A World Record Rainfall Rate at Holt, Missouri: Was It Due to Cold Frontogenesis Aloft?

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(Manuscript received 10 February 1995, in final form 23 June 1995)

ABSTRACT

On 22 June 1947, Holt, Missouri, experienced a world-record rainstorm when 304.8 mm (~1 ft) of rain fell in 42 minutes. In this paper, evidence is presented that this extremely heavy rain may have been produced by cold frontogenesis aloft (CFA). It is shown that what was earlier analyzed as a surface cold front was probably a drytrough, and that CFA was located at 700 hPa east of the drytrough, close to the location of the squall line that produced the record precipitation rate.

1. Introduction

Holt, which is located about 25 km northeast of Kansas City in northwest Missouri, could be one of many small midwestern agricultural towns. However, this changed over the course of just 42 minutes on 22 June 1947 when a world record 304.8 mm (12 in.) of rain fell on Holt (Fig. 1). This measurement was made in a bucket 11 inches across and 14 inches deep; the measurement was consistent with those of nearby observers who recorded measurements of up to 11 in. in time periods of 42 to 50 min (U.S. Department of Commerce 1947). Homes were filled with more than two feet of water and mud as the extreme precipitation rate exceeded the ability of even level ground to drain the water fast enough to prevent flooding. The Holt storm contributed to the wettest June on record (since 1888) in Northern Missouri.

Seven years after the Holt storm, Lott (1954) described the synoptic and mesoscale conditions in which the storm developed. He concluded that the "Holt storm occurred as a local intensification in a long, narrow, warm sector convective system (the leading edge of which may be interpreted as an instability line) a short distance ahead of a surface cold front." By contrast, in this paper we show that the Holt storm can be analyzed more satisfactorily in terms of a new conceptual model for cyclonic storms in the Midwest described by Hobbs et al. (1990), Martin et al. (1995), and Locatelli et al. (1995), which is described briefly in the next section. Since very little data are currently available for the Holt storm, our reanalysis relies heavily on the data presented by Lott.

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2. The STORM conceptual model

Heavy rain and snow, plunging temperatures, tornadoes, and hailstorms are typical of the weather at various times of the year and in various regions of the central United States. They are often produced by cold fronts, squall lines, arctic fronts, lee troughs, and drylines that develop with cyclogenesis east of the Rockies. It is not surprising that many of these features do not fit readily into the classical Norwegian cyclone model, which was based on observations of marine cyclones making landfall in northwestern Europe. Based on our own studies and the integration of apparently disparate features that have been identified previously, we have developed a new conceptual model (called STORM for Structurally Transformed by Orography Model) for

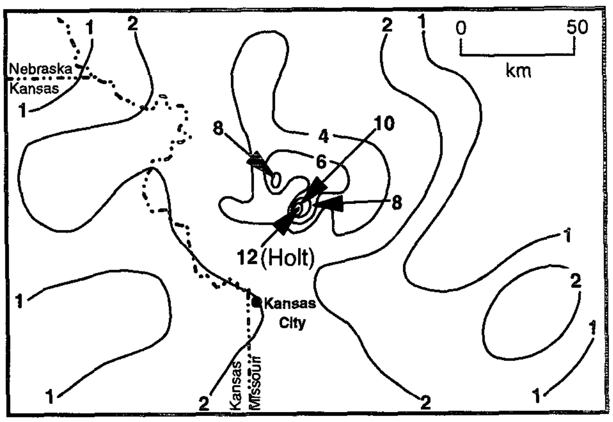

FIG. 1. Isohyetal map of the rainfall around Holt, Missouri, on 22 June 1947, adapted from Lott (1954), showing the results of a Corps of Engineers bucket survey. Precipitation amounts are in inches (1 inch = 25.4 mm).

