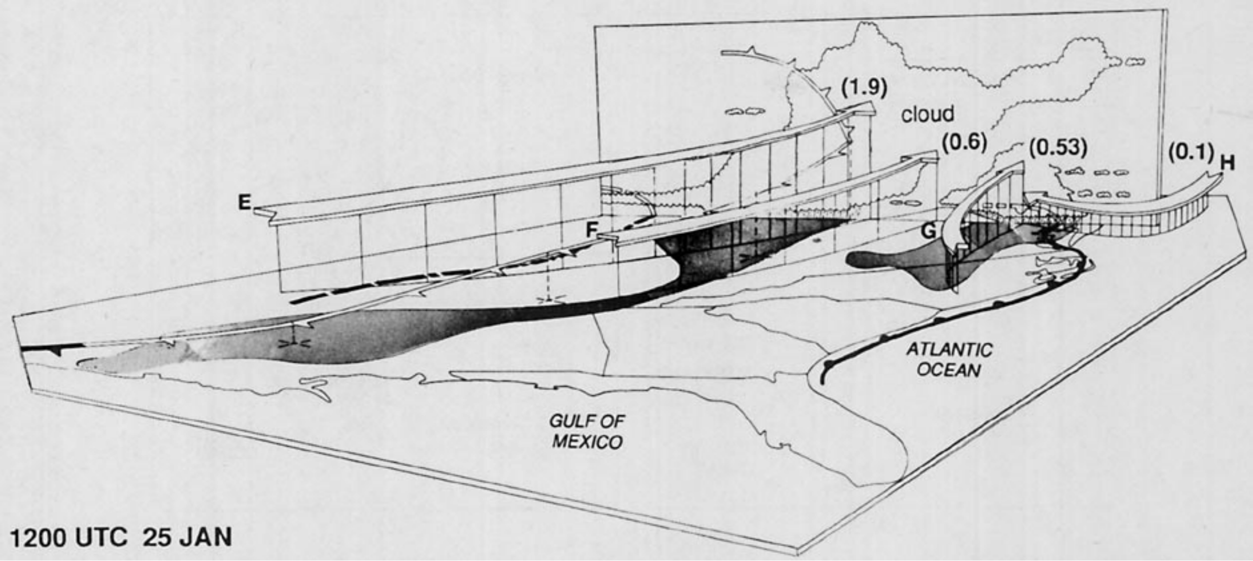

FIG. 26. Three-dimensional representation of the frontal structure at 1200 UTC 25 January 1986. Open cold-frontal symbols represent the positions of the cold front in the middle troposphere. Solid cold-frontal symbols represent its extension to the ground. The dashed line represents the position of the leeside trough and, further north, the dashed-dot line represents the shallow arctic front. Solid warm-frontal symbol represents the position of the coastal front. The broad arrows represent 11 h trajectories ending at 1200 UTC 25 January 1986 (see text for explanation). Values of net vertical displacement (km) are indicated at head of trajectories. Scalloped areas indicate regions of cloudiness. Shaded areas indicate areas of precipitation.

With the absence of strong flow across the mountains, the pressure signal is generally less pronounced in spring and summer and it is overwhelmed by the moisture signal. With the migration southward of the jet stream in winter, the effect of troughing in the pressure field becomes stronger than the mositure signal, which is reduced by the cooler, drier air of winter. Thus, it is likely that similar processes, that differ only in degree by season, are associated with the generation of both troughs in the lee of the Rockies and the Mexican Plateau and the dryline.

