A New Conceptual Model for Cyclones Generated in the Lee of the Rocky Mountains

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ABSTRACT

When a shortwave trough moves eastward over the Rocky Mountains and into the central United States, the following important features may form: a drytrough (i.e., a lee trough that also has the characteristics of a dryline), an arctic front, a low-level jet, and two synoptic-scale rainbands (called the cold front aloft rainband and the pre-drytrough rainband) that can produce heavy precipitation and severe weather well ahead of the drytrough. These features are incorporated into a new conceptual model for cyclones in the central United States. Use of this model can aid the interpretation of observational data and numerical model output, and it may also help to improve short-range forecasting in the central United States.

1. Introductory remarks

Despite the fact that the Norwegian Cyclone Model was based on maritime cyclones making landfall in northwestern Europe (Bjerknes and Solberg 1922), it has been applied essentially unchanged to cyclones in the central United States for 70 years (Friedman 1989; Mass 1991). This is not without some justification, since one of the main features of the Norwegian model are fronts demarcating airmasses, which are also a characteristic of cyclones in the central United States. However, in view of the unique geography of the central United States, it would not be surprising if cyclones in this region displayed structural differences from those in Europe.

In this paper we present a new conceptual model for the structure and evolution of cyclones in the central United States.[1] This model is based on a series of studies by Locatelli et al. (1989, 1995), Martin et al. (1990, 1995), Hobbs et al. (1990), and Wang et al. (1995), as well as on regular observations of cyclones in the central United States. It is important to note that we are not proposing that all cyclones that form in the lee of the Rocky Mountains are described by our model. However, many cyclones that form in the winter, spring, and even into early summer, in the lee of the Rockies, and move eastward into the central United States, appear to be described better by the conceptual model presented here than by the Norwegian model.

Our conceptual model highlights a number of important nonclassic features associated with cyclones in the central United States, some of which have been known for many years. These include *lee troughs* (Carlson 1961; Steenburgh and Mass 1994), *drylines* (Fujita 1958; McGuire 1960; Schaefer 1974, 1986), *low-level jets* (Bonner 1968; Djuric and Damiani 1980; Djuric and Ladwig 1983), *arctic fronts* (Wexler 1936; Showalter 1939; Wang et al. 1995), *elevated mixed layers* (Carlson et al. 1983; Benjamin and Carlson 1986), and *cold fronts aloft* (Holtzman 1936; Lichtblau 1936; Lloyd 1942; Omoto 1965; Hobbs et al. 1990). In our conceptual model, these features are viewed as interdependent phenomena, produced by synoptic-scale waves moving eastward over the Rocky Mountains and interacting with warm, moist

[1] A video that depicts this new conceptual model is available from the author.

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subtropical air from the Gulf of Mexico and cold, dry air from the Canadian Arctic. The new model also highlights a number of important weather-producing features that previously have not been explicitly recognized.

There is evidence that some cyclones that fit our conceptual model maintain their structures into the eastern United States (Locatelli et al. 1989), while others evolve into more classic wave cyclones. In this paper we will confine our attention to the evolution of cyclones from the lee of the Rockies to the Mississippi River.

2. Nonclassic cyclonic features included in the new conceptual model

Virtually all eastward moving cyclones have to pass over the high terrain of the Rocky Mountains before they reach the central United States. The topography of the region channels warm moist air from the Gulf of Mexico northward and cold dry arctic air from Canada southward. These two very different air masses, together with westerly downslope flow off the Rockies (Fig. 1a), have important influences on the structure of cyclones in the central United States.

As a shortwave trough moves eastward, westerly downslope flow increases over the Rockies. This produces adiabatic warming and a pressure trough at the surface in the lee of the Rockies, called the lee trough. A surface low pressure center often forms within the lee trough (Fig. 1b).

The confluence into the lee trough of warm, dry air off the Rockies and warm, moist air from the Gulf of Mexico produces a strong west–east gradient in moisture and a line of maximum potential temperature along the lee trough. Since the lee trough is characterized by significant horizontal convergence at low levels, the moisture contrast across it gradually increases. Thus, the lee trough can eventually take on the characteristics of a dryline, which marks a narrow zone over which the dewpoint at the surface changes rapidly in the west–east direction. In our conceptual model, a lee trough that also has the characteristics of a dryline is called a drytrough (Fig. 1c). Not all lee troughs become drytroughs, but lee troughs in the south-central United States generally provide the setting for the formation of drylines.

A dryline that has a weak trough associated with it may not have the warm frontal-like circulation necessary to lift the potentially unstably stratified air away from the surface. A lee trough without a moisture contrast may have a warm frontal-like circulation, but it will not be associated with potentially unstable air. The term drytrough is introduced to identify a surface lee trough that has a warm frontal-like circulation that lifts potentially unstable air.

