Synoptic-Scale Environments Associated with High Plains Severe Thunderstorms

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Abstract

Typical synoptic-scale features are described for summertime severe thunderstorms on the High Plains. Severe weather generally occurs on several days in succession, under conditions that are relatively benign in terms of conventional severe weather parameters. Low-level conditions strongly resemble previously described convective flash flood situations. Moderate westerly flow is indicated at mid- and upper-levels, with the jet stream axis typically across or north of the threat area. Preexisting mesoscale systems often play a significant role in organizing the activity. Examples are shown, including one involving a thunderstorm outflow boundary.

1. Introduction

Although nearly daily thunderstorms are a well-recognized phenomenon along the lee slopes of the Rocky Mountains in the summer, they remain a challenging problem to forecasters at the National Severe Storms Forecast Center (NSSFC). It is the need to identify situations capable of producing *severe* thunderstorms along the High Plains that has prompted this effort. Geographically, for this study, the High Plains is that region between the Continental Divide and roughly 102°W, north of about 37°N.

Hail occurrences, sometimes reaching severe limits (2 cm or larger) are common in the region, but tornadoes are generally regarded as infrequent. Cook (1953) has stated that tornado forecasts in the High Plains are ". . . a difficult, and perhaps an impossible, problem." Auer (1967), commenting on a series of tornadic storms in 1965, echoed the statement that tornadoes are rare in association with High Plains thunderstorms.

More recently, Prosser (1976), Golden (1978), and Zipser and Golden (1979) have described noteworthy High Plains tornado events. Perhaps the most significant High Plains tornado in recent history is the one which struck Cheyenne, Wyo., on 16 July 1979 (Beebe, 1979; Politovich and Martner, 1979; Zipser and Golden, 1979). This tornado was responsible for the first Wyoming tornado fatality in more than 20 years and produced more damage than any other tornado in Wyoming history. In fact, 1979 brought a marked increase in the number of June and July severe storms reported on the lee slopes, especially in Wyoming and Colorado, continuing the trend that began in 1978 (Ostby and Wilson, 1980). At least one High Plains severe event occurred on 30 separate days during those months. Altogether, that two-month period recorded 156 High Plains severe thunderstorm reports, including 64 tornadoes. Those tornadoes represent nearly a quarter of all tornadoes reported nationwide during that time!

Severe weather reports are plotted, for June and July 1979, in Fig. 1. Also shown are smoothed terrain features and some of the major highways in the region. It is strikingly apparent that population centers and major highways (e.g., Interstate 76 or U.S. 50 in Colorado) are preferred locations for severe weather *reports*. The emphasis is on reports because, as has long been known (Cook, 1953; Galway, 1977; Kelly *et al.*, 1978), such reports are heavily biased by population density. On the sparsely populated lee slopes, even highways can function as local "population" maxima.

Also apparent from Fig. 1 is the rarity of reports west of the Continental Divide. While terrain features have a very real influence on weather distributions, the crudeness of severe weather reports makes such influences difficult to assess. For example, the terrain ridge in southeastern Wyoming is thickly scattered with reports, while a similar feature in east-central Colorado is nearly devoid of reports. Is this difference real? If so, is it anomalous?

In any case, Fig. 1 certainly supports the statement by Maddox (1975) that severe weather and tornadoes are not the rare event on the High Plains they were once thought to be. As energy resources like coal and oil shales are increasingly exploited in this region, greater population is making it possible to document severe thunderstorm events that have likely been occurring all along, but remained unreported. Since the enhanced population is vulnerable to severe weather like the Cheyenne tornado, the region's severe weather synoptic climatology may be a valuable aid to operational meteorologists.

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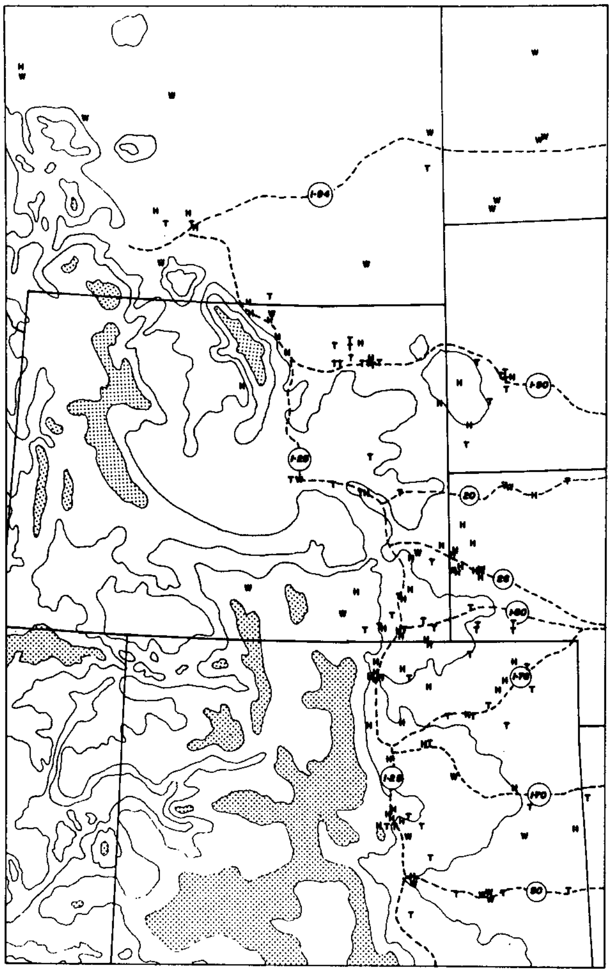