Concerning the possibility that squall lines might be associated with cold fronts aloft, Newton (1950) states: "A difficulty with this explanation is the frequent lack of any evidence of a front aloft prior to the formation of the squall line." Browning (1985) suggested that squall lines in the midwestern United States often result from "split-front" structures. He did not, however,

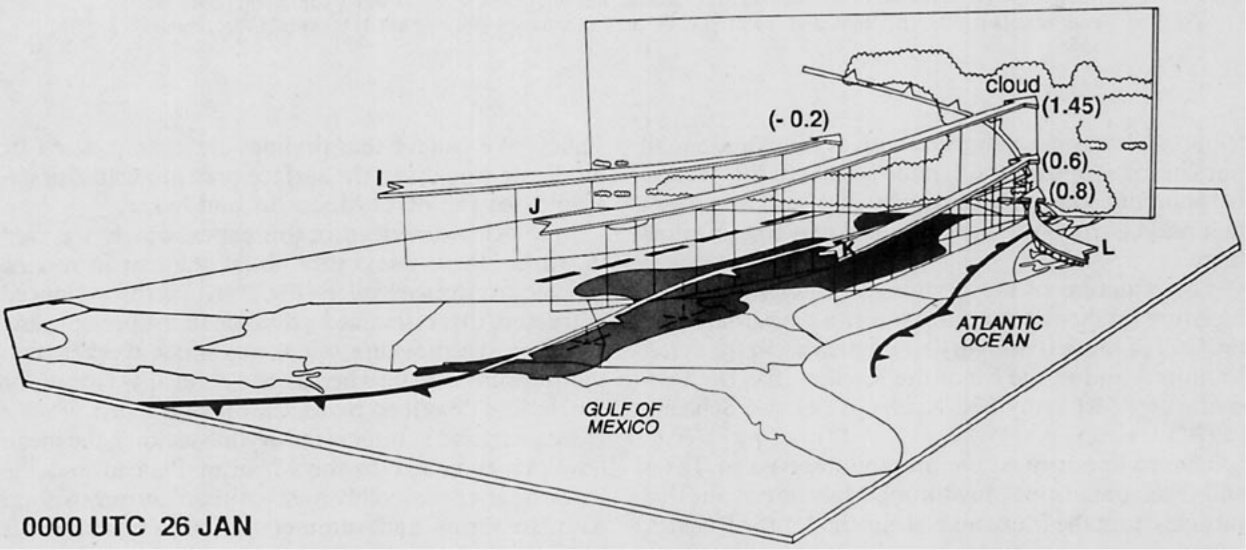

FIG. 27. As for Fig. 26 but for 0000 UTC 26 January 1986.

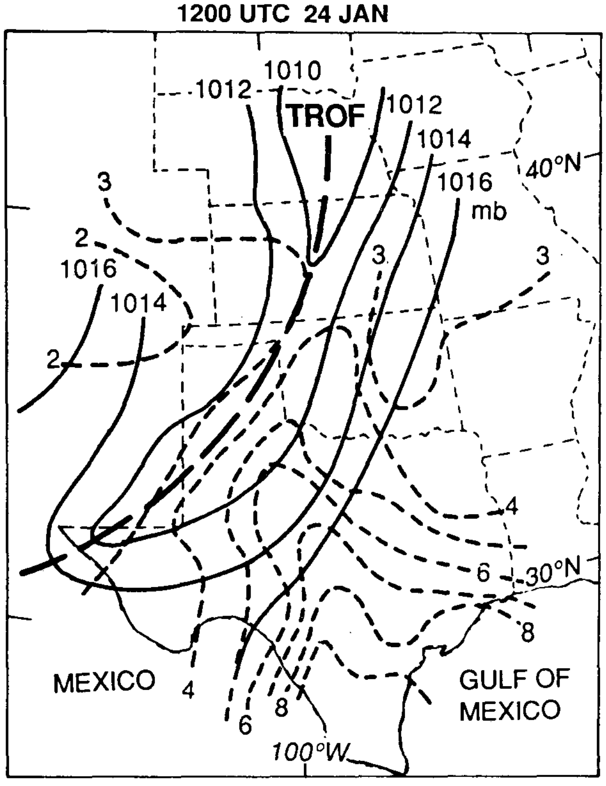

FIG. 28. Surface pressure (solid lines) in millibars and mixing ratio (dashed lines) in g kg^{-1} for 1200 UTC 24 January 1986.

present any observational evidence to support this suggestion. Locatelli et al. (1989) also speculated on the possibility that squall lines may be generated by cold fronts aloft, although there was no evidence of a squall line in the case they described. The thermodynamic structure and progression of the middle-tropospheric cold front in the case described in this paper sheds light on the role of middle-tropospheric fronts in squall line generation.

