Cold Fronts Aloft and the Forecasting of Precipitation and Severe Weather East of the Rocky Mountains

PETER V. HOBBS, JOHN D. LOCATELLI AND JONATHAN E. MARTIN

Atmospheric Sciences Department, University of Washington, Seattle

(Manuscript received 12 December 1989, in final form 12 July 1990)

ABSTRACT

Brief descriptions are given of four cases that illustrate the important role that cold fronts aloft (CFA) can play in producing significant weather east of the Rocky Mountains. In all four cases, the CFA, and its associated short wave, were located ~200–300 km ahead of a surface trough. Precipitation (and in some cases severe weather) developed along the leading edge of the CFA. The nested grid model generally did a good job of locating the CFA. Analysis of absolute momentum confirms that these features were fronts, in a dynamic, as well as a thermodynamic sense.

A conceptual model for CFA is presented. In the cases examined, this model provides not only a useful picture of the distribution of clouds and precipitation associated with CFA, but also means for locating them. It also helps to define a major class of systems that do not fit the Norwegian cyclone model. Therefore, it should help in the identification of CFA and in improving the forecasting of precipitation and severe weather associated with them.

1. Introduction

This paper is concerned with cold fronts aloft (CFA) east of the Rocky Mountains. The importance of such features in this region was discussed over 50 years ago by Holzman (1936) and Lichtblau (1936), who believed that a majority of significant winter precipitation in the Midwest was associated with CFA. Lloyd (1942) discussed the structure of what he termed "upper-air cold fronts" and their apparent relation to the development and movement of tornadoes. Subsequently, and possibly due to the ascendancy of the Norwegian frontal model, recognition of the importance of CFA appears to have been largely lost.

Recently, the term "upper-level cold front" has been used to describe fronts that form at or near the tropopause (e.g., Keyser and Shapiro 1986). Rather than using this term to describe cold-frontal zones whose bases are situated above the surface in the lower or middle troposphere, we use the term CFA.

We use the term "cold front" to refer to the leading edge of a transitional zone that separates advancing cold air from warm air, the length of which is significantly greater than the width of the transitional zone. This zone is characterized by larger-than-background gradients in temperature and absolute momentum as well as high stability. The term "arctic front" refers to a shallower (extending up to 800–700-mb) surface cold front, usually found in the northwest quadrant and to the rear of the center of a cyclone. A "trough" (indicated on the figures by TROF) is a line of maximum cyclonic curvature in the surface isobars, but it does not have the thermal character of a front (Reed 1979). The term "Norwegian cyclone model" refers to a cyclonic system containing a surface cold front, a surface warm front, and a warm sector.

We begin this paper with brief descriptions of four case studies that illustrate CFA and the important role they can play in producing precipitation and triggering severe weather east of the Rockies. These case studies also demonstrate how the Norwegian cyclone model could mislead forecasters. We then present a conceptual model for CFA together with means for identifying them, which may aid in the forecasting of frontal precipitation and, in some cases, severe weather east of the Rockies.

2. Case studies

The first two cases deal with (a) troughs in the lee of the Rocky Mountains and (b) cold fronts at the surface and aloft. The third and fourth cases are CFA associated with troughs aloft that migrated across Arizona and New Mexico into Texas.[1]

Corresponding author address: Peter V. Hobbs, Dept. of Atmospheric Science, AK 40, University of Washington, Seattle, WA 98195.

[1] Three of these cases have been described in detail elsewhere: see Martin et al. (1990) for the 25 January 1986 case, Locatelli et al. (1989) and Sienkiewicz et al. (1989) for the 6 March 1986 case, and Businger et al. (1990) for the 13 March 1986 case.

a. 25 January 1986

At 1200 UTC 23 January 1986 a well-defined, short-wave trough was present at 500 mb over northern California and southern Oregon. This produced strong winds perpendicular to the ridge of the Rocky Mountains and a lee-side trough. The thermal structure of the trough was discernable from the surface to 700 mb, as the axis of warmest air occupied the trough axis. In the 24-h period ending at 1200 UTC 24 January 1986, two important processes occurred. First, the circulation induced by the thermal structure of the lee trough (a thickness ridge along the axis of the trough) was such that the sharpness of the trough decreased with height. Thus, the region of strongest warm air advection occurred farther north with height, resulting in a modestly frontogenetic, sloping zone of warm air advection that produced a warm-frontal surface east of the trough axis. Second, the 500-mb short-wave moved eastward, so that by 1200 UTC 24 January, the CFA associated with the wave had overtaken the warm-frontal surface, north of Oklahoma, to form an occluded-like structure in the middle troposphere. By 0900 UTC, the remnant

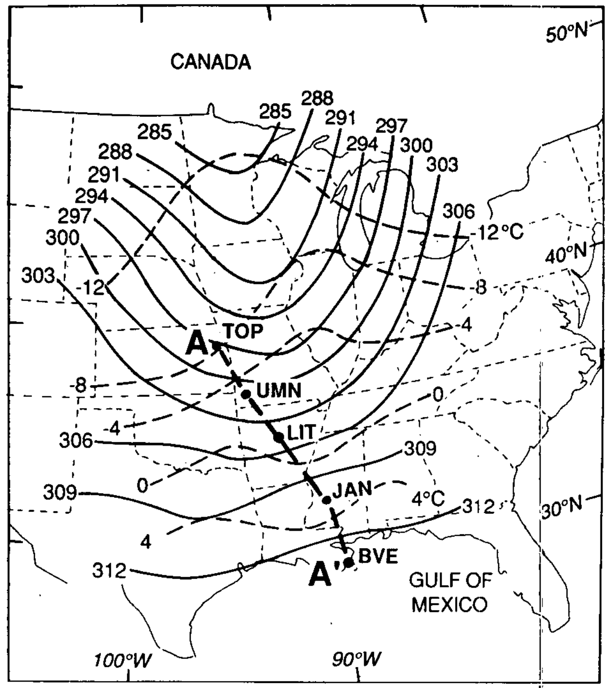

FIG. 1b. 700-mb analysis for 0000 UTC 25 January 1986. Shown are geopotential heights (continuous lines, labeled in tens of meters and contoured every 30 m) and temperatures (dashed lines, labeled in °C and contoured every 4°C). A cross-section along A–A' is shown in Figs. 2 and 3.

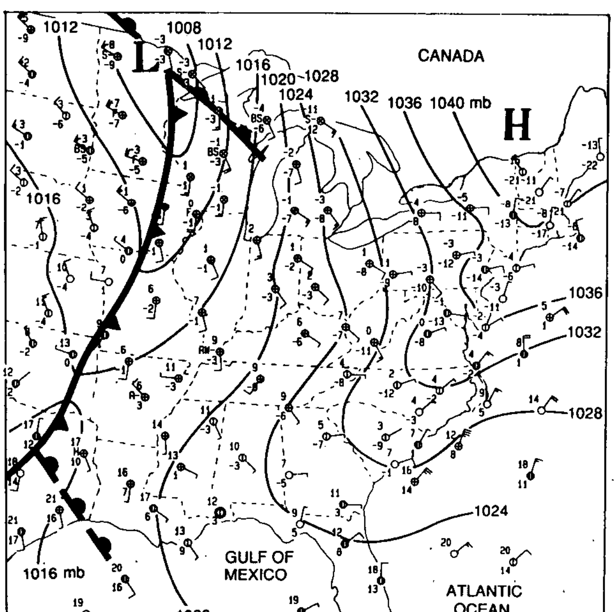

FIG. 1a. Surface pressure analysis for 0000 UTC 25 January 1986. Isobars are labeled in millibars and contoured every 4 mb. Surface frontal analysis is that of the NMC, with fronts indicated by the usual symbols. For each surface station, the following data are shown: temperature (labeled in °C to the upper left of the station symbol), dewpoint (labeled in °C to the lower left of the station symbol), wind direction and speed, skycover 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 +—overcast, and ×—sky obscured. Wind speeds are indicated by: a circle around a circle—calm, short barb—2.5 m s^{-1}, long barb—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.

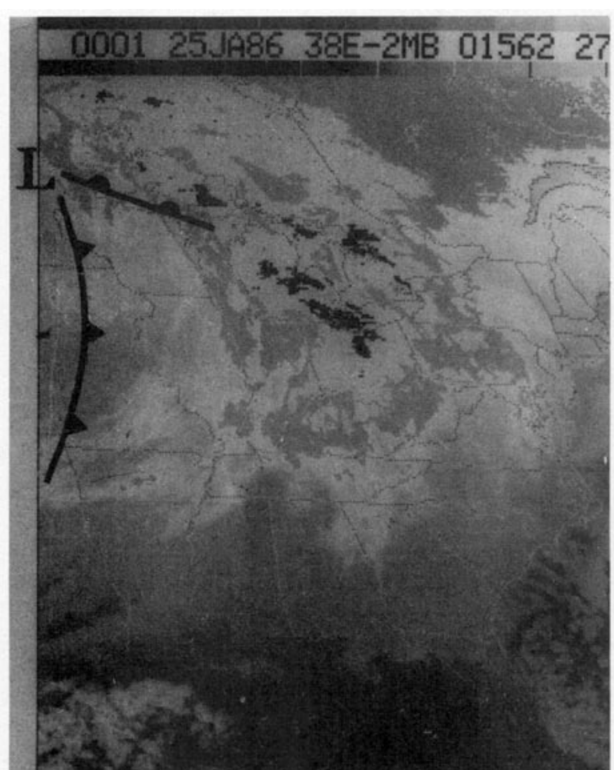

FIG. 1c. Infrared satellite image for 0000 UTC 25 January 1986. Surface frontal analysis is that of the NMC.