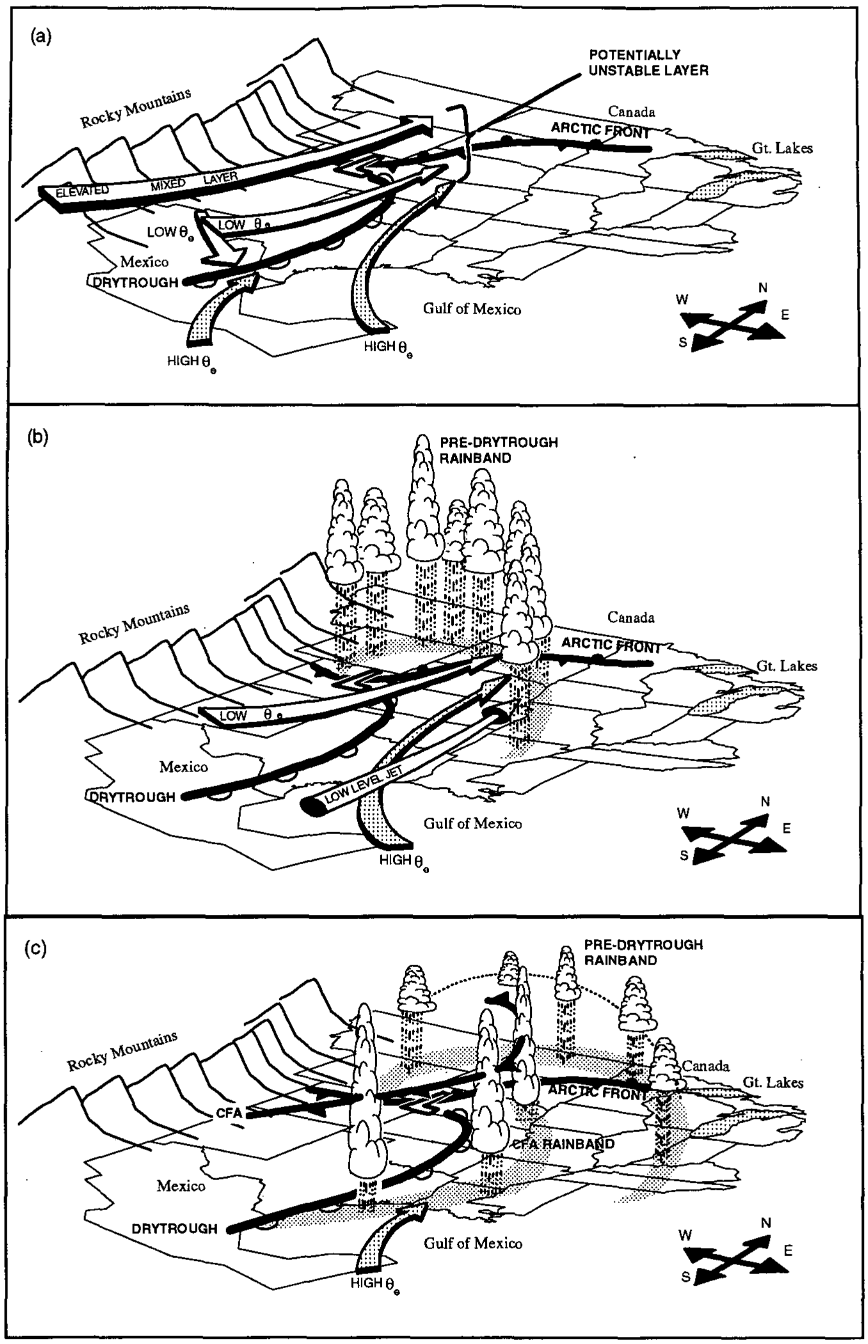

FIG. 2. Schematic of some of the main features of the STORM conceptual model. (a) The circulation around the drytrough before the formation of the pre-drytrough rainband. (b) The circulation around the drytrough during the mature stage of the pre-drytrough rainband. (c) The CFA rainband and the decaying pre-drytrough rainband as CFA moves east of the surface position of the drytrough.

easterly migrating, topographically altered, cyclones in the Central United States. (The essential features of the STORM model are depicted in a video, which is available from the corresponding author.) This model accounts for the role of the Rocky Mountains in modifying cyclogenesis and the structures of cyclones in the