FIG. 1. Severe weather reports during June and July 1979. Tornadoes are denoted by "T," large hail by "H," and severe windstorms by "W." Also shown are the 5000, 7000, and 9000 ft terrain contours (approximately 1500, 2100, and 2700 m) above sea level and selected major highways (numbers preceded by "I" denote interstates).

2. Data and approach

Reports in Fig. 1 are confirmed severe weather events taken from a log maintained at NSSFC. As already discussed, this record is likely only part of the true distribution, but is does indicate the extent of the problem. Note that the eastern cut-off in plotted reports is roughly along 102°W longitude, but the decision to include severe weather events near this cut-off (e.g., western Nebraska) as "High Plains" events was done on a case-by-case basis.

Daily subjective analyses are retained for two years at NSSFC for poststorm studies. These include surface, 850, 700, and 500 mb level charts and a tropopause/maximum wind chart. Further, an experimental chart, including some selected kinematic and thermodynamic parameters (Doswell and Lemon, 1979) calculated from the soundings, was available for study. The entire two-month period of June and July 1979 has been scrutinized. It is obviously of interest to see how the synoptic patterns evolve, including periods of little or no activity.

A listing of the severe weather days during the period (Table 1) reveals a marked tendency for severe thunderstorms on the High Plains to occur in sequences four to five days long. Therefore, synoptic analysis should offer some explanation for this tendency. Further, it may be possible to determine parameter thresholds for initiating and terminating such a sequence.

3. The composite High Plains severe weather events

Examination of the charts has shown that most of the severe weather during the period was associated with a nearby long-wave ridge axis (in the vicinity of 100–110°W). Such a feature is common during the summer months, resulting in part from the strongly heated continental land surface. Weather systems during this season are generally weaker and harder to distinguish in the upper atmosphere. Small-scale systems become more significant as a result of the general absence of strong large-scale disturbances.

TABLE 1. Severe weather days in June and July 1979, including the total number of High Plains severe thunderstorm reports and the number of tornadoes among that total.

Date	Number of severe reports	Number of tornadoes
06 June	2	2
15 June	7	1
16 June	8	2
17 June	5	0
18 June	6	3
21 June	1	0
23 June	3	0
24 June	8	3
26 June	9	4
27 June	11	7
28 June	8	4
29 June	3	3
30 June	9	2
03 July	2	0
04 July	1	1
05 July	3	0
06 July	13	6
08 July	7	1
14 July	4	2
15 July	2	1
16 July	4	4
17 July	5	2
18 July	1	1
22 July	3	2
25 July	5	1
26 July	5	3
27 July	4	2
28 July	3	2
29 July	5	2
30 July	9	3