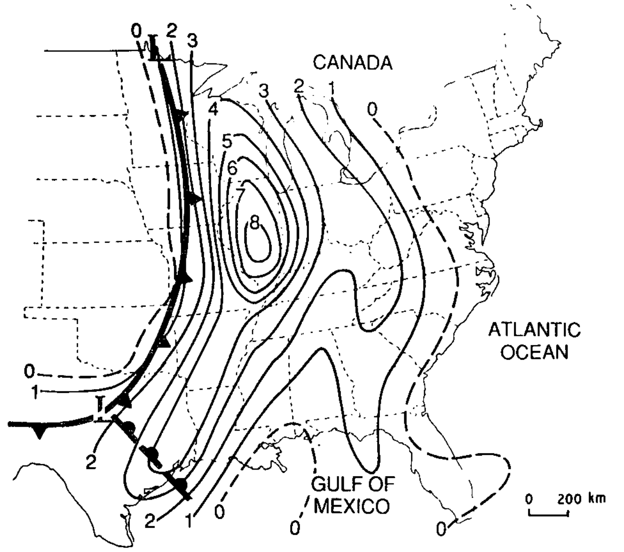

FIG. 1d. The 12-h forecast of the vertical velocity field at 700 mb valid at 0000 UTC 25 January 1986 from NMC's nested grid model. Shown are contours of upward vertical velocity labeled in cm s^{-1} and contoured every 1 cm s^{-1}. Surface frontal analysis is that of the NMC.

surface trough, which had begun as a lee-side trough, was analyzed by the National Meteorological Center (NMC) to contain a surface cold front.

By 0000 UTC 25 January, the surface trough had begun to weaken, but it still exhibited the characteristics of a lee trough (rather than a cold front), with temperatures actually rising slightly to the west of the trough axis (Fig. 1a). The leading edge of the cold air advection at 700 mb ran from northwestern Illinois, through east central Missouri, to central Arkansas (Fig. 1b), well to the east of the surface trough. However, the NMC analyzed a surface cold front in the center of the trough. There was, in fact, only a degenerating lee trough with an arctic front at its northern end. Notice that precipitation was occurring well ahead of the surface trough (Fig. 1a), in fact it was along the leading edge of a CFA. The CFA was a preferred region for quasi-geostrophic lifting, because the frontal zone contained large vertical and lateral shear (i.e., positive vorticity advection by the thermal wind). The infrared satellite image (Fig. 1c) also shows the cloudiness associated with the CFA to be well ahead of the surface cold front analyzed by NMC.

The nested grid model (NGM) 12-h forecast of 700-mb vertical velocity valid at 0000 UTC 25 January (Fig. 1d) shows that it correctly predicted strong vertical motions well ahead of the surface trough (the latter is indicated in Fig. 1d by the cold front analyzed by NMC).

Figure 2 shows a vertical cross-section along the line A–A' in Fig. 1b through the CFA at 0000 UTC 25 January 1986. The leading edge of the frontal zone is well ahead of the surface trough. A convectively unstable region was just ahead of the advancing CFA. In the next 3 h, this instability was released and thunderstorms broke out in Arkansas and Mississippi, well in advance of the surface trough.

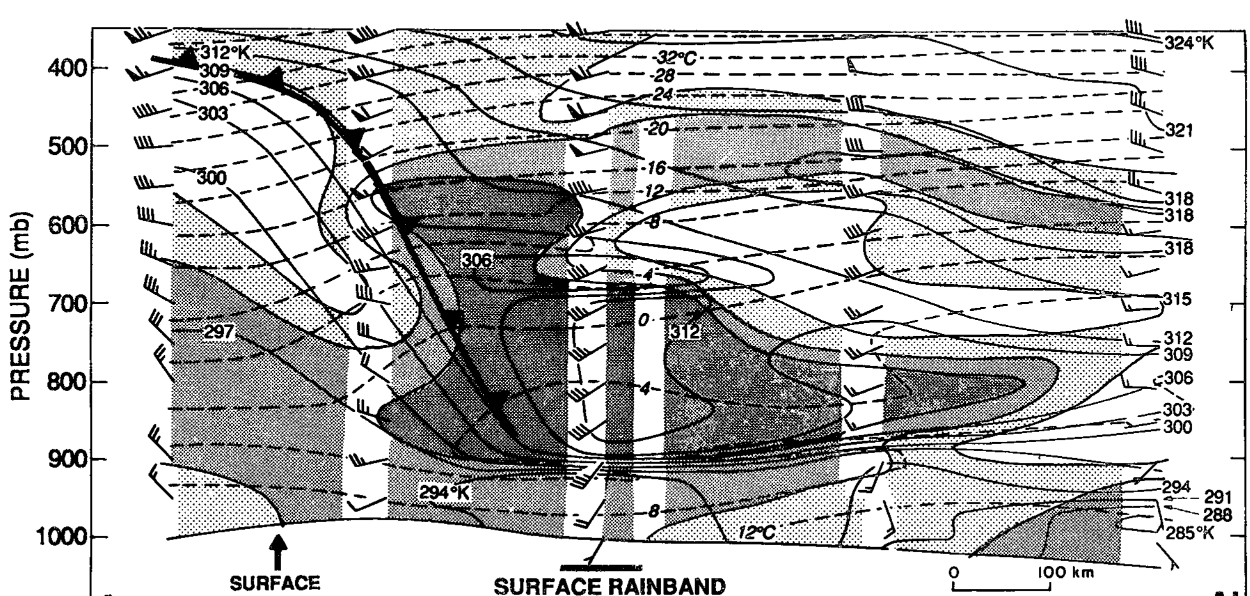

FIG. 2. Vertical cross-section through the CFA (along A–A' in Fig. 1b) from Topeka, Kansas (TOP) to Monett, Missouri (UMN), to Little Rock, Arkansas (LIT), to Jackson, Mississippi (JAN), to Boothville, Louisiana (BVE) at 0000 UTC 25 January 1986. Solid lines are contours of equivalent potential temperature (θ_e) in °K labeled every 3 degrees. Dashed lines are isotherms labeled in °C every 4 degrees. Wind speed is indicated as in Fig. 1. Solid cold-frontal symbols indicate the position of the CFA analyzed by the authors. Shading indicates values of relative humidity (see Fig. 6 for key).

We refer to this mid-tropospheric baroclinic zone as a cold front aloft for the following reasons. The absolute momentum, M, is given by (Eliassen 1962):

$$M = U - fy$$

where U is the geostrophic wind along the front, f the Coriolis force, and y the across-front distance (positive toward the cold air). To the extent that the atmosphere can be described semi-geostrophically, M is conserved and can be used to define frontal zones (Shapiro 1981), because vertical and lateral gradients in M represent temperature gradients across the fronts and absolute vorticity, respectively. Of particular value in determining the boundaries of a frontal zone are the hypergradient regions of M, namely, those regions where the product $|(\partial M/\partial p)(\partial M/\partial y)|$ is largest, where p is pressure. M was calculated from the NGM C-grid initialized data at 0000 UTC 25 January 1986. We have chosen $|(\partial M/\partial p)(\partial M/\partial y)| = 5 \times 10^{-8}$ m^2 kg^{-1} as the boundary of the hypergradient region in M, because this value was two to four times larger than background values. Figure 3 shows the value of M in the same cross section shown in Fig. 2. Although the hypergradients are not strong, they are present and therefore substantiate the presence of a CFA in a dynamic sense.

In the next 24 h, this system progressed eastward across the United States, spreading light rain, snow showers, and convective showers along the mid-Atlantic Coast in advance of the surface trough. There was heavy precipitation (mixed snow and rain) in the Philadelphia area between 1200 UTC 25 January and 0000 UTC 26 January (with total amounts near 20 mm). This heavy precipitation was restricted to the region in which the CFA became superimposed on a stationary coastal front. The trough weakened as it moved east, but the NMC analysis continued to show it as a cold front.

This case has similarities to the classical Norwegian warm-occlusion model. A cold-frontal zone and a

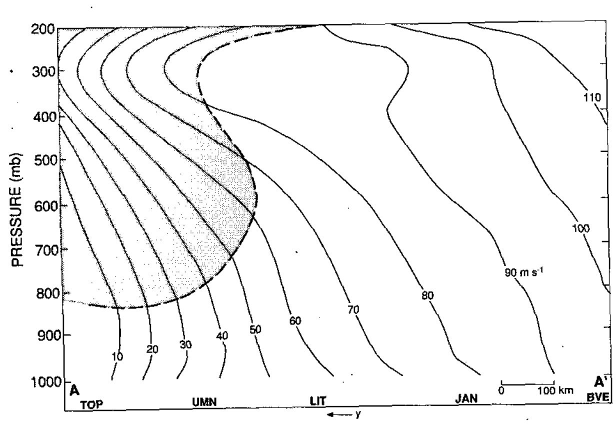

FIG. 3. Vertical cross section (along line A–A' in Fig. 1b) at 0000 UTC 25 January 1986. Thin solid lines are contours of absolute momentum, M (labeled in m s^{-1} and contoured every 10 m s^{-1}). The shading indicates the region in which $|(\partial M/\partial p)(\partial M/\partial y)| > 5 \times 10^{-8}$ m^2 kg^{-1}.

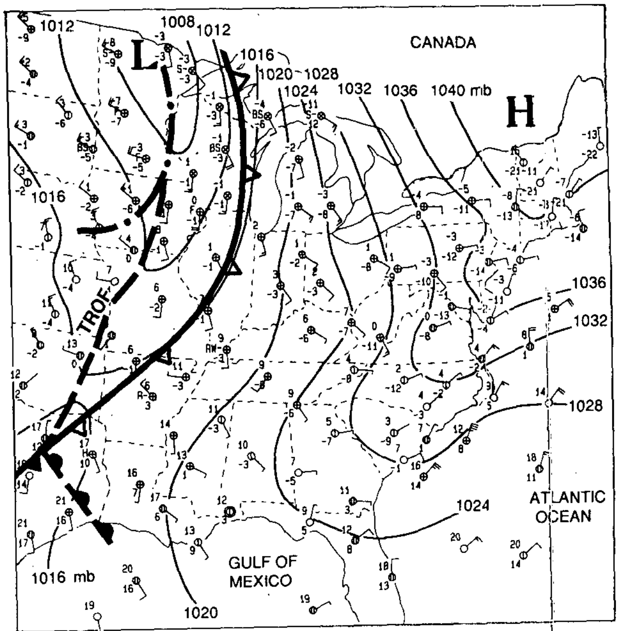

FIG. 4. Authors' reanalysis of the surface map for 0000 UTC 25 January 1986. Dashed–dot line indicates the axis of the arctic front; dashed line indicates the axis of the surface trough. Open cold-frontal symbols show the location of the CFA. Other symbols as in Fig. 1.

warm-frontal zone intersected; but they did so only in the middle troposphere, without leaving a surface occluded front, or any occlusion-like characteristics, below their point of intersection. However, perhaps with the Norwegian cyclone model in mind, the NMC analyzed a surface cold front in the center of the lee-side trough. Meanwhile, a surging CFA was outrunning the surface lee-side trough and spreading precipitation well ahead of the surface cold front analyzed by the NMC.