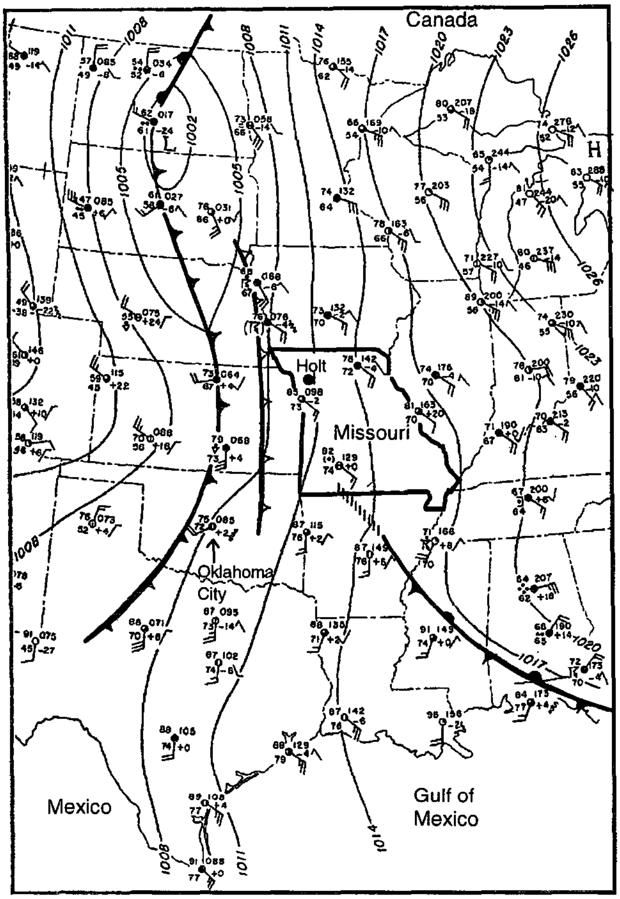

FIG. 3. Sea level pressure (in hPa) analysis, performed by the Weather Bureau Analysis Center, for 1830 UTC 22 June 1947. The surface data is plotted in the standard station model format. From Lott (1954) with geographical names added.

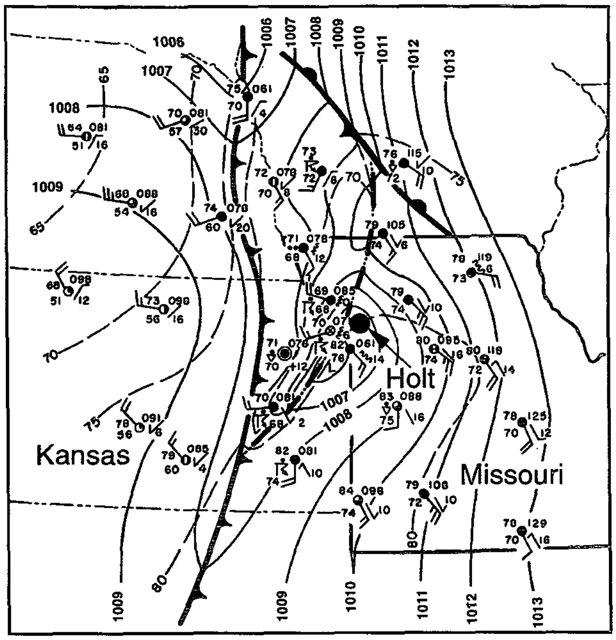

FIG. 4. Sea level pressure (continuous lines labeled in hPa) and surface isotherms (dashed lines labeled in °F) for 0030 UTC 23 June 1947. The dashed-dotted line indicates the position of a squall line. From Lott (1954) with geographical names added.