We will now describe the components of the circulation associated with a drytrough. Convergence of air into a drytrough, caused by the frictional turning of the wind in the boundary layer, in conjunction with weak frontogenesis and associated warm-air advection, forces the northward flowing moist air from the Gulf of Mexico to rise and turn toward the northeast as it approaches the drytrough (Fig. 1d). The downslope flow of warm, dry air from the Rockies reaches its lowest altitude over the drytrough and then rises above the warm, moist air from the Gulf of Mexico (Fig. 1e). In late winter, air that has been heated and well mixed over the high Mexican plateau (and sometimes farther north) flows eastward above the other two air streams (Fig. 1f). As the airflow associated with a drytrough develops, the strong southerly flow ahead of the drytrough leads to the formation of a southerly low-level jet (Bonner 1968; Djuric and Ladwig 1983). This jet enhances the transport of warm, moist air northward (Fig. 1f).

As in the case of a warm front, the drytrough juxtaposes potentially warmer air over potentially cooler air in an upward-sloping zone. However, there are some important differences between a warm front and a drytrough. In a typical warm front, moist air is superimposed over drier air. Stated another way, in a warm front, air with high equivalent potential temperature is superimposed over air with a low equivalent potential temperature. This produces a potentially stable stratification. As the potentially stable layer is lifted to saturation in a warm front, the layer remains stable. Therefore, the cloud and precipitation that develop tend to be stratiform.

By contrast, in a drytrough, dry air (from the downslope flow off the Rockies) is superimposed over moist air (from the Gulf of Mexico). Thus, air with a low equivalent potential temperature is superimposed over air with a high equivalent potential temperature, which produces a potentially unstable stratification. As this potentially unstable layer is lifted to saturation in a drytrough, it becomes unstable, which produces convective clouds and precipitation. The air most likely to reach saturation first is located at the leading edge of the potentially unstable air, since vertical displacements are largest in this region. This can