With these observations in mind, we reanalyzed the surface map for 0000 UTC 25 January 1986 (Fig. 4). What the NMC analyzed as a cold front, we analyze as a degenerating lee-side trough, with an arctic front at its northern extent. Most importantly, we analyze a CFA.

b. 6 March 1986

At 0000 UTC 5 March 1986 a surface low-pressure center was located in southern North Dakota. Associated with this feature was a trough of low pressure that extended from central New Mexico northeastward to the surface low. There was also a surface cold front, with a tipped-forward structure, which ran east–west from the low-pressure center through southern Montana (east of the Rockies), and a shallow arctic front further north. The surface pressure trough, which remained quasi-stationary, had formed in the lee of the Rocky Mountains in response to strong subsidence along the mountains. In the 24 h leading up to 0000 UTC 6 March, the primary surface cold front raced southward and slowly began to occupy the remnant lee trough. By this time, the system occupied the central

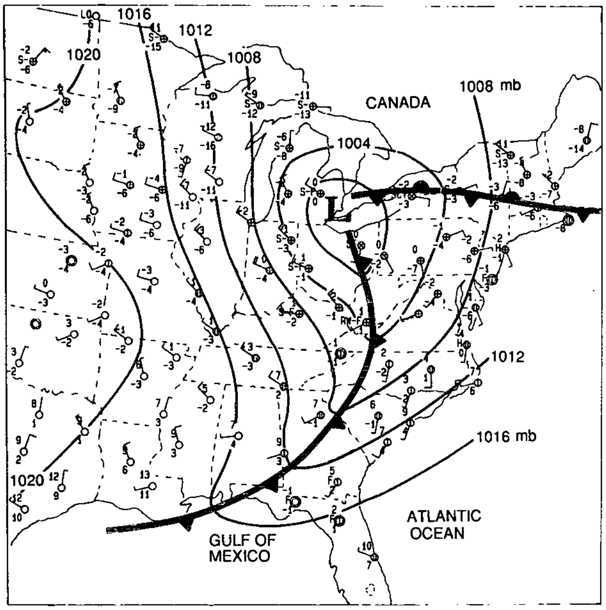

FIG. 5a. As for Fig. 1a, except for 1200 UTC 6 March 1986.

Mississippi River Valley. A more detailed synoptic description of this system has been given by Locatelli et al. (1989).

The gradual encroachment onto the surface trough of the tipped-forward cold front and the arctic front served to strengthen the surface pressure signal. Thus, the trough remained an unmistakable feature in the surface pressure field, even though it had moved significantly east of the Rockies. By 1200 UTC 6 March, rainbands had formed in central Virginia some 200 km ahead of the surface trough (Fig. 5a). The 700-mb analysis at 1200 UTC 6 March (Fig. 5b) shows the leading edge of the cold-air advection to be east of the surface trough (in which the NMC had analyzed a cold

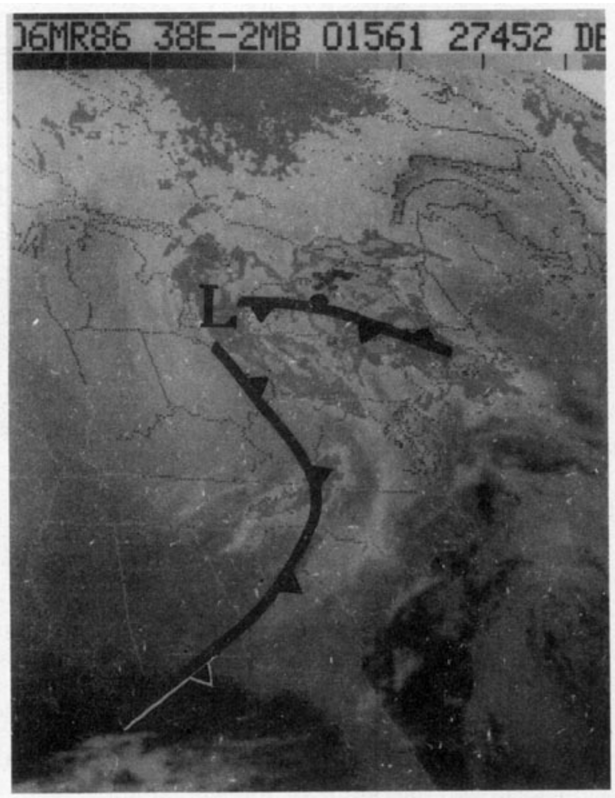

FIG. 5c. As for Fig. 1c, except for 1200 UTC 6 March 1986.

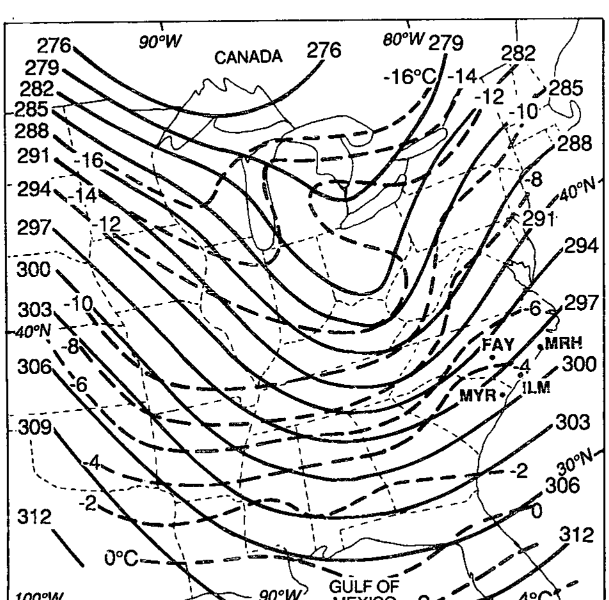

FIG. 5b. As for Fig. 1b, except for 1200 UTC 6 March 1986 and temperatures are contoured every 2°C.

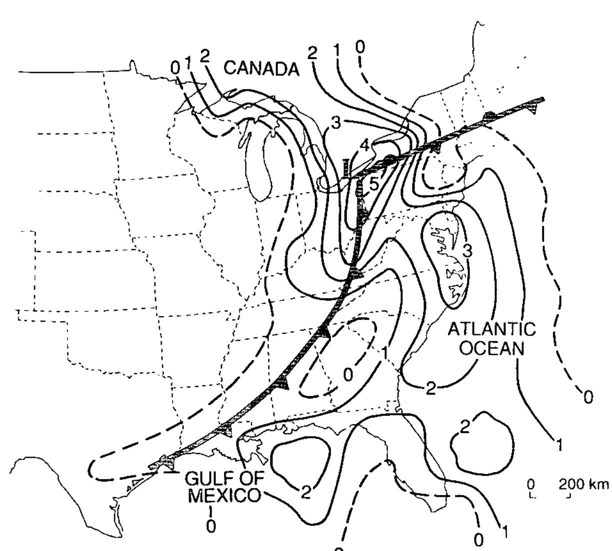

FIG. 5d. As for Fig. 1d, except for 1200 UTC 6 March 1986.

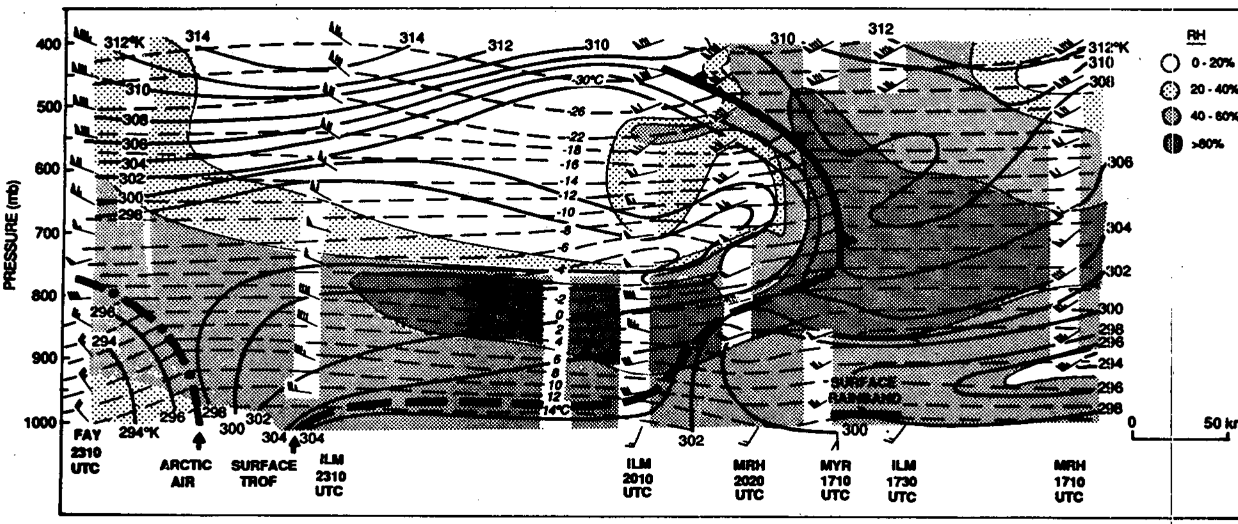

FIG. 6. Time height cross section through the CFA, at approximately 1900 UTC 6 March 1986, based on sounding data from the four stations (FAY, ILM, MRH, and MYR) shown in Fig. 5b. The time of launch of each sounding is shown below the sounding data. Shown are equivalent potential temperature, θ_e (dashed lines, labeled in °K and contoured every 2 degrees) and temperature (solid lines, labeled in °C and contoured every 2°C). Relative humidity is shown by the shading, and wind speed is indicated as for Fig. 1. The heavy dashed line indicates a line of maximum θ_e connecting the surface trough to the base of the CFA. The heavy dashed-dot line indicates the position of the arctic front.

front). The position of the leading edge of the CFA coincided with the outbreak of precipitation.