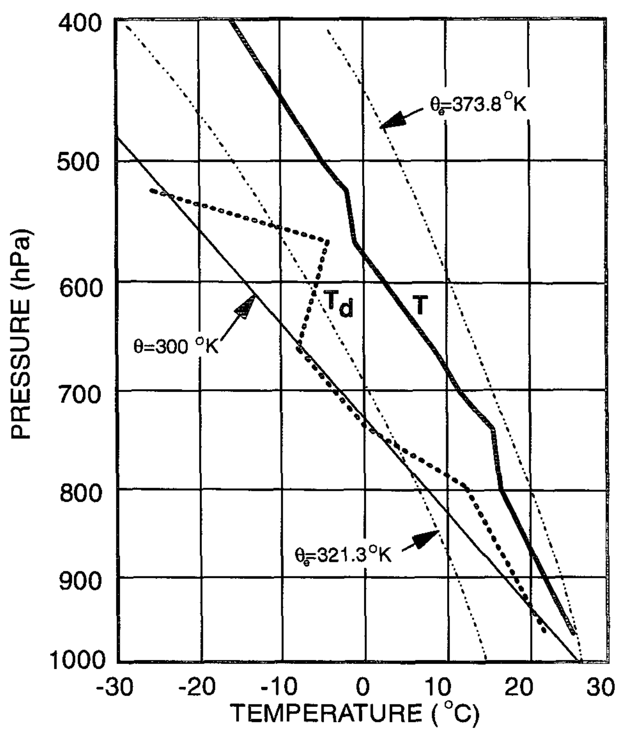

FIG. 5. Sounding for Oklahoma City, Oklahoma, at 1500 UTC 22 June 1947 adapted from Lott (1954). Temperature (T) and dewpoint (T_d) are plotted on a pseudoadiabatic diagram.

Central United States, and it explains many of the nonclassical weather features that are common in the region.

Figure 2 illustrates some of the main features of the STORM model. Figure 2a depicts the structure of a cyclone immediately in the lee of the Rockies, where the low pressure center, the *drytrough* (i.e., a combined lee trough and dryline) and its related warm-frontal-like circulation, the arctic front, and the elevated mixed layer have formed. Note the sloping, potentially unstable layer that is formed by the juxtaposition of high equivalent potential temperature (θ_e) air from the Gulf of Mexico and low θ_e air from the Rockies and Mexican Plateau. The continued lifting of this potentially unstable layer results in the formation of a synoptic-scale rainband, which we call the *pre-drytrough rainband* (Fig. 2b). Also shown in Fig. 2b are the developing low-level jet and a southward-moving arctic front.