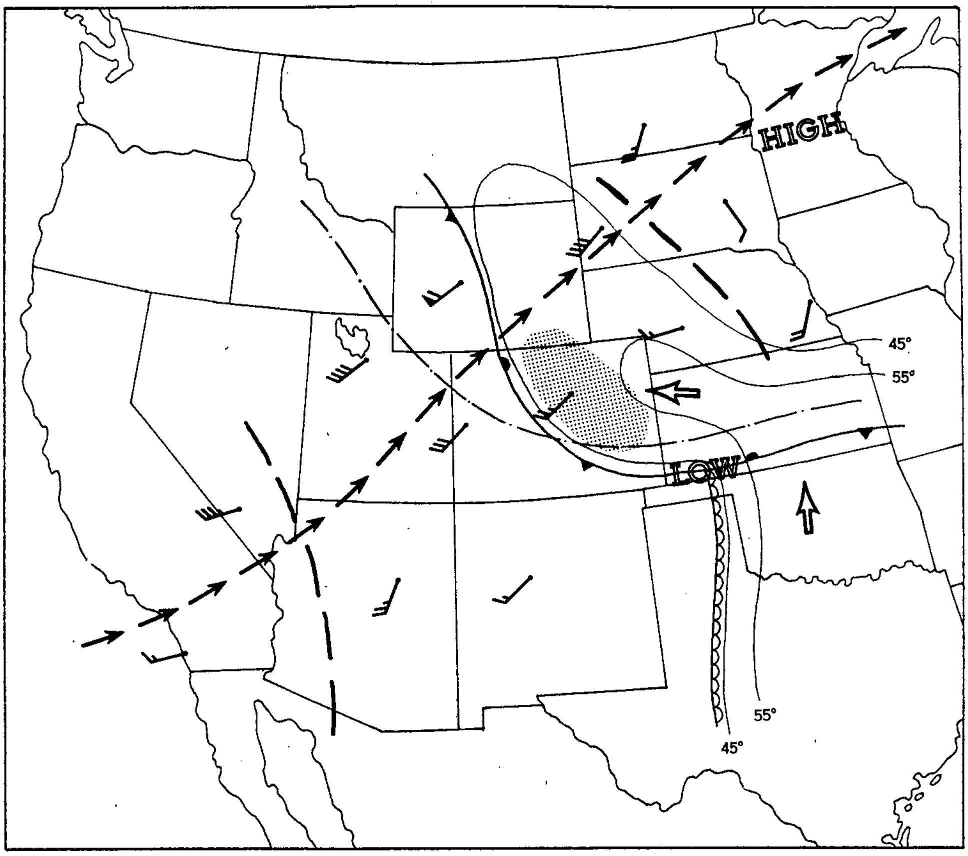

FIG. 2. Composite High Plains severe thunderstorm parameter chart. Frontal symbols are conventional, surface isodrosotherms (°F) denoted by fine lines, scalloped line indicates surface dryline, large arrows depict surface flow, and "High" and "Low" refer to surface pressure centers. Dash-dot line locates the 700 mb thermal ridge. Wind barbs show 500 mb winds (full barb signifies 5 m s^{-1}, flag signifies 25 m s^{-1}), and heavy dashed lines locate short-wave trough axes. Chain of arrows is aligned along core of strong high-level winds, above 500 mb. Stippling denotes region of expected severe thunderstorms.

The sequence of events prior to a High Plains severe thunderstorm situation typically begins two or three days before the storms with the intrusion of a polar air mass into the plains along the northern tier of states. The cold front marking its leading edge initially moves fairly rapidly southward, into the region of weak westerly flow aloft. Frontal passage is usually not accompanied by severe thunderstorms.

Behind the front, a large anticyclone moves southeastward, then more eastward, replacing the departing surface cyclone. The front slows down and generally becomes stationary in Kansas or Nebraska (also noted by Wetzel and Sinclair, 1973). The southward intrusion of relatively cool air may bring the belt of strong flow aloft farther south, although the strongest winds (the jet stream) generally remain north. In this process, the upper ridge axis may shift east or west of its original position, but not drastically so.

At this point, it should be noted that there is often a significant threat of severe weather in association with the surface cyclone, which by now is in the Great Lakes or Ohio Valley region. Thus, attention is frequently drawn away from the High Plains, where generally anticyclonic flow aloft prevails and, owing to the recent frontal passage, daily temperature maxima are moderating (in the 70s) and the moisture has been decreasing. Along the eastern slopes, surface dewpoints generally drop to less than 40°F.

With this brief sketch of preceding events in mind, consider the "Composite Chart" derived from the June and July 1979 cases (Fig. 2). This composite chart has been derived partly from subjective analysis and partly from an average of rawinsonde parameters at 1200 (all times GMT) on the first day of a High Plains severe storm episode (15 and 23 June; 3, 14, and 25 July). The features depicted are intended to represent the patterns at 1200 on the first in a sequence of severe thunderstorm days. Note that this example is for southwesterly 500 mb flow. Since the mean ridge axis is generally nearby, the 500 mb flow can be southwesterly, northwesterly, or nearly zonal. Low-level features tend to be similar in most cases.

When other features are favorable, the return of 45°F or greater dewpoints to the immediate lee of the front