Figure 5c shows the infrared satellite image at 1200 UTC 6 March. The cloudiness and precipitation were ahead of the surface trough, which is consistent with other observations, including the NGM 12-h prediction of the 700-mb vertical velocity valid at 1200 UTC 6 March. Once again, the NMC nested grid model predicted a region of upward vertical motion well ahead of the surface cold front analyzed by NMC, but at the location where we place the leading edge of the CFA (Fig. 5d).

Figure 6 shows a derived time-height cross-section, based on radiosonde data from stations located in eastern North and South Carolina (see Fig. 5b), at approximately 1900 UTC 6 March. The location of the soundings on the cross section has been adjusted, in space and time, relative to the position of the surface rainband. This section vividly illustrates the vertical structure of the tipped-forward CFA that produced the rainband on the surface. Flow fields, derived from Doppler radar measurements, revealed strong convergence at the head of the CFA (Locatelli et al. 1989; Sienkiewicz et al. 1989). Construction of the cross section shown in Fig. 6 was possible with the temporally dense sounding data available. However, construction of a reasonable approximation to this time-height section with NGM model data (which is available only every 6 h) was not possible; for this reason, we do not show an analysis of M.

This case exhibits some similarities to the warm-occlusion model. The temperature, wind, humidity, and θ_e fields are similar to those in warm occlusions. Also, strong cold-air advection at 700 mb existed in advance of the surface front (Fig. 5b). Further, the surface front resembled a warm occluded front with warm-air advection ahead of it and cold-air advection behind it. Consequently, it would have been understandable had the NMC analyzed a warm occlusion, with a surface occluded front and a CFA (even though the occluded front was not produced by a cold front overtaking a warm front as envisaged in the Norwegian

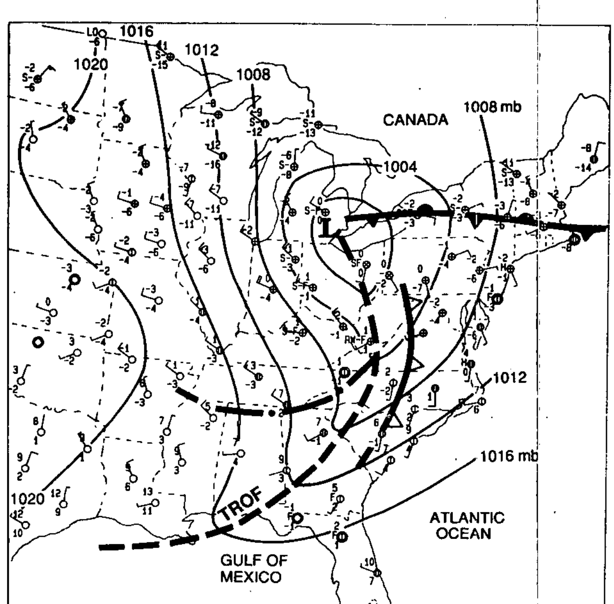

FIG. 7. Authors' reanalysis of the surface map for 1200 UTC 6 March 1986. The stationary front is indicated by conventional symbols. Other symbols as in Figs. 1 and 4.

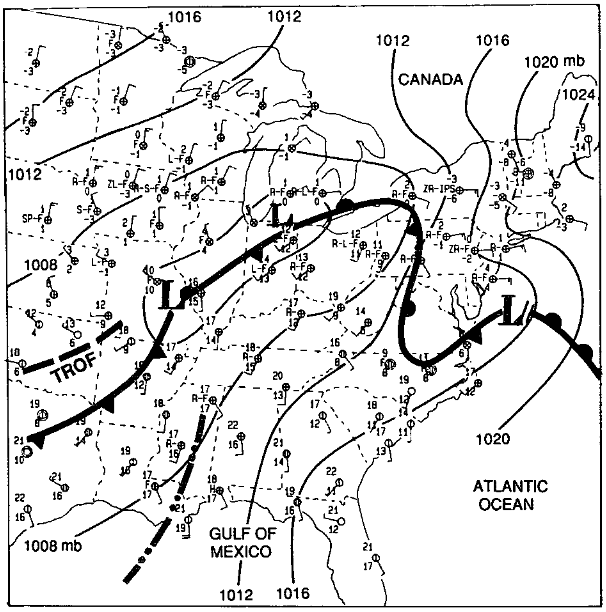

FIG. 8a. As for Fig. 1a, except for 0000 UTC 5 February 1986. The dashed line is a trough, the dashed double-dot line is the squall line. The surface cold front, warm front, and stationary front (as analyzed by NMC) are indicated by conventional symbols.

frontal model, but instead by a tipped-forward cold front overtaking a surface lee-side trough). In fact, the NMC analyzed a warm front and a dry cold front. However, in association with the CFA, there were clouds and light precipitation in central Virginia beginning around 1200 UTC 6 March.

Our reanalysis of the 1200 UTC 6 March 1986 surface map is given in Fig. 7. We analyze the NMC surface cold front as a trough, with warm occlusion-like characteristics to the south and arctic front characteristics to the north. Also, as in the previous case, we analyze a CFA well ahead of the surface trough. Because NMC analyzed the surface trough as a cold front, they were forced to conclude that it was a dry front.

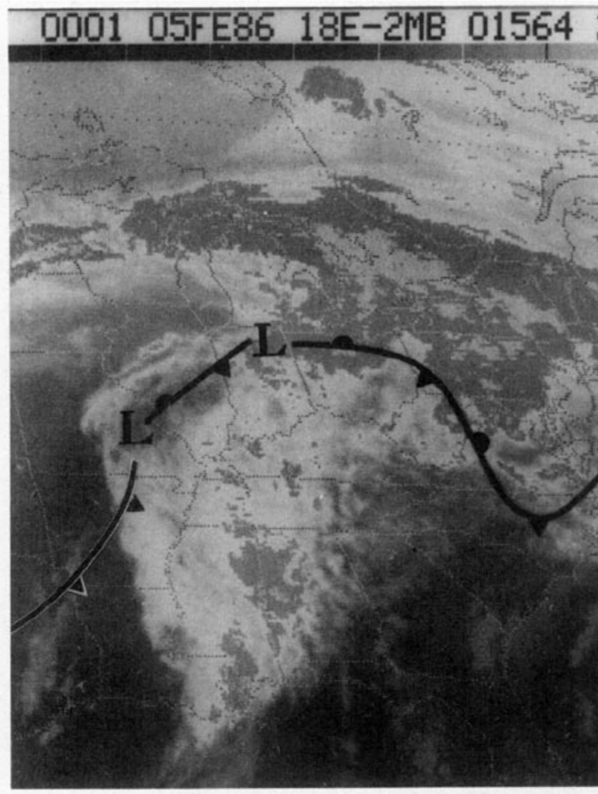

FIG. 8c. As for Fig. 1c, except for 0000 UTC 5 February 1986.

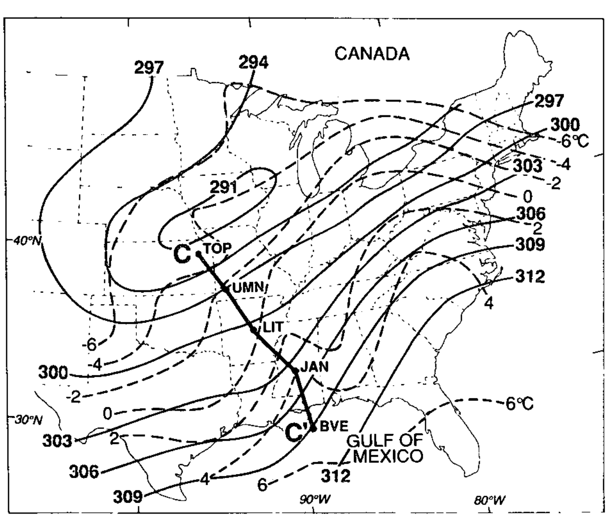

FIG. 8b. As for Fig. 1b, except for 0000 UTC 5 February 1986 with temperatures contoured every 2°C. A cross section along *C–C′* is shown in Figs. 9 and 10.

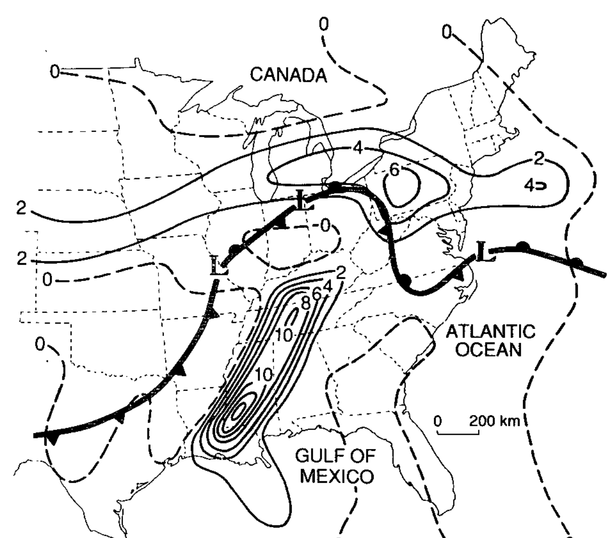

FIG. 8d. As for Fig. 1d, except for 0000 UTC 5 February 1986 and with vertical velocity contoured every 2 cm s^{-1}.

c. 5 February 1986

At 1200 UTC 3 February 1986, a 1006-mb surface low was centered just to the south of the Oklahoma panhandle, near Amarillo, Texas. A weak trough of low pressure extended south southwestward from the low center into El Paso, Texas. A stationary front, extending from the low center through central Missouri, southern Indiana, Ohio, and on into Maryland, was responsible for light but steady precipitation in those areas. There was also an isolated region of light showers centered near the Dallas/Fort Worth area, some 550 km east of the weak surface trough.