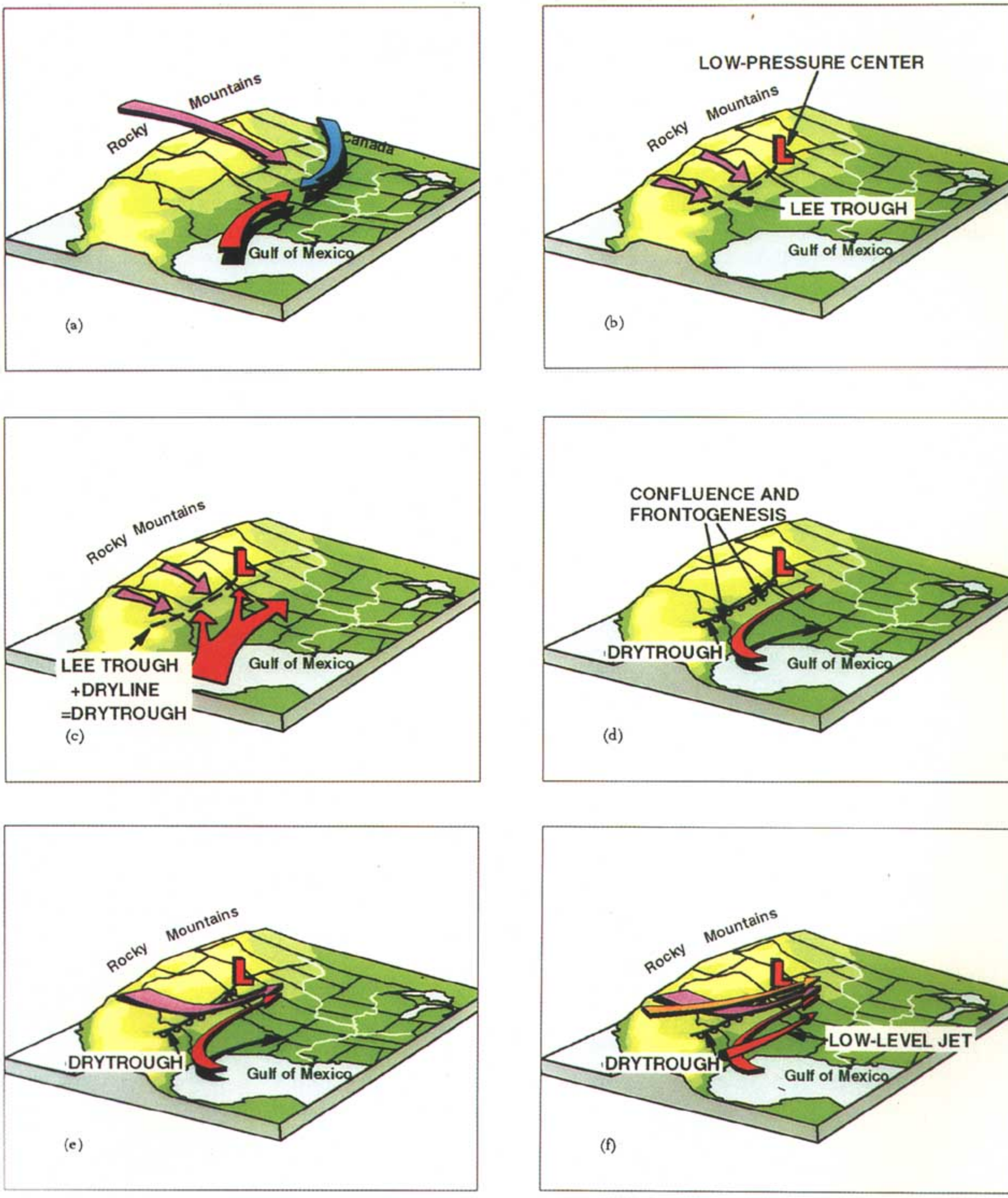

FIG. 1. Schematics illustrating airflows and the formation of a drytrough as an eastward moving, shortwave trough passes over the Rocky Mountains. (a) The confluence of westerly downslope flow off the Rockies, warm, moist air from the Gulf of Mexico, and cold, dry arctic air. (b) Adiabatic warming of downslope air from the Rockies produces a lee trough. (c) The lee trough acquires the characteristics of a dryline and becomes a drytrough. (d) Confluence and frontogenesis east of the drytrough causes air from the Gulf of Mexico to rise and turn toward the northeast as it approaches the drytrough. (e) Downslope flow of warm, dry air from the Rockies reaches its lowest altitude over the drytrough then rises above the warm, moist air from the Gulf. (f) The elevated mixed layer from the Mexican plateau flows above the other two airstreams. Also, a low-level jet of warm, moist air flows northward.

lead to the formation of a convective rainband that is sometimes situated well ahead of the surface location of the drytrough; in our model, this rainband is referred to as the pre-drytrough rainband (Fig. 2a).

If the lifting associated with the warm frontal-like circulation continues, the pre-drytrough rainband moves northward and eastward away from the surface position of the drytrough and it may eventually extend over many states. In Fig. 2a, the pre-drytrough rainband is depicted as a single large band, but in reality it may be composed of several subbands. As the pre-drytrough rainband moves progressively ahead of the drytrough, it can develop lightning, turbulence, and icing conditions hazardous to aircraft.

We now describe the arctic front (Figs. 2a,b) and show how it can combine with the pre-drytrough rainband (Fig. 2c). Arctic fronts are common in winter cyclones in the central United States. They are formed by the southward movement of cold air from Canada. The northward flow of warm moist air over the arctic front, and the lifting of warm moist air around the low pressure center, produces precipitation that is often in the form of freezing rain and snow (Fig. 2b). The lifting of the air around the low pressure center, combined with the upslope flow of the arctic air along the western Great Plains, contributes to occasional heavy snowfall in this region.

As the cyclone moves eastward, the arctic air west of the low pressure center moves south as a cold front. However, most of the precipitation associated with the arctic front generally remains near the low pressure center and is associated with the stationary or northward moving part of the arctic front located east of the low pressure center (Fig. 2c). West of the drytrough, the southward moving arctic front lifts warm dry air over the southeastward moving cold arc-