Figure 29 shows a 3-D schematic of the structure of the middle-tropospheric cold-front at 0000 UTC 25 January with trajectories ending at 0000 UTC 25 January. Trajectory C (12 h) shows that air rose from central Oklahoma to the north of the middle-tropospheric cold front. Subsidence well to the west of this front is indicated by trajectory D (8 h). The origin of the dry cap observed just ahead of the middle-tropospheric cold front was the elevated, arid Mexican plateau. This dry air subsided gently (trajectory A, 23 h) into central Texas and then, caught in the combined circulation of the lee trough and approaching cold front, it rose to a position just above the warm, moist tongue of air with $\theta_e > 312$ K (trajectory B, 23 h) that rode over the warm-frontal surface. In this manner, an elongated band of convectively unstable air developed just ahead of the advancing middle-tropospheric cold front (see Fig. 16b). The line of thunderstorms that developed from southeastern Missouri through northwestern Louisiana between 0000 and 0300 UTC was presumably the result of the release of instability provided by lifting ahead of the middle-tropospheric cold front. These thunderstorms persisted for nearly 6 h. Thus, in this case, it is beyond doubt that a line of severe weather, resembling a squall line, was generated by the passage of a middle-tropospheric cold front.

d. Comparisons with conceptual models

Despite growing awareness that current conceptual models for middle-tropospheric fronts [e.g., the classical occlusion model (Bjerknes and Solberg 1922), the trowal model (Penner 1955), and the split-front model (Browning and Monk 1982)] are deficient (for example, see Locatelli and Hobbs 1987), various segments of the meteorological community find these models useful (e.g., Browning 1985; Reynolds and Dennis 1986). Hence, although these models may not be perfect, they probably contain various elements of the truth. If better conceptual models are to be developed, we must begin to describe how the existing models differ from real weather systems.

The weather system described in this paper does not fit any of the established conceptual models. This system did not have a surface occluded front, or the lower-level occluded front characteristic of a warm occlusion, although a cold and warm front did intersect aloft. The system had a middle-tropospheric cold front (as depicted in the split-front model), but, contrary to that model, it had neither a trailing surface cold front nor a line of maximum θ_e connecting the base of the middle-tropospheric cold front to a surface cold front. The intersection of the warm and cold fronts aloft (shown as the position of the middle-tropospheric cold front in Figs. 8, 14, 18 and 21) sloped upwards from the surface, which fits the definition of a trowal. The system, however, did not develop in the fashion envisaged for a trowal.

Differences in the development of this system from the one described by Locatelli et al. (1989) have been discussed in section 2. Although both systems resulted from the overtaking of a trough in the lee of the Rockies by a cold front, the system described in this paper did not exhibit the structure of a warm occlusion either at the surface or at low levels, while the system described by Locatelli et al. did. We attribute this difference to the fact that in the case described in this paper the faster-moving front was in the middle troposphere, while in this case described by Locatelli et al. it was on the surface. Also, in the latter case, the presence of a surface cold front was necessary for the formation of a surface occluded front. In the present case, there was no surface cold front and the lee-side trough retained its structure as it moved away from the Rockies. Additionally, the trough weakened along its southern portion where it was not overtaken by an arctic front (see