By 0000 UTC 4 February, the region of light showers had developed dramatically into a squall line and moved eastward toward the Texas–Arkansas border. This squall line was responsible for a vast area of flooding in northeastern Texas, a region that had not seen significant rain in over 50 days. Numerous road closures and one bridge collapse were attributed to the heavy precipitation. By 1200 UTC 4 February, the squall line had raced eastward into central Louisiana, and the NMC had analyzed a cold front in the middle of the original surface pressure trough, some 300–350 km to the west of the squall line. Damage was extensive in eastern Louisiana: many large trees were uprooted and numerous homes sustained damage.

At 0000 UTC 5 February the squall line was spreading precipitation into central Mississippi, while the trough and wind shift line remained nearly 350 km to the west (Fig. 8a). Behind the first windshift line (the one NMC analyzed as a cold front) there was a wide region of slight temperature gradient, separated from much colder air to the north by a second windshift line at a pressure trough through central Oklahoma. At 700 mb (Fig. 8b), the leading edge of the cold-air advection was well in advance of the surface windshift lines and roughly coincident with the location of the squall line. The infrared satellite image taken at 0000 UTC 5 February (Fig. 8c) shows clearly that the cloud edge was well ahead of the surface windshift and nowhere near the cold front analyzed by NMC. The NGM 12-h forecast of the vertical velocity field at 700 mb, valid at 0000 UTC 5 February 1986, is shown in Fig. 8d. This field shows that the strong lifting was located well ahead of the surface front analyzed by NMC. Hence, once again, the numerical model results provide support for a CFA.

Figure 9 shows a cross-section along the line marked *C–C′* in Fig. 8b. What is hinted at by the region of 700-mb cold-air advection in Fig. 8b is brought to light in Fig. 9: it is, once again, a CFA, located well ahead of any surface baroclinic zone. Notice that the nose of the cold front is located over Jackson, Mississippi in the same location as the squall line. Also, the broad surface baroclinic zone is between Monett, Missouri and Topeka, Kansas, nearly 350 km behind the nose of the CFA. The peculiar temperature structure below 800 mb, between Monett and Jackson, was probably due to the subsidence of air behind the CFA.

The origin of the air in the frontal zone can be roughly determined by analyzing the potential vorticity, P, defined by (Ertel 1942):

$$P = -(\zeta_\theta + f)\frac{\partial\theta}{\partial p}$$

where, ζ_θ is the relative vorticity on isentropic surfaces,

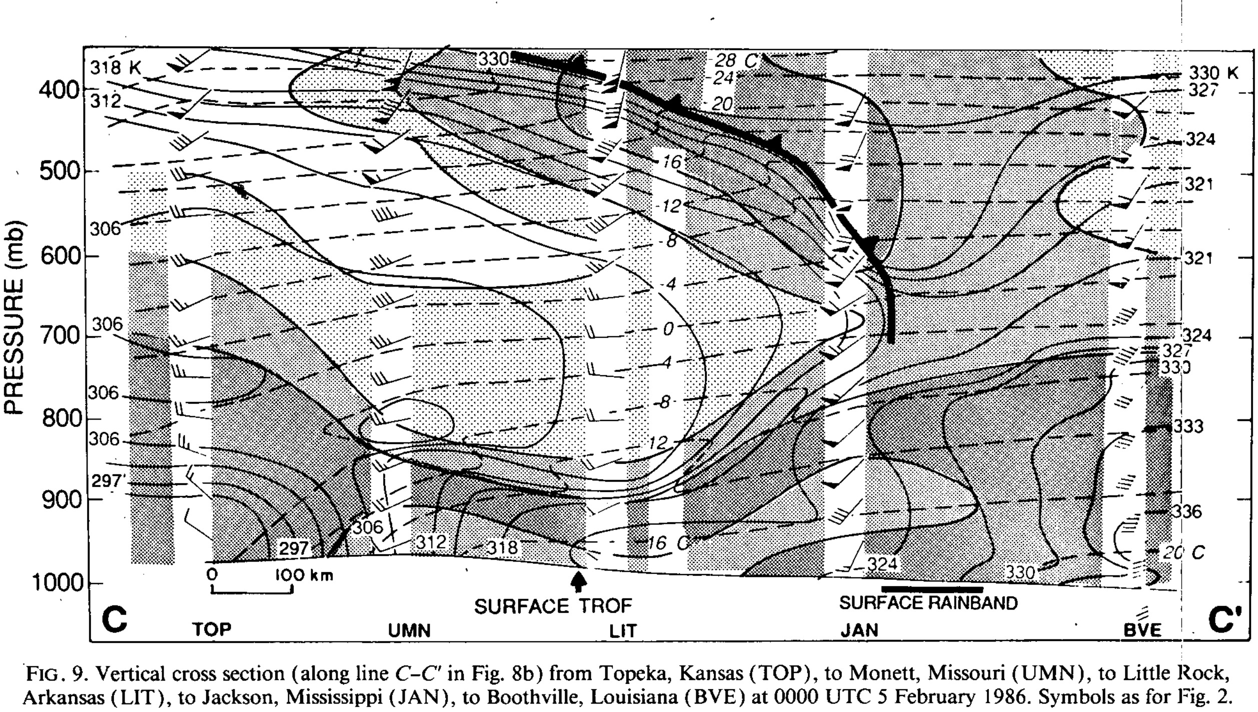

FIG. 9. Vertical cross section (along line *C–C′* in Fig. 8b) from Topeka, Kansas (TOP), to Monett, Missouri (UMN), to Little Rock, Arkansas (LIT), to Jackson, Mississippi (JAN), to Boothville, Louisiana (BVE) at 0000 UTC 5 February 1986. Symbols as for Fig. 2.

θ the potential temperature, and p pressure. Potential vorticity is useful in frontal analysis because it combines two important frontal parameters: absolute vorticity and stability. Stratospheric and tropospheric air are characterized by significantly different values of P. For example, Reed (1955) used P to show that upper-level frontal zones contain air of stratospheric origin and are regions of stratospheric extrusions into the troposphere. We show in Fig. 10 our analyses of M and P (both calculated from the NGM C-grid initialized data at 0000 UTC 5 February 1986) for the cross section depicted in Fig. 9. It can be seen in Fig. 10 that both M and P reveal that the CFA we have analyzed was a moderately strong frontal zone. The profile of P hints that the air in the frontal zone may have had its origin in the stratosphere sometime prior to 0000 UTC 5 February. As this air entered the confluent eastern side of the upper-level trough, where the front was embedded, vigorous vertical motions were produced as the temperature gradient across the front was further strengthened by horizontal confluence.

The NMC analyzed this case as an open wave with a cold and warm front. Presumably, they interpreted the squall line as a warm-sector squall line, in which case further thunderstorms may have been expected as their analyzed surface cold front advanced eastward. Our reanalysis of the surface map for 0000 UTC 5 February (Fig. 11) shows quite a different picture. We attribute the squall line to the passage of a CFA. Behind this front was a surface trough instead of the cold front depicted by the NMC. Hence, after the CFA had passed over, there was no additional source of synoptic-scale lifting. Behind the surface trough was another windshift associated with an arctic front through northern Oklahoma.

d. 13 March 1986

At 0600 UTC 12 March 1986, a surface low-pressure center of 996 mb was located at Amarillo, Texas, with

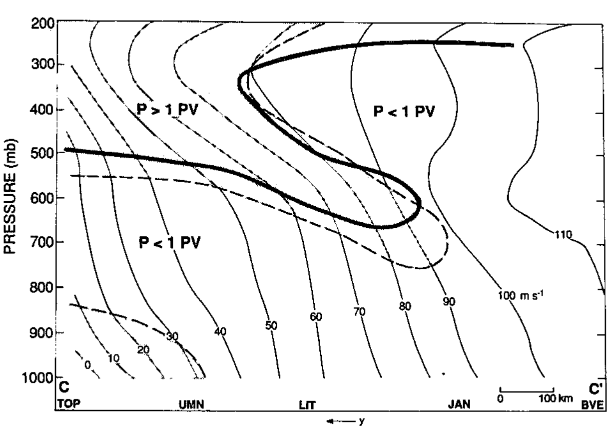

FIG. 10. Vertical cross section (along line C–C' in Fig. 8b) at 0000 UTC 5 February 1986. Symbols as for Fig. 3; heavy solid line indicates a potential vorticity (P) of 1 PV unit ($=10^{-6}$ m^2 s^{-1} K° kg^{-1}).

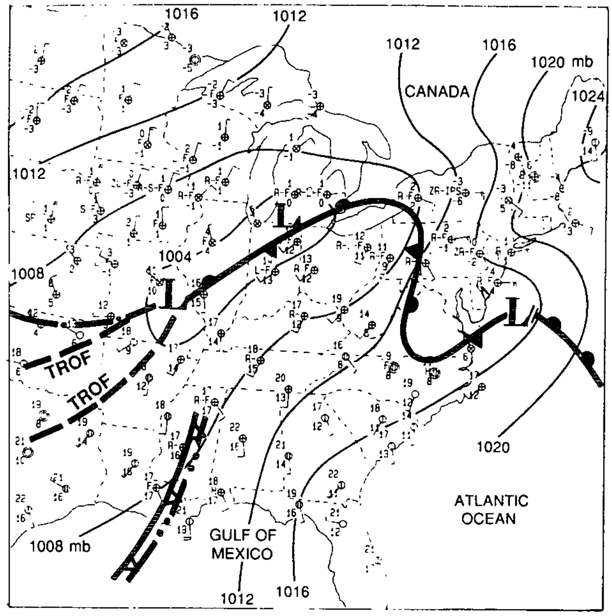

FIG. 11. Authors' reanalysis of the surface map for 0000 UTC 5 February 1986. The dashed–double dot line shows the squall line and the open cold-frontal symbols a CFA (these two features are coincident). Other symbols as in Figs. 1 and 4.

a warm front extending across the Missouri–Arkansas border, through central Tennessee, and into central North Carolina. The NMC analyzed a cold front along a line of windshift and dewpoint gradient, which extended through eastern Texas, and a trough line that extended through central Texas. Associated with the trough line was a second windshift line and a sharp temperature drop. Prior to 0000 UTC 12 March, a squall line developed well to the east of the cold front analyzed by NMC. This squall line had moved into eastern Arkansas by 0600 UTC 12 March, bringing with it damaging winds that were responsible for unroofing two schools, blowing numerous cars and trucks off the road, and derailing a freight train. Seventeen people were injured in eastern Arkansas and western Tennessee due to the severe weather.