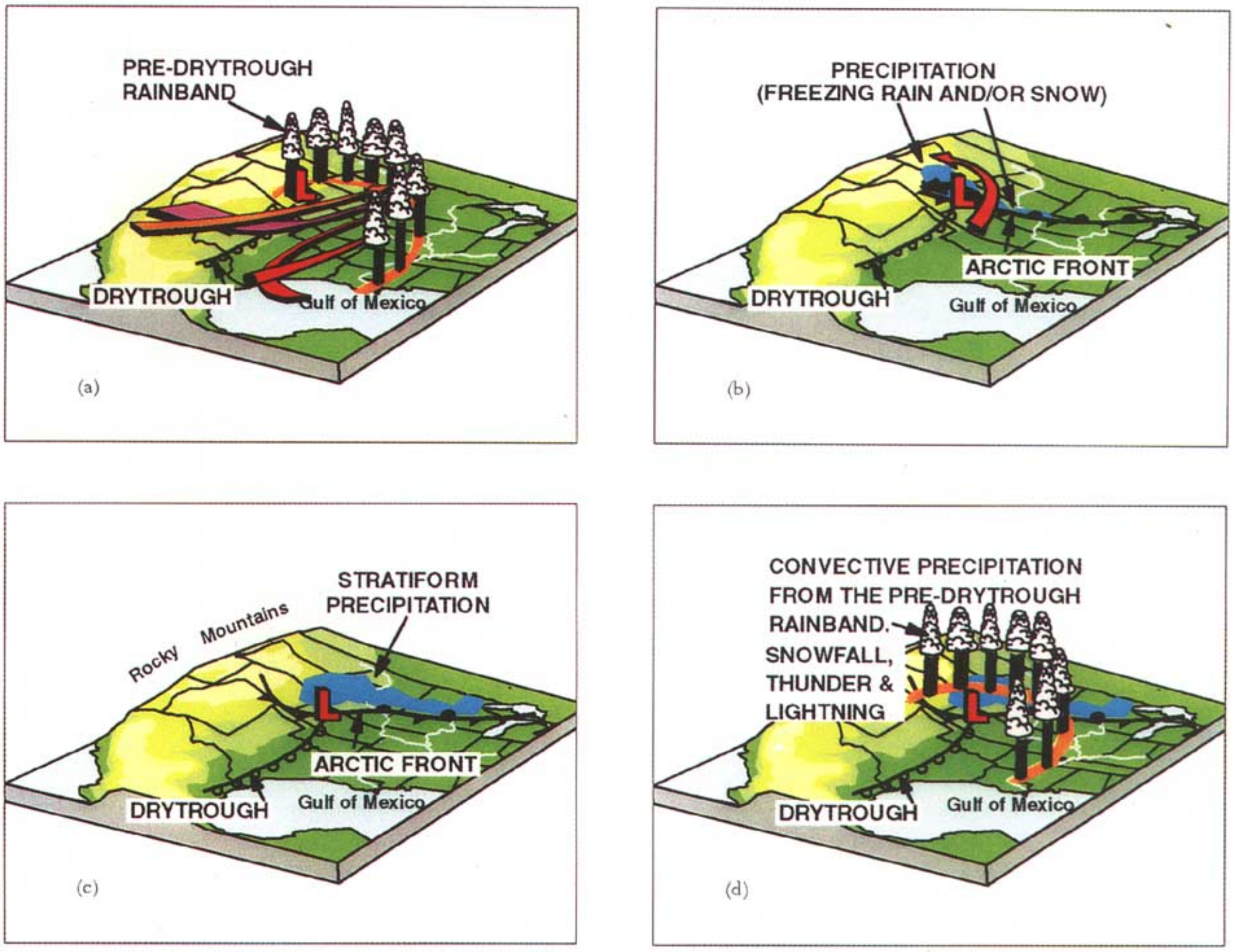

FIG. 2. (a) Lifting of the potentially unstable air ahead of a drytrough produces a pre-drytrough rainband. (b) and (c) Southward movement of cold arctic air near the surface produces an arctic front. Associated with this may be freezing rain and/or snow and stratiform precipitation. (d) Precipitation from the pre-drytrough rainband originates from higher levels and is convective in nature.

tic air, but this generally produces little or no precipitation. The precipitation associated with the arctic front is produced at low levels and is stratiform in nature, while the precipitation from the pre-drytrough rainband originates at higher levels and is convective. This can result in the unusual simultaneous occurrence of snowfall, thunder, and lightning (Fig. 2d).

Another important feature of many cyclones in the central United States are cold fronts aloft (CFA).[2] They develop as follows. Shown schematically in Fig. 3a are contours of geopotential height and isotherms at 500 mb as a shortwave trough moves over the Rockies. The isotherms indicate a baroclinic zone that is characterized by cold advection and by frontogenesis. The leading edge of this baroclinic zone is marked as a heavy line in Figs. 3a,b. As this upper-level baroclinic zone, or CFA, moves over the Rockies, it may be associated with a front at the surface. However, as it moves down the eastern slope of the Rockies and out over the Great Plains, adiabatic warming associated with the low-level downslope flow tends to erode the baroclinic zone at the surface.

As the CFA advances over the drytrough, it occludes with the upward-sloping region of high equivalent potential temperature air ahead of the drytrough to form a warm occluded-like structure (Fig. 3c). Two processes may then act to form a rainband in the vicinity of the leading edge of the CFA. The first process is frontogenesis associated with the CFA, which leads to upward motions that are often concentrated just ahead of the nose of the CFA (Fig. 3d). The second process is associated with the forward motion of the cold air aloft, which produces the upward motion of air beneath the nose of the CFA in the following way. Beneath the nose of the CFA, the rate at which the pressure falls decreases due to the advection of cold air aloft. This produces an ageostrophic wind, convergence, and upward movement of air. This second process is discussed in more detail by Locatelli et al. (1995). The net result of the two processes is to produce two regions of upward air motion that augment each other (Fig. 3e).

Prior to the arrival of the CFA, air with low equivalent potential temperature ahead of the drytrough is situated above air with high equivalent potential temperatures. The upward movement of air produced by the passage of the CFA can lift the potentially unstable lower air to produce what is called a CFA rainband in our model (Fig. 3f). Since the location of the CFA rainband is tied to the leading edge of the CFA, it moves eastward with the CFA. The CFA rainband may cover several states and it may be composed of several squall lines that can give rise to tornadoes, large hailstones, and flash floods.