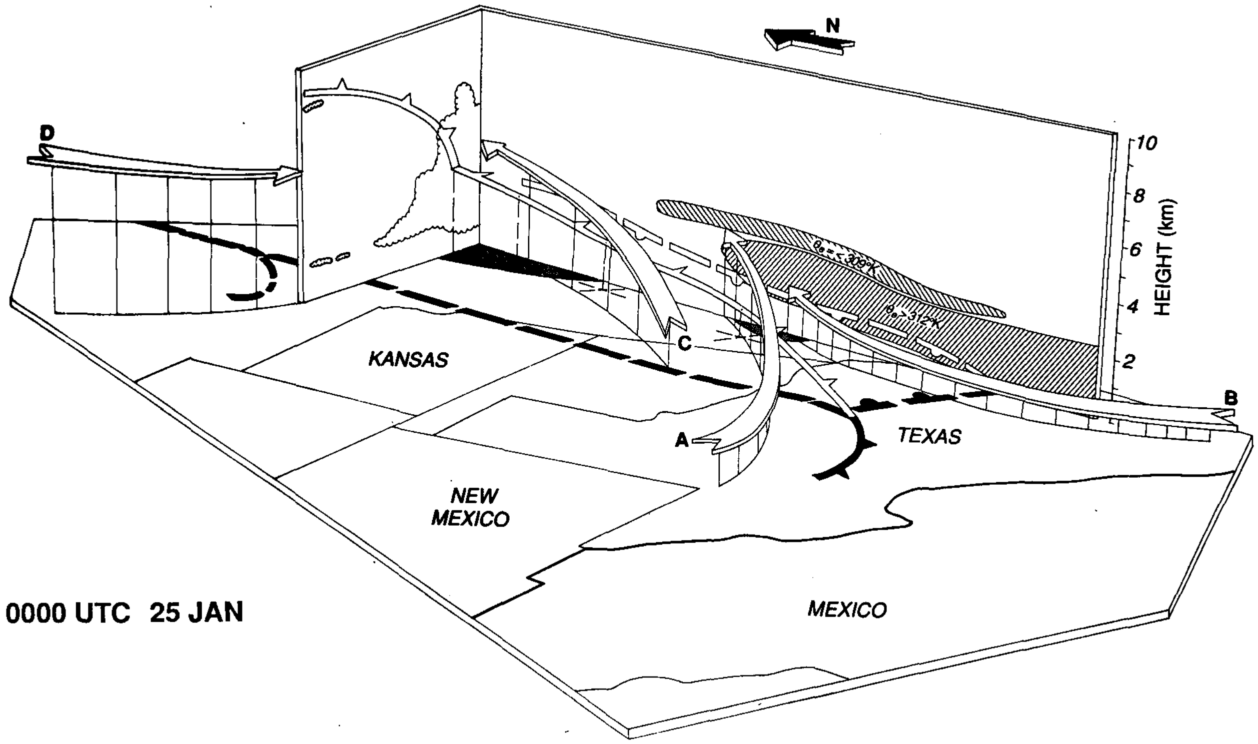

FIG. 29. Three-dimensional representation of the frontal structure at 0000 UTC 25 January 1986. As for Fig. 26 except A and B are 23-h trajectories, C is a 12-h trajectory, and D is an 8-h trajectory; all ending at 0000 UTC 25 January 1986.

section 2). We suggest that a lee-side trough can move eastward away from the Rockies without weakening only if it is transformed by being overtaken by a surface cold front or an arctic front.

4. Summary and conclusions

In this paper we have described the development and eastward progression of a warm occlusion-like structure that formed in the lee of the Rocky Mountains, moved eastward and produced precipitation in the eastern United States.

The following principal results have emerged from this study:

- A lee-side trough developed east of the Rocky Mountains in response to the adiabatic warming produced by westerly flow across the mountains.
- The 3-D structure of the leeside trough resulted in a circulation that was modestly frontogenetical. This produced a warm front in a zone of warm-air advection east of the leeside trough.
- When a short wave at 500 mb and an associated middle-tropospheric cold front overtook the trough and the warm front, a middle-tropospheric occluded-like structure formed. This structure differed from a classical warm occlusion in that prior to the "occlusion process" there was no surface cold front and after the occlusion process there was not an occluded front at the surface.
- The lifting associated with the eastward advance of the middle-tropospheric cold front triggered a line of thunderstorms in the lower Mississippi River Valley, where the stratification was convectively unstable.
- We suggest that lee troughs and drylines are formed by similar physical processes, with seasonally varying factors accounting for differences between the two features.
- The structure and formation of this frontal system is inadequately described by present conceptual models.

Acknowledgments. We wish to thank Ernest Recker, Hampton Terry and Bart Geerts for computer support and assistance, and Kumud Biswas for technical support. This research was funded by the National Science Foundation under Grants ATM-8311147 and ATM-8809061.

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