Between 1800 UTC 12 March and 0000 UTC 13 March, while severe thunderstorms with damaging winds and golf ball-sized hail pummelled most of Mississippi and Alabama, eleven tornadoes roared along the Mississippi–Alabama border. The strongest and longest lived tornadoes, including the first F4 storm of the year, were in the vicinity of Meridian, Mississippi, between 1800 and 1900 UTC 12 March.

The surface pressure field at 0000 UTC 13 March (Fig. 12a) shows that the squall line responsible for the widespread region of severe weather was located about 300 km to the east of the cold front analyzed by NMC. At 700 mb (Fig. 12b), the leading edge of the cold-air advection (the CFA) was well in advance of the surface windshift and coincident with the squall line. The trough aloft moved eastward through Ari-

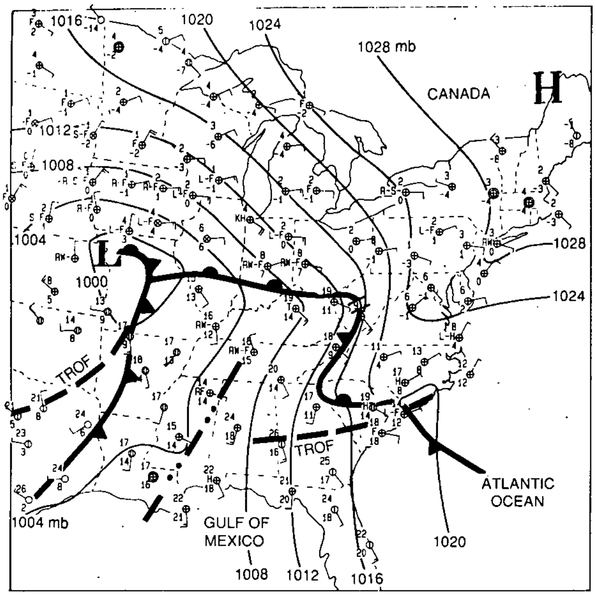

FIG. 12a. As for Fig. 1a, except for 0000 UTC 13 March 1986. The dashed lines are troughs and the dashed–double dot line a squall line. The surface cold front, warm front, stationary front, and occluded front (as analyzed by NMC) are indicated by conventional symbols.

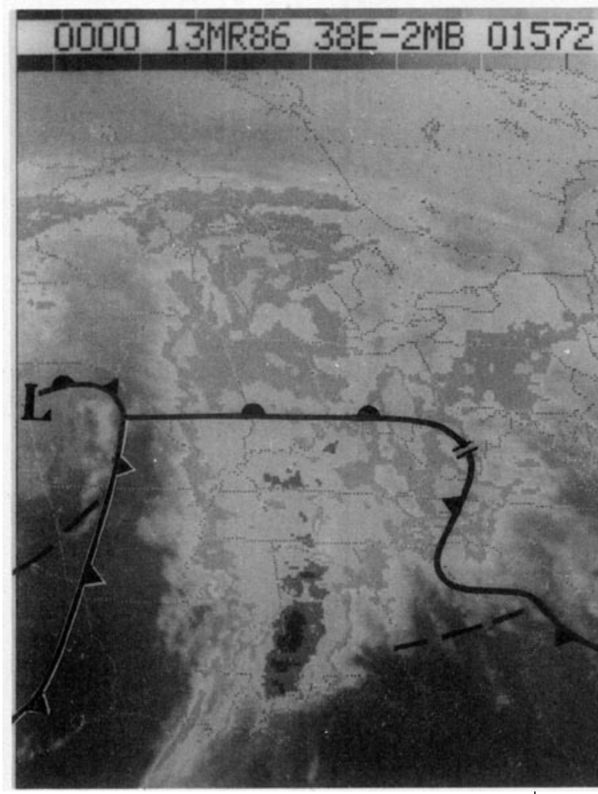

FIG. 12c. As for Fig. 1c, except for 0000 UTC 13 March 1986.

zona, New Mexico, and Texas (as in the 5 February case). The infrared satellite imagery for 0000 UTC 13 March is shown in Fig. 12c. The cloudiness evident in this image is coincident with the leading edge of the cold-air advection at 700 mb (Fig. 12b) and the region of lifting at 700 mb predicted by the NGM (Fig. 12d); the cloudiness was located nowhere near the surface windshift lines (Fig. 12a).

Figure 13 shows a cross-section, along the line D–D' in Fig. 12b, at 0000 UTC 13 March 1986. It clearly demonstrates the presence of the CFA well ahead of the surface trough. The leading edge of the CFA is seen to be coincident with the squall line (Fig. 12a). The strength of the 900-mb wind at Centreville, Alabama further attests to the strength of the squall line generated ahead of the CFA. Figure 14 shows the analyses of M and P for the same cross section and for the same time

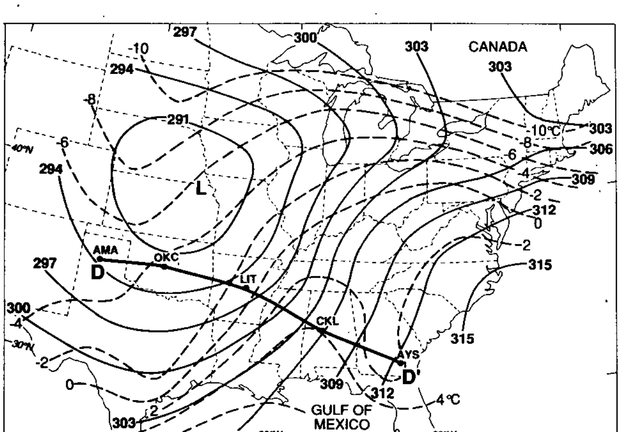

FIG. 12b. As for Fig. 1b, except for 0000 UTC 13 March 1986 and temperatures contoured every 2°C. Cross section for D-D' is shown in Figs. 13 and 14.

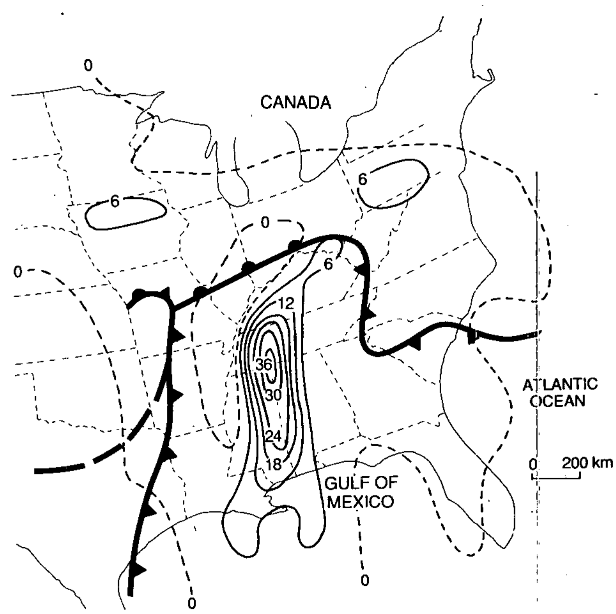

FIG. 12d. As for Fig. 1d, except for 0000 UTC 13 March 1986 and with vertical velocities contoured every 6 cm s^{-1}.

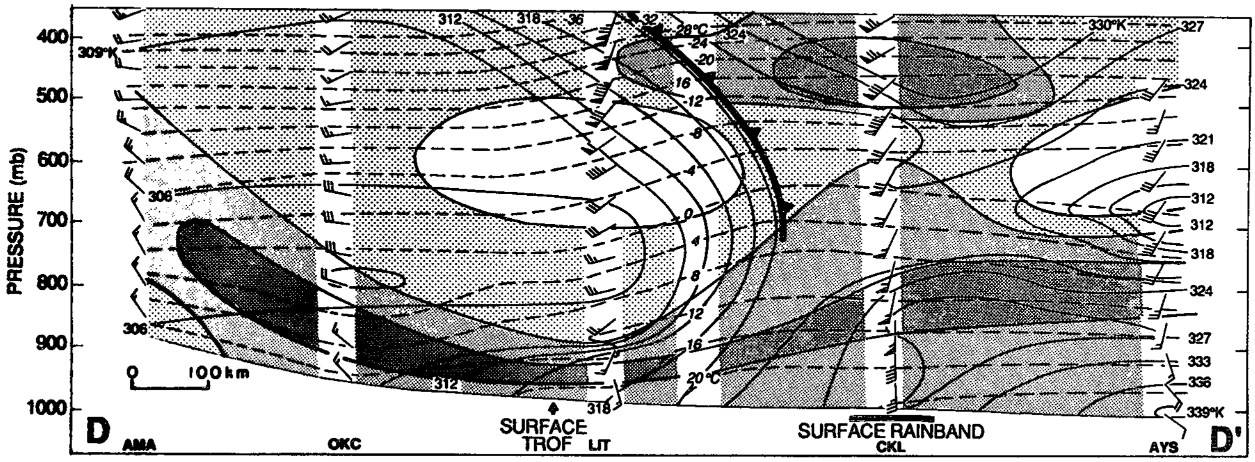

FIG. 13. Vertical cross section (along line *D–D'* in Fig. 12b) from Amarillo, Texas (AMA), to Oklahoma City, Oklahoma (OKC), to Little Rock, Arkansas (LIT), to Centreville, Alabama (CKL), to Waycross, Georgia (AYS) at 0000 UTC 13 March 1986. Symbols as for Fig. 2.

as Fig. 13. *M* and *P* were calculated from the NGM C-grid initialized data at 0000 UTC 13 March. It can be seen that the *M* values show the CFA to be a strong front, and there is a hint that it originated as an upper-level front. The CFA also played a role in the generation of a squall line in eastern North Carolina later in the day on the 13 and 14 March (Businger et al. 1990), which, in contrast to this event, went largely unforecast.