3. Some common pitfalls in analyses

Cyclones that fit the conceptual model described in this paper have a sea level pressure pattern associated with the drytrough and the arctic front that is similar to the classic open-wave cyclone depicted in the Norwegian Cyclone Model. Also, the surface isotherms associated with our model resemble those in a classic open wave. Consequently, the drytrough and arctic front are often analyzed as a cold front and as a warm front, respectively, and rainbands east of the "cold front" are viewed as boundary-layer driven warm-sector squall lines (Fig. 4a). In Fig. 4a, the pre-drytrough rainband has a question mark alongside it, since this rainband is not a feature of the classic cyclone model. In terms of our conceptual model the analysis is quite different, namely, a drytrough, an arctic front, and a CFA rainband and a pre-drytrough rainband (Fig. 4b).

Many examples could be given to illustrate the pitfalls associated with trying to use the Norwegian Cyclone Model to describe cyclones in the central United States [see, for example, Young and Fritsch (1989) and Mass (1991)]. Here we describe briefly just two examples. The first is of historical interest, since it was one of the first published attempts to apply the Norwegian Cyclone Model to the United States (Rossby and Weightman 1926). The second example is associated with a world record rainfall rate in Holt, Missouri (Lott 1954).

Figure 5 shows Rossby and Weightman's analysis of a cyclone as it passed through the central United States on 18 February 1926. They analyzed the lines

[2] Hobbs et al. (1990) used the term CFA to indicate a cold front aloft. Locatelli et al. (1995) used the term to refer to cold frontogenesis aloft. In this paper CFA refers to the leading edge of a transition zone above the surface that separates advancing cold air from warmer air. The length of the transition zone is much greater than its width, and the gradients of temperature and absolute momentum in the transition zone are much greater than in adjacent regions. Defined in this way, CFA encompasses features ranging from regions of concentrated upper-level cold-air advection within migrating upper shortwave troughs to bona fide upper-level frontal zones of the type discussed by Reed and Sanders (1953), Reed (1955), and Keyser and Shapiro (1986). The important dynamical characteristic that these features have in common is the occurrence of active frontogenesis in association with baroclinic zones of varying strengths. Defined in this manner, the term CFA stands for cold front aloft.