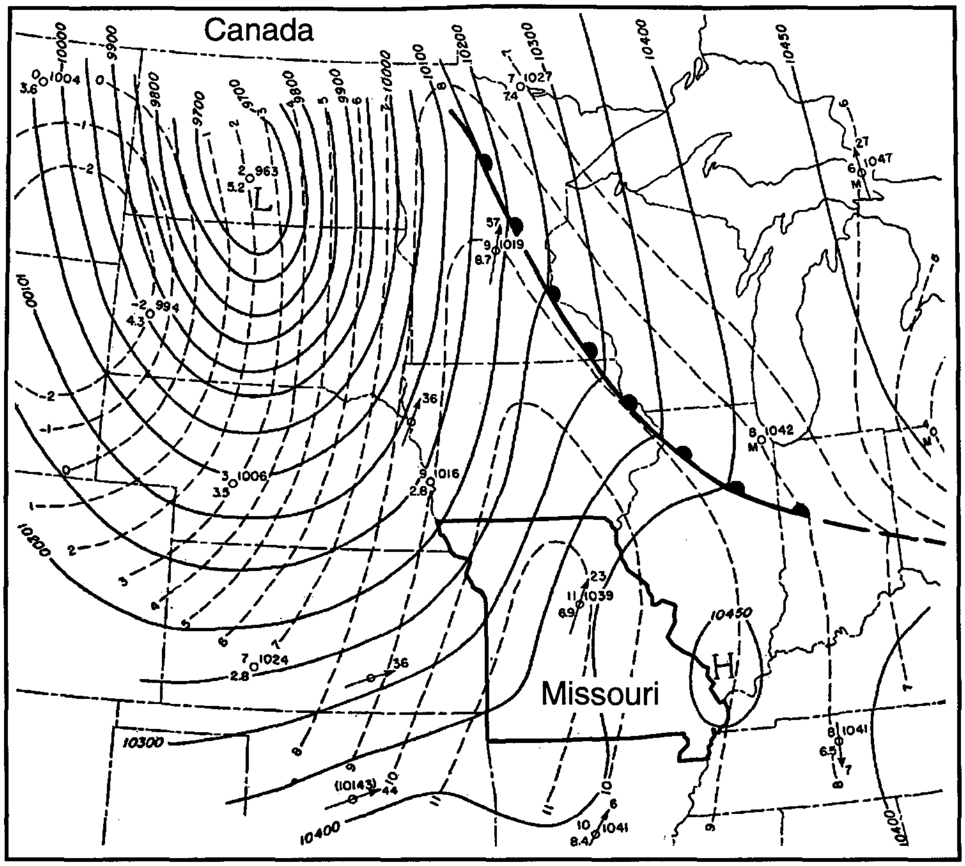

FIG. 6. The 700-hPa analysis at 0300 UTC 23 June 1947, from Lott (1954), with geographical names added. Solid lines are geopotential heights labeled in feet (10 000 ft = 3048 m). Dashed lines are isotherms labeled in degrees Celsius. The directions in which the wind is blowing toward are indicated by the arrows; the wind speed is indicated in knots at the arrow head (10 knots = 5.1 m s^{-1}).

As the leading edge of cold frontogenesis aloft (CFA)[1] moves east of the surface position of the drytrough, cold-air advection associated with the upper-baroclinic zone encounters warm-air advection associated with the drytrough (Fig. 2c). The CFA produces another rainband (the *CFA rainband*), which is often associated with severe weather.

3. Surface analysis

Figure 3 shows a surface synoptic map for 1830 UTC 22 June 1947, which was about 6 h before the Holt

[1] Hobbs et al. (1990) used the term CFA to indicate a cold front aloft. We now use this term to refer 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, the CFA encompasses features ranging from regions of concentrated upper-level cold-air advection within migrating upper shortwaves to upper-level frontal zones of the type discussed by 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 (frontal or nonfrontal).

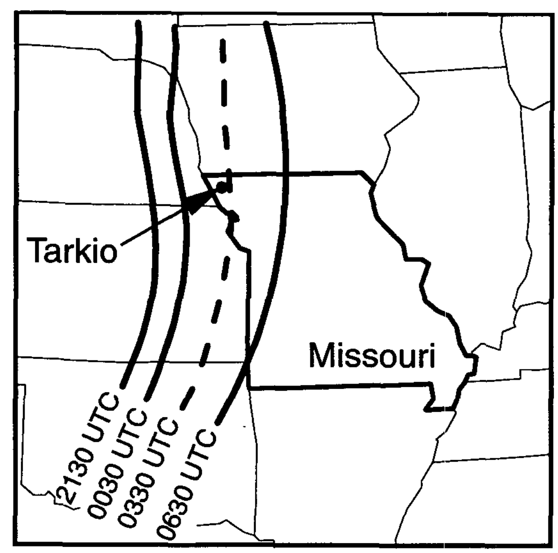

FIG. 7. Analyzed positions of the surface cold "front" at three times on 22 and 23 June 1947. The dashed line is an interpolated frontal position.

TABLE 1. Surface weather observations for Tarkio, Missouri, from 2132 UTC 22 June 1947 to 0527 UTC 23 June 1947. TRW− = light thunder shower, TRW+ = heavy thunder shower, F = fog, and R− = light rain.