Hence, once again, this system should not have been analyzed as an open wave, because there was no evidence of a surface cold front. Instead, there was a surface trough and an arctic front trailing a CFA; the cold front aloft aided in the triggering of the squall line (the subsequent propagation of which was well forecast by the NWS).

With these observations in mind, we reanalyzed the 0000 UTC 13 March 1986 surface map (Fig. 15).

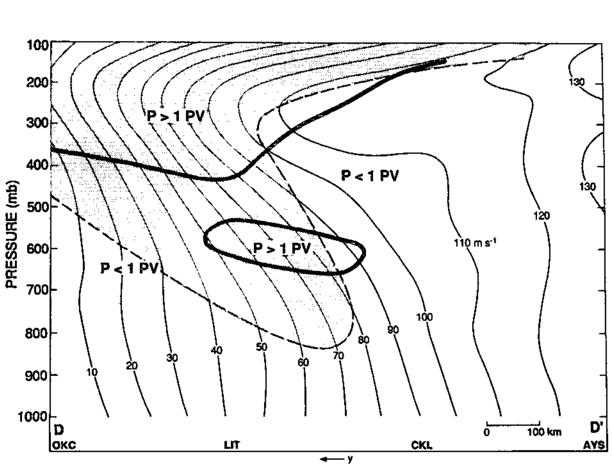

FIG. 14. Vertical cross section along line *D–D'* in Fig. 12b, at 0000 UTC 13 March 1986, except beginning at OKC. Symbols as for Fig. 3; heavy solid line indicates potential vorticity (P) of 1 PV unit ($=10^{-6}$ m^2 s^{-1} $K°$ kg^{-1}).

Much like the 5 February case, the NMC cold front is now shown as a trough trailed by an arctic front. We attribute the squall line to the advance of the CFA.

3. A conceptual model

The four cases described above are characterized by a CFA that was located ahead of a surface trough. The CFA was responsible for the initiation of precipitation as it moved across the High Plains and the eastern United States and, in two of the cases, it triggered severe weather.

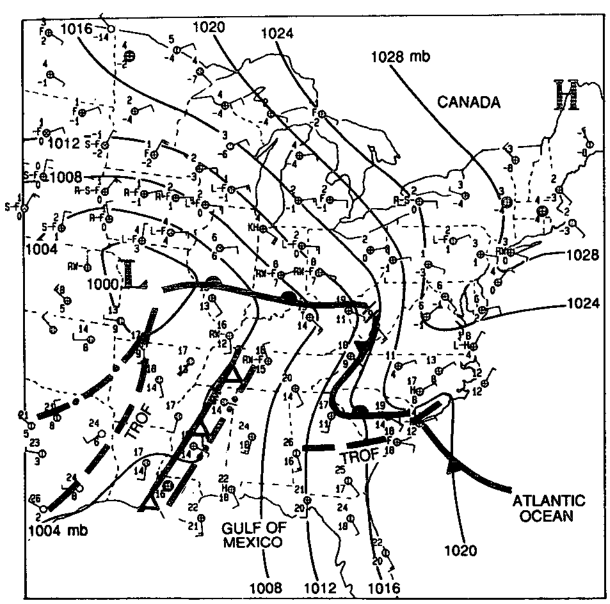

FIG. 15. Authors' reanalysis of the surface map for 0000 UTC 13 March 1986. The dashed–double dot line shows the squall line and the open cold-frontal symbol a CFA (these two features are coincident). Other symbols as in Figs. 1 and 4.

In each of the four cases, the frontal structure was misanalyzed by NMC, apparently due to reliance on the Norwegian frontal model of a cyclone. Thus, the systems were analyzed as open waves, with warm and cold fronts on the surface separated by a warm sector. In fact, in none of the cases was there a cold front on the surface as depicted in the Norwegian frontal model. There was only a windshift line associated with a surface trough and, in some cases, an arctic front occupying the northern portion of the trough.

The potential for this type of incorrect frontal analysis may be quite high. From 15 January through 15 March in the years 1980 through 1985, the NMC analyzed some 36 surface fronts with a northeast to southwest orientation on the East Coast of the United States. Fourteen (39%) of these were considered dry cold fronts, some of which may well have been troughs with CFA ahead of them. Also, in winter in the eastern United States, convective activity is common ahead of north-south oriented cold fronts. During the period 15 January through 15 March 1980–1985, NMC analyzed 11 cold fronts with this orientation, of which four were considered to be dry cold fronts and four were associated with squall lines (GALE Experimental Design 1985). During the period of GALE (15 January through 15 March 1986), the NMC showed 16 surface cold fronts crossing the GALE region, nine of which were dry fronts; the first four of these nine cases that we have analyzed were found to have CFA ahead of troughs on the surface.

To help avoid such misanalysis, a new conceptual model is needed that recognizes the existence of CFA even in the absence of trailing fronts on the surface. Such a conceptual model, based on the cases described in section 2, is shown in Fig. 16. In this model, which we will refer to as the *cold front aloft model* (CFA), we indicate:

- A warm or arctic front at the surface.
- A CFA, which produced the main precipitation at the surface.
- A surface trough, some 200–300 km behind the leading edge of the CFA.

The surface trough may take the form of a cold front, a warm occluded front (as in the 6 March 1986 case), a lee trough (the 25 January 1986 case), or a lee trough/arctic front combination (as in the 5 February and 13

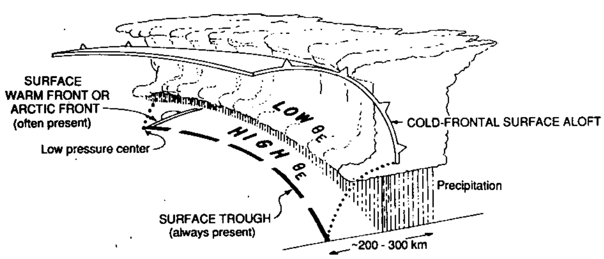

FIG. 16. Schematic of the cold front aloft (CFA) conceptual model.

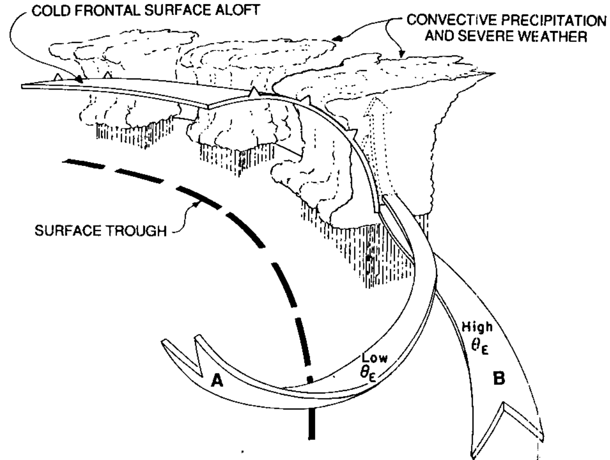

FIG. 17. Schematic of the process by which a CFA can trigger severe weather. The arrow *A* shows the flow of dry air that initially descends along the eastern slopes of the Rockies. The arrow *B* shows the flow of warm, moist air from the Gulf of Mexico.

March 1986 cases). Between the surface trough and the base of the CFA the air is convectively unstable (i.e., the equivalent potential temperature, θ_e, decreases with height), with the instability peaking along the dotted line in Fig. 16. It should be noted that with a warm front on the surface, trailed by something resembling a surface cold front (actually a surface trough), an analyst, with the Norwegian model in mind, might be deterred from indicating a CFA.

When the surface trough in the CFA model takes the form of a warm occluded front, the situation reduces to the warm occlusion model (Bjerknes and Solberg 1922). When the surface trough is a cold front, and a line of maximum θ_e runs from the surface front to the base of the CFA, the CFA model reduces to the split cold front model (Browning and Monk 1982), although we have not observed this structure. By relaxing the stricter requirements of these two conceptual models, the CFA model can be applied to a much broader range of frontal features.

As we have seen in section 2, thunderstorms, squall lines, and tornadoes can be associated with the passage of a CFA and its associated short wave at 500 mb. In the 25 January, 5 February, and 13 March cases, the thunderstorms and severe weather were triggered when potentially unstable air was lifted by the advancing CFA. In the lee of the Rockies, the CFA may serve to both set up the necessary potential instability, and to trigger severe weather through the lifting of air (as shown schematically in Fig. 17). This was the case on 25 January. On this occasion, warming downslope air produced a lee-side trough east of the Rockies. Then an upper-level, short wave trough and a CFA traversed the mountains. This increased the flow over the Rockies, deepened the lee-side trough, and increased the low-level, southerly current of warm, moist air (*B*) from the Gulf of Mexico, which was ahead of the surface trough. The warm, dry downslope air (A) from the Rockies was caught in the circulation of the CFA and it moved northward above the warm, moist air. The two currents of air were then forcibly lifted by the vertical motions associated with the advancing CFA. This lifting released the potential instability inherent in dry air being situated above warm, moist air, and thunderstorms were produced in Arkansas and Mississippi.

Carr and Millard (1985) documented a case of dry-slot convection that they attributed to destabilization as dry air intruded aloft over warm, moist air advection at low levels. The potential instability in their case was realized through lifting generated by surface convergence and heating (the sky was clear), and not by a CFA. However, the passage of a CFA could result in the development of similar dry-slot convection.

Cotton and Anthes (1989) refer to two types of squall lines: "prefrontal," which are located within the warm sectors of mid-latitude cyclones, and "the ordinary squall line", which are associated with weak cyclonic storms, stationary fronts, or have no relationship to a cyclonic storm system. Based on the observations presented in this paper, we propose a third type of squall line, namely, those associated with CFA.

The four cases described in section 2 have the following features in common:

- They were not well described by the Norwegian frontal model of a cyclone.
- A CFA, and its associated short wave at 500 mb, were ahead of a surface pressure trough.
- Precipitation developed along the leading edge of the CFA, well to the east of the surface trough, and it remained ahead of the surface trough all the way to the East Coast.
- The main cloud band, as seen in infrared satellite imagery, was situated along the CFA (not along the surface pressure trough).