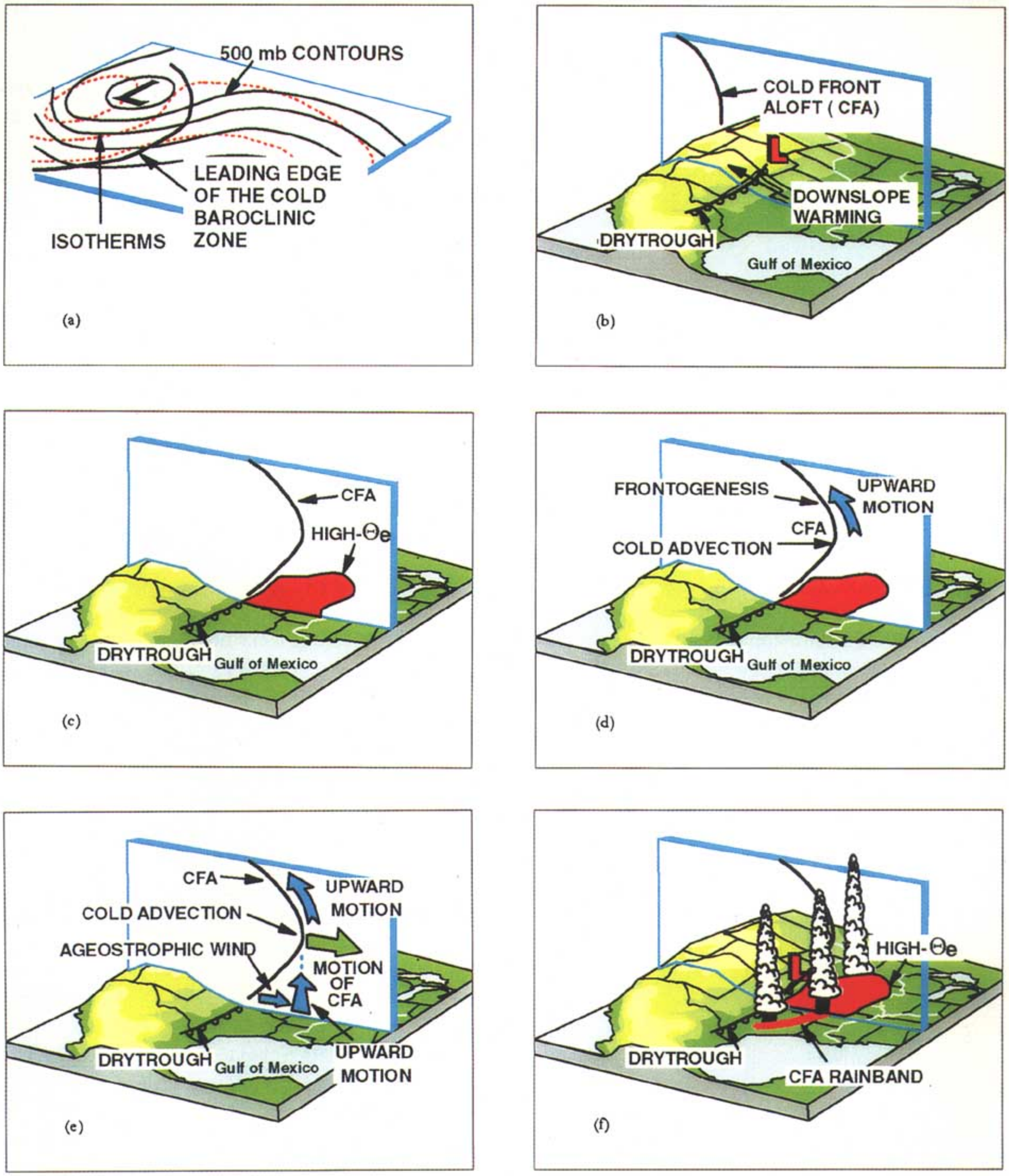

FIG. 3. Schematics illustrating the approach of the CFA and the formation of the CFA rainband.

marked C_p and W_1 in Fig. 5 as a cold and a warm front, respectively. They suggested that the large area of precipitation contained within the dashed line in Fig. 5 was produced by lifting at the warm front. However, W_1 does not lie within a prominent pressure trough, and there is no significant wind shift across it. Interestingly, Rossby and Weightman deduced from kite observations that thunderstorms associated with this area of precipitation originated in convection generated 2 km above the surface.

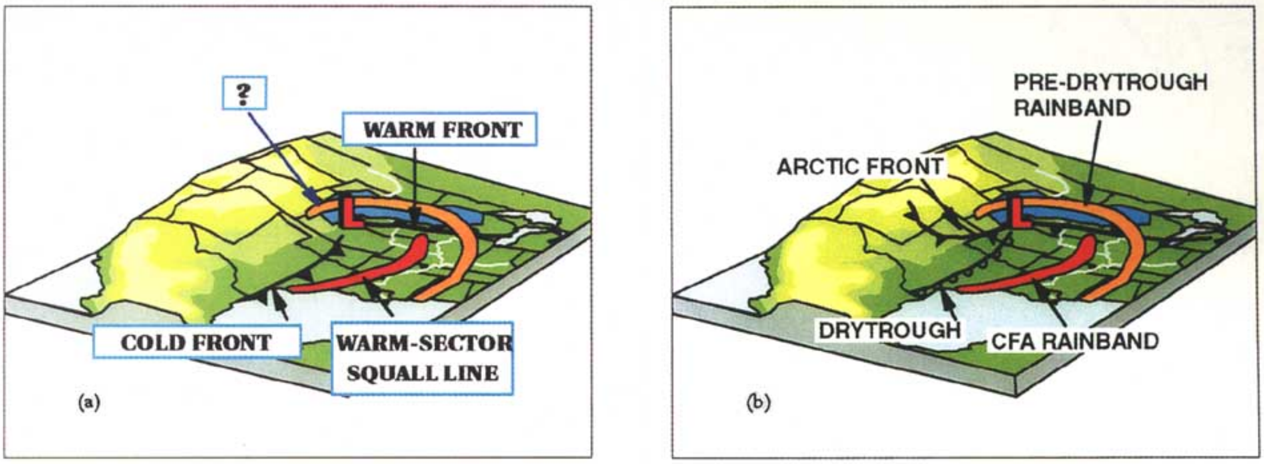

FIG. 4. (a) A common misanalysis. (b) Analysis in terms of the conceptual model described in this paper.

If the synoptic situation depicted in Fig. 5 is reanalyzed in terms of our conceptual model, the anomalies in Rossby and Weightman's analysis disappear. Thus, we would locate a drytrough on the sharp windshift line (C_p) in central Texas, W_1 would be dropped as a feature, and C_2 would be analyzed as an arctic front. The precipitation stretching from Kansas southeastward to Mississippi is then seen to be a pre-drytrough rainband, triggered by the release of convective instability aloft ahead of the drytrough.

The Holt storm occurred on 22 June 1947 when 12.00 in. (~304.8 mm) of rain fell in 42 minutes! Figure 6 shows the U.S. Weather Bureau's surface analysis about 6 h before the Holt storm. It depicts a cold front aloft (indicated by open cold-frontal symbols) ahead of the surface cold front. On the other hand, Lott's (1954) surface analysis shows a warm-sector squall line (dashed–dotted line in Fig. 7) extending across northern Missouri, just west of Holt. Consequently, Lott concluded that the "Holt storm occurred as a local intensification in a long, narrow, warm sector convective system . . . a short distance ahead of a surface cold front." The squall line was well developed, with a mesolow and a trailing region of rain-cooled air. However, apart from this mesoscale region of cooling, the station reports and Lott's isotherm analysis indicate only a slight temperature change across the surface cold front that he analyzed. The best signature for Lott's cold front is the rapid decrease in moisture. This distribution of temperature and moisture is more characteristic of a drytrough than a cold front (Martin et al. 1995). Also, the sounding for Oklahoma City at 1500 UTC 22 June 1947 (not shown) reveals an elevated mixed layer overrunning moist and potentially cooler air. This structure is more characteristic of the air ahead of a drytrough than it is of a warm sector, since the circulation of a drytrough superimposes dry descending air from the Rockies over warm, moist air from the Gulf of Mexico.