	22 June 1947				23 June 1947						
Time (UTC)	2132	2147	2228	2329	0030	0048	0127	0229	0326	0428	0527
Temperature (°F)	81		72	72	71		70	69	68	68	67
Dewpoint (°F)	74		70	68	68		68	68	68	68	62
Sea level pressure (mb)	1006.4		1007.5	1008.5	1007.8		1008.5	1009.8	1010.8	1012.5	1012.5
Wind direction	SSE	SSW	SSE	SSE	SSE	SE	SSE	SSE	SSW	SW	WNW
Wind speed (mph)	27	22	16	17	5	9	8	8	6	5	16
Present weather	TRW−	TRW+	F	F	R−						

storm. Lott presents this figure without commenting on the analysis by the Weather Bureau of an upper-level cold front (indicated by open cold-frontal symbols) ahead of the surface cold front. Figure 4 shows Lott's surface analysis for 0030 UTC 23 June, close to the time of the Holt storm. He shows a warm-sector squall line across northern Missouri slightly west of Holt. The squall line is well developed, with a mesolow and a trailing region of rain-cooled air. 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 south of Holt, Missouri. This can be seen also from Kansas southward in Fig. 3. The best signature for this front is the rapid decrease in moisture (seen in the dewpoints). For example, Fig. 4 shows that the temperature

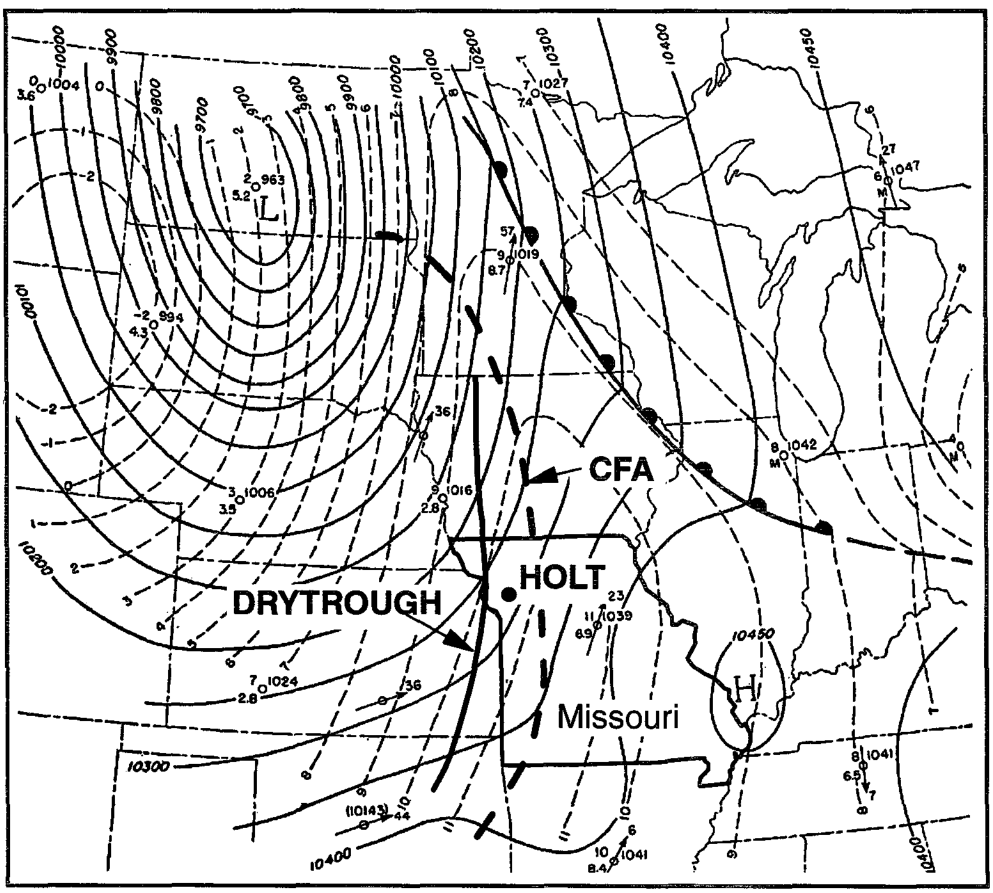

FIG. 8. Reanalysis of the 700-hPa chart shown in Fig. 5. The heavy solid line shows the interpolated position of the surface "front," which was most likely a drytrough. The heavy dashed line indicates CFA, which earlier coincided with the record rainfall rate at Holt, Missouri.