It is beyond the scope of this paper to discuss in any detail the origins of CFA east of the Rockies. We simply note here that for the 25 January case a cold front that moved inland from the Pacific Ocean initially extended to the surface. However, during its passage across the Rocky Mountains, the lower portion of the front was destroyed, leaving a CFA that continued to move eastward. In the 6 March case, a surface cold front overtook a lee-side trough to form an occluded-like structure with a CFA. For both the 5 February and 13 March cases, it is possible that an upper-level cold front formed in the northwesterly jet of an upper-level trough. It may have then rotated around the trough (into the confluent eastern side of the trough) and moved ahead of the surface trough as a CFA.

4. Identification of cold fronts aloft

Identification of a CFA is clearly the key to deciding whether the CFA conceptual model described above should be applied to a particular situation. To help in the identification, location, and forecasting of CFA, we suggest that the majority of the following criteria be satisfied before labelling a feature a CFA:

- There is a trough on the surface and the main precipitation is located ahead of this surface feature. There is also a larger-than-background temperature gradient in the mid-troposphere above the precipitation region. Locate the leading edge of the CFA above the region of peak precipitation on the surface and on the warm edge of the temperature gradient in the mid-troposphere (e.g., Figs. 4, 7, 11, 15).
- Satellite photographs indicate that a cloud band is situated ahead of a trough on the surface. This cloud band often crosses the surface position of an indicated warm or stationary front, but it is aligned along the CFA (e.g., Figs. 1c, 5c, 8c, 12c).
- Behind the CFA, cloud tops decrease rapidly in height (e.g., Figs. 1c, 5c, 8c, 12c).
- The leading edge of the cold-air advection aloft, as indicated on the 700-mb map, is ahead of a trough on the surface (e.g., Figs. 1b, 5b, 8b, 12b).
- Cross sections of equivalent potential temperature, and wind and temperature derived from radiosonde data, indicate a CFA ahead of a surface trough or arctic front (e.g., Figs. 2, 6, 9, 13).
- The 1000–500-mb thickness and sea-level pressure charts show a thickness "front" ahead of the sea-level pressure trough (Fig. 18).

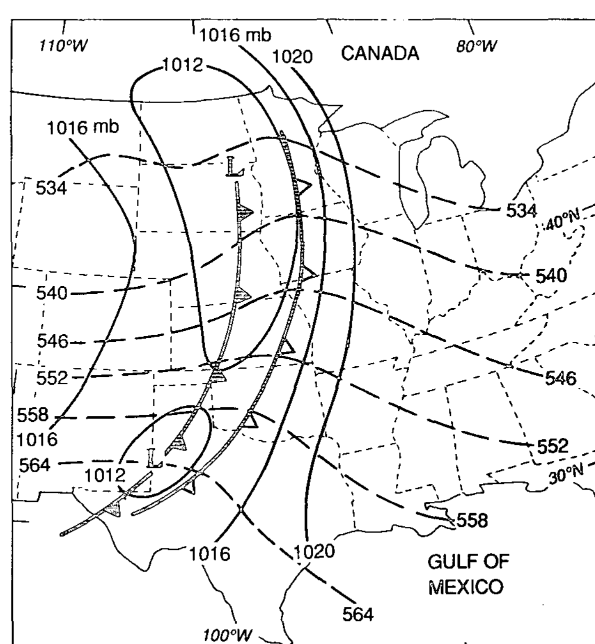

FIG. 18. 1000–500-mb thickness (dashed lines, labeled in tens of meters and contoured every 60 m) and sea-level pressure (solid lines, labeled in mb and contoured every 4 mb) from the NMC's LFM model initialization at 1200 UTC 24 January 1986. Solid cold-frontal symbols indicate the surface frontal position analyzed by the NMC, and the open cold-frontal symbols indicate the CFA which coincides with the thickness "front".

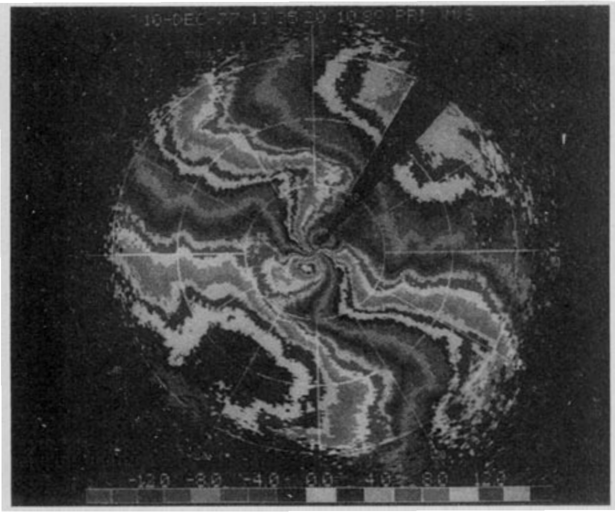

FIG. 19. PPI radar display of doppler velocities showing a CFA in which the wind backed with height from 250° below the frontal surface to 200° above the frontal surface. From Matejka and Hobbs (1981), who show this photograph color coded.

- The vertical velocity field from numerical models (e.g., the NGM) show upward motions located well ahead (~200–300 km) of a trough on the surface (e.g., Figs. 1d, 5d, 8d, 12d).
- The geostrophic wind along the CFA has a concentrated region of vertical and lateral shear, as revealed by the field of absolute momentum (e.g., Figs. 3, 10, and 14).
- PPI displays from doppler radar (such as those that will be available in real time from the NEXRAD radars) show a pattern similar to that in Fig. 19. This pattern, which was first identified by Baynton et al. (1977) who refer to it as a "backward S," indicates cold-air advection associated with a CFA.

5. Conclusions

In this paper, we have used four case studies to illustrate the role of CFA east of the Rockies. The NGM did a good job of locating upward velocities in the vicinity of the CFA. However, the NMC frontal analyses generally depicted the systems as open waves with warm and cold fronts. They did not identify the CFA and the potential for weather associated with them. Hypergradient zones in the profiles of absolute momentum show that CFA are associated with a dynamic as well as a thermodynamic signal. Hence, the CFA conceptual model (depicted in Figs. 15 and 17) is a convenient shorthand, easily evaluated from conventional weather analyses, that provides physical insights consistent with those derived from the more explicit quasi- and semi-geostrophic theories. The conceptual model, together with the means for recognizing CFA that are listed in section 4, should also help in the identification of CFA and the important role they can play in triggering precipitation, and sometimes severe weather east of the Rockies.

Acknowledgments: This work was supported by NSF Grant ATM 88009061.

REFERENCES

Baynton, H. W., R. J. Serafin, C. L. Frush, G. R. Gray, P. V. Hobbs, R. A. Houze, Jr. and J. D. Locatelli, 1977: Real-time wind measurements in extratropical cyclones by means of Doppler radar. *J. Appl. Meteor.*, **16**, 1022–1028.

Bjerknes, J., and H. Solberg, 1922: Life cycle of cyclones and the polar front theory of atmospheric circulations. *Geophys. Publ.*, **3**, 3–18.

Browning, K. A., and G. A. Monk, 1982: A simple model for the synoptic analysis of cold fronts. *Quart. J. Roy. Meteor. Soc.*, **108**, 435–452.

Businger, S., W. H. Bauman III and G. F. Watson, 1990: Coastal frontogenesis and associated outbreak of severe weather on 13 March 1986. *Mon. Wea. Rev.* (Submitted).

Carr, F. H., and J. P. Millard, 1985: A composite study of comma clouds and their association with severe weather over the Great Plains. *Mon. Wea. Rev.*, **113**, 370–383.

Cotton, W., and R. Anthes, 1989: *Cloud and Storm Dynamics.* Academic Press, 630–657.

Eliassen, A., 1962: On the vertical circulation in frontal zones. *Geophys. Publ.*, **24**, 147–160.

Ertel, H., 1942: Ein neuer hydrodynamischer wirbelsatz. *Meteor. Z.*, **59**, 271–281.

Genesis of Atlantic Lows Experiment (GALE): Experimental Design, 1985, pp. 199. (Available from GALE Project Office, NCAR, Boulder, Colorado.)

Holzman, B., 1936: Synoptic determination and forecasting significance of cold fronts. *Mon. Wea. Rev.*, **64**, 400–413.

Keyser, D., and M. A. Shapiro, 1986: A review of the structure and dynamics of upper-level frontal zones. *Mon. Wea. Rev.*, **114**, 452–499.

Lichtblau, S., 1936: Upper cold fronts in North America. *Mon. Wea. Rev.*, **64**, 414–425.

Locatelli, J. D., J. M. Sienkiewicz and P. V. Hobbs, 1989: Organization and structure of clouds and precipitation on the mid-Atlantic coast of the United States. Part I: Synoptic evolution of a frontal system from the Rockies to the Atlantic Coast. *J. Atmos. Sci.*, **46**, 1327–1348.

Lloyd, J. R., 1942: The development and trajectories of tornadoes. *Mon. Wea. Rev.*, **70**, 65–75.

Martin, J. E., J. D. Locatelli and P. V. Hobbs, 1990: 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. *Mon. Wea. Rev.*, **118**, 195–217.

Matejka, T. J., and P. V. Hobbs, 1981: The use of a single doppler radar in short-range forecasting and real-time analysis of extratropical cyclones. In *Nowcasting: Mesoscale Observations and Short-Range Prediction.* European Space Agency Publication SP-165, 177–182.

Reed, R. J., 1955: A study of a characteristic type of upper-level frontogenesis. *J. Meteor.*, **12**, 226–237.

——, 1979: Cyclogenesis in polar air streams. *Mon. Wea. Rev.*, **107**, 38–52.

Shapiro, M. A., 1981: Frontogenesis and geostrophically forced secondary circulations in the vicinity of jet stream–frontal zone systems. *J. Atmos. Sci.*, **38**, 954–973.

Sienkiewicz, J. M., J. D. Locatelli, P. V. Hobbs and B. Geerts, 1989: Organization and structure of clouds and precipitation on the mid-Atlantic coast of the United States. Part II: The mesoscale and microscale structure of some frontal rainbands. *J. Atmos. Sci.*, **46**, 1349–1364.