The situation shown in Fig. 7 is reanalyzed in terms of our conceptual model in Fig. 8. The feature analyzed as a cold front by Lott is now shown as a drytrough. Also shown in Fig. 8 is the CFA deter-

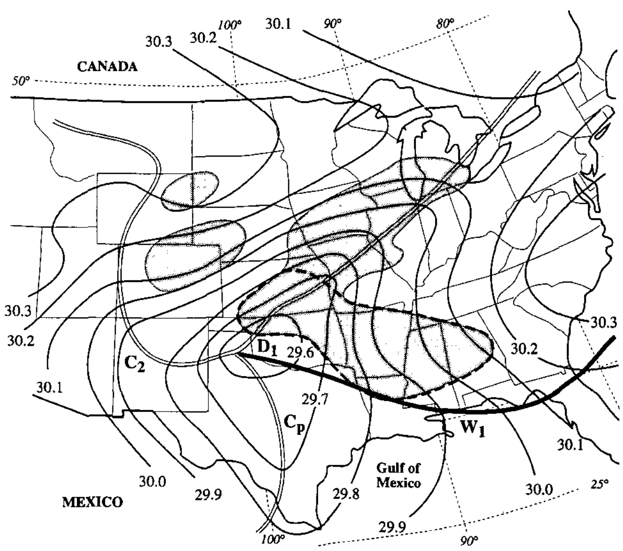

FIG. 5. Rossby and Weightman's (1926) analysis of sea level pressure for 0100 UTC 18 February 1926 (isobars are labeled in inches of mercury); C_p was analyzed as a cold front, W_1 as a warm front, C_2 as a secondary cold front, and D_1 as the low pressure center. Regions of precipitation are shaded. The dashed line encircles the position of the pre-drytrough rainband obtained by applying the conceptual model described in this paper to Rossby and Weightman's analysis.

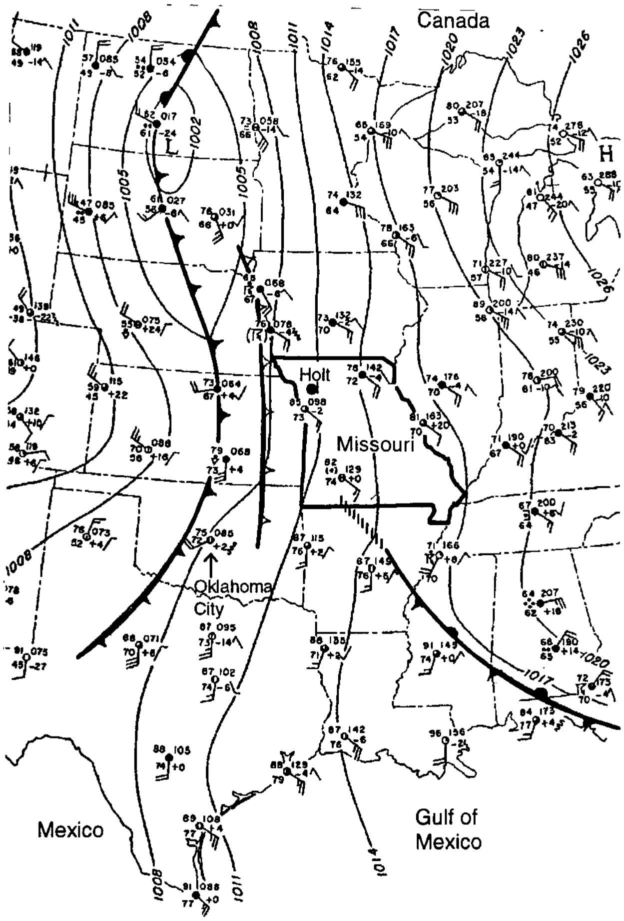

FIG. 6. U.S. Weather Bureau analysis of sea level pressure (in hPa) for 1830 UTC 22 June 1947. The surface data are plotted in the standard station format.