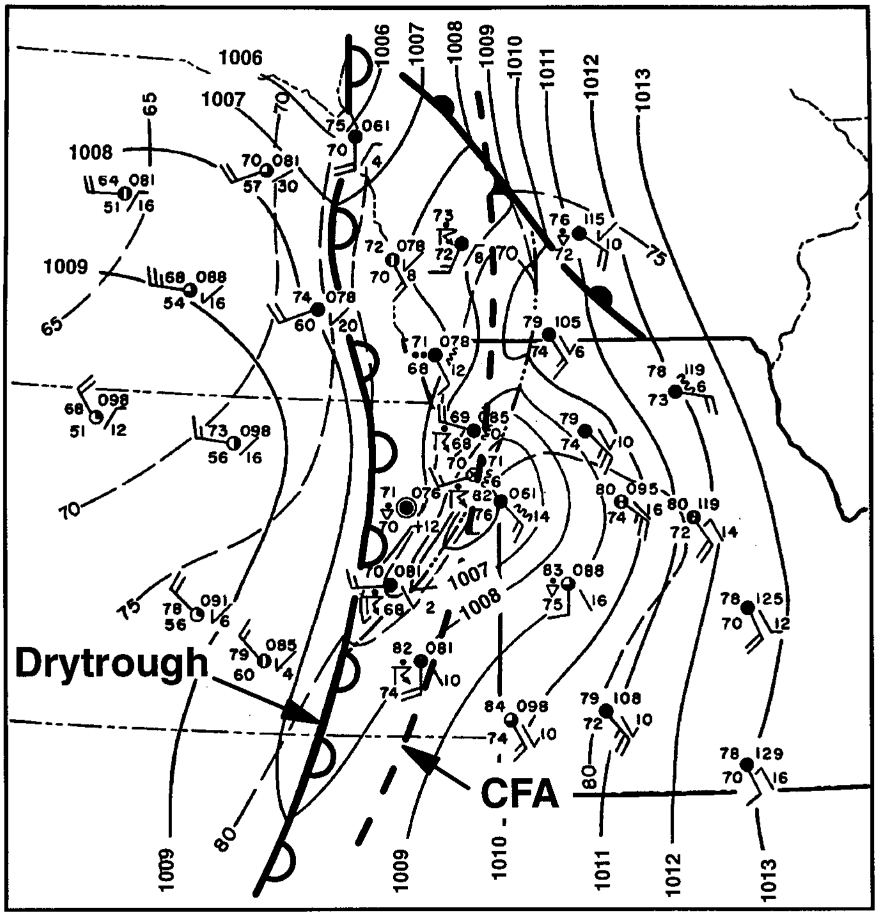

FIG. 9. Reanalysis of the surface chart shown in Fig. 3. The solid line with the open warm-frontal symbols indicates the surface position of the drytrough. The heavy dashed line indicates the position of cold frontogenesis aloft (CFA) at 700 hPa.

across the analyzed cold front in southeastern Kansas dropped by only 2°C (3°F), while the dewpoint dropped by 8°C (14°F). This distribution of temperature and moisture is more characteristic of a drytrough than it is of a cold front (Martin et al. 1995).

4. Sounding

Lott showed one sounding (Oklahoma City at 1500 UTC) ahead of the surface cold front that he analyzed; he concluded that this sounding was typical of the air in the warm sector. This sounding, shown in Fig. 5, shows a moist layer below 800 hPa, capped by a potentially warmer but drier layer; these two layers are separated by a stable transition layer from 730 to 800 hPa. From the ground to 660 hPa, the atmosphere is potentially unstable. Such a column, when lifted to saturation, would have a lapse rate greater than moist adiabatic and be strongly unstable. The lapse rate in the drier capping air is close to dry adiabatic.

The sounding shown in Fig. 5 is typical of a well-mixed layer of air, formed by diabatic heating over the elevated regions of the Rocky Mountains and the Mexican plateau, overrunning moist and potentially cooler air in the south-central United States. The stable transition layer is formed by the vertical juxtaposition of the base of the elevated mixed-layer and the low-level isentropes (Carlson et al. 1983). This type of sounding indicates that the elevated mixed layer was able to move freely over the moist air. This is more likely if the surface trough is a drytrough rather than a surface cold front, because the tipped forward structure of a drytrough superimposes dry descending air from the Rockies over warm, moist air from the Gulf of Mexico (Martin et al. 1995).