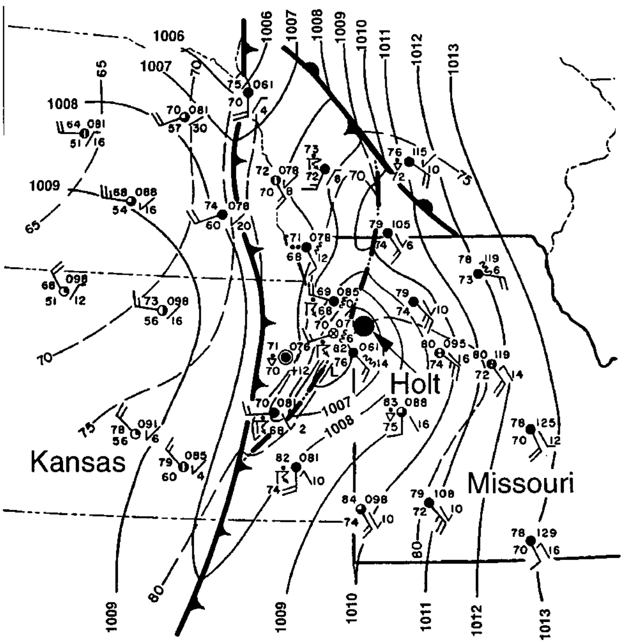

FIG. 7. Lott's (1954) analysis of sea level pressure (continuous lines labeled in hPa) and surface isotherms (dashed lines labeled in °F) for 0030 UTC 23 June 1947. The heavy dashed–dotted line indicates the position of the squall line.

mined from Lott's 700-hPa analysis; it is located about 150 km east of the drytrough. It can be seen that the CFA was aligned quite closely with the squall line. In fact, Lott's 700-hPa chart could be analyzed so that the CFA coincides exactly with the squall line. Locatelli and Hobbs (1995) provide detailed evidence to support this interpretation.

The Holt storm demonstrates that the conceptual model described in this paper is not confined to winter cyclones. Many summer squall lines in the central United States are CFA rainbands, although previously they have not been recognized as such.

4. The new conceptual model as an aid to forecasting

Synoptic-scale numerical weather prediction models now play a dominant role in forecasting. In the near future, mesoscale numerical models will also become important in operational weather forecasting. However, good conceptual models will continue to be needed as an aid in the interpretation and use of numerical model outputs, as well as an indispensable guide in the difficult task of digesting the ever-increasing quantities of data available to the forecaster.

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The wrong conceptual model can lead to incorrect analyses and poor forecasts. For example, with the Norwegian Cyclone Model in mind, one tends to associate heavy precipitation and possibly severe weather with the passage of the cold front. Therefore, this is a feature commonly shown on surface charts.

As we have seen, in the central United States, the drytrough can be misanalyzed as a cold front (see also Maddox 1980). Our conceptual model focuses attention well ahead of the drytrough, where heavy precipitation and severe weather are often associated with the CFA rainband and the pre-drytrough rainband. In the absence of a conceptual model that includes these important features, they can be overlooked, even though they may extend over several states and be present in numerical model outputs and in the data.

Since cold frontogenesis aloft is a synoptic-scale feature, high-resolution numerical models (such as the National Weather Service's Nested Grid Model) sometimes do well in predicting its location and movement. Since the location of the CFA determines the position of the CFA rainband, awareness of the existence of CFA and predictions of its movement can help improve forecasts of the severe weather associated with this feature.

5. Conclusions

The new conceptual model described in this paper captures many of the important weather-producing features of cyclones in the central United States. Use of this conceptual model should help in the identification of these features, aid synoptic and mesoscale analyses, and increase the accuracy of short-range forecasts of precipitation and severe weather in the region.

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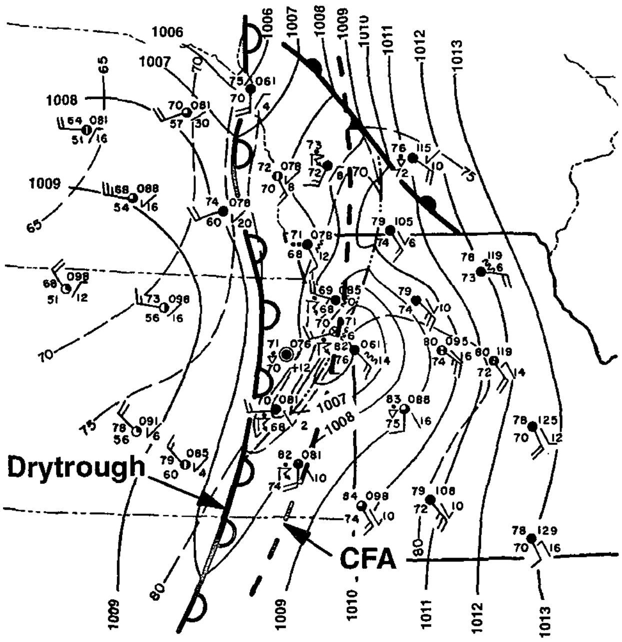

FIG. 8. Reanalysis of the surface chart shown in Fig. 7 in terms of the conceptual model described in this paper. The heavy solid line with the open warm-frontal symbols indicates the surface position of the drytrough. The heavy dashed line indicates the location of the CFA at 700 hPa. The light dashed–dotted line is the position of the squall line from Fig. 7. From Locatelli and Hobbs (1995).

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