5. Upper-air analysis

Figure 6 shows Lott's 700-hPa analysis for 0300 UTC 23 June 1947, which is less than 3 hours after the Holt storm. His analysis clearly shows a tongue of warm air and a leading edge to a cold baroclinic zone (the start of cold-air advection) running from central Missouri northward to the Canadian border. To determine if this baroclinic zone at 700 hPa is east or west of Lott's surface cold front, we need to estimate the location of the surface features. We know the position of the so-called surface cold front at two times (2130 UTC 22 June and 0030 UTC 23 June) from Lott's analysis and a position for the front at 0630 UTC 23 June from the National Weather Service Daily Map Series. We have confidence in the analyzed position of the surface front from these sources, since the coincident surface trough is well marked by wind shifts. Figure 7 shows the three known positions of the surface front and our interpolated position of this feature at 0330 UTC 23 June.

The available surface data for 0030 UTC 23 June provides support for our interpolated position of the front. Table 1 shows the surface station reports from Tarkio, Missouri (location shown in Fig. 7), starting at 2132 UTC 22 June 1947. The falls in temperature and dewpoint, the decrease in wind speed, the momentary shift in the wind direction from south-southeast to south-southwest and the concurrent heavy thunder shower are consistent with the passage of a squall line between 2147 and 2228 UTC. After this passage the wind remained constant in direction from the south-southeast for 4 h, but between 0229 and 0326 UTC 23 June the wind direction shifted to the south-southwest. Concurrent with this wind shift was an increase in the rate of pressure rise but no significant change in temperature and no precipitation. Since we know from Lott's surface analysis that the squall line was east of Tarkio but the surface front was still west of Tarkio at 0030 23 June, we conclude that the second wind shift marked the surface front that passed Tarkio between 0229 and 0326 UTC. This conclusion agrees with the interpolated position of the surface front at 0330 UTC 23 June shown in Fig. 7.

In Fig. 8, we show the position of the leading edge of the advancing cold air at 700 hPa (labeled CFA) and the position of the interpolated surface cold front. Clearly, the CFA at 700 hPa lies to the east of the surface cold front. This is strong evidence that the so-called surface cold front was, in fact, a drytrough. This conclusion is consistent with the lack of any significant temperature drop accompanying the wind shift at Tarkio during the passage of the front.

Figure 9 is our reanalysis of the synoptic situation at the time of the Holt storm, showing a surface drytrough and CFA to the east of the drytrough.

6. Conclusions

This case study illustrates the influence that a conceptual model can have in the analysis and interpretation of weather data. The earlier analysis of the Holt storm by Lott was cast in terms of the Norwegian Cyclone Model. Accordingly, the pressure trough was labeled a cold front even though there was only a slight temperature drop across this feature. The region of exceptionally heavy precipitation ahead of the cold front was then viewed as a warm-sector squall line. From the viewpoint of the STORM conceptual model, the interpretation of this event is quite different. The feature analyzed as a cold front by Lott is now viewed as a drytrough, which is consistent with the pressure, temperature, and humidity gradient across the feature, and the squall line that produced the record rainfall rate is attributed to cold frontogenesis aloft (CFA) located at 700 hPa east of the surface drytrough.

Previously, we have linked CFA to severe weather in the Midwest during winter, when strong cold baroclinic zones aloft are most likely to combine with strong drytroughs (e.g., Hobbs et al. 1990). However, the reanalysis of the Holt storm presented in this paper suggests that CFA can occur also in early summer in the Midwest and that it can produce heavy rainfall, squall lines, and the potential for severe weather in this season as well as in winter.

Acknowledgments. We thank the National Climatic Data Center for supplying data. This research was supported by Grant ATM-9106235 from the Atmospheric Research Division of the National Science Foundation.

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