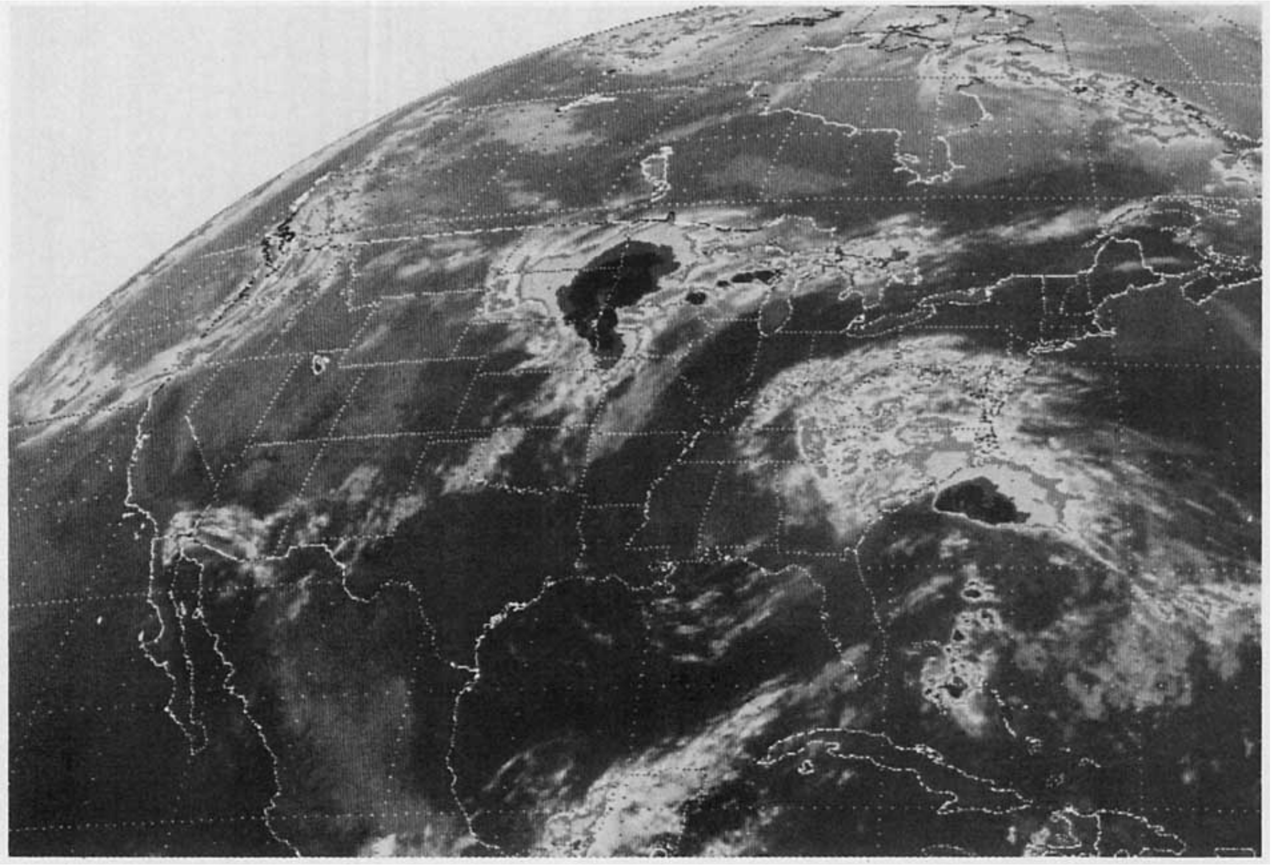

FIG. 3. Enhanced GOES infrared image at 1215 GMT, 16 June 1979.

ranges signals the beginning of severe weather potential. The appearance of the surface isodrosotherms in the composite suggests that the moisture source is the maritime tropical (mT) air south of the front. That is, the moisture is lifted over the front east of the threat area, mixed downward, and caught up in the easterly flow behind the surface front.

Generally in severe weather situations winds up to the 850 mb level to the east of the High Plains have some easterly component at 1200. As noted by Modahl (1979), the easterly component increases during the afternoon on severe weather days. On those severe weather days when low-level winds are *not* easterly at 1200, they develop such a component early in the day (at the surface) and it is usually present by 0000. Although Fig. 1 indicates that easterly flow at low levels is not always perpendicular to the small-scale terrain gradients, the overall effect of the low-level flow is clearly to develop upslope lift. Some lift may also arise from isentropic "overrunning" in the vicinity of the frontal boundary, as well as from any weak short-wave troughs that may be present.

Since the mean ridge axis is nearby, the suggestion from the upper air is that the region is likely to remain inactive with respect to severe thunderstorms. Flow at 500 mb and above over the threat area usually exceeds 10 m s^{-1} by the time of the composite. This is in contrast to the convective flash flood situations described by Maddox *et al.* (1978), where upper-level flow is typically weak (≤ 5 m s^{-1}). Prior to the composite time, 500 mb winds may have been weak but the trend is to stronger flow.

There are two weak short-wave troughs indicated in the composite 500 mb flow. The first is over Nebraska and South Dakota, and may have been accompanied by nocturnal thunderstorms. The second trough is located in Nevada and Arizona. Such troughs may not always be easily detected in conventional data, if they are present at all. It seems clear that vorticity analyses and satellite imagery can be valuable in locating and predicting the track of such small-scale features. It is not clear that such systems are always present nor that they are significant, based on this limited sample. However, they are shown on the composite since poststorm analysis can usually reveal some indication of a minor feature aloft (such as that described by Duker and Barber, 1979), frequently at 300 mb or above (see Hales, 1979).

The maximum winds aloft axis shown in the composite is associated with speeds in the threat area of about 20–30 m s^{-1}. The resulting wind structure, i.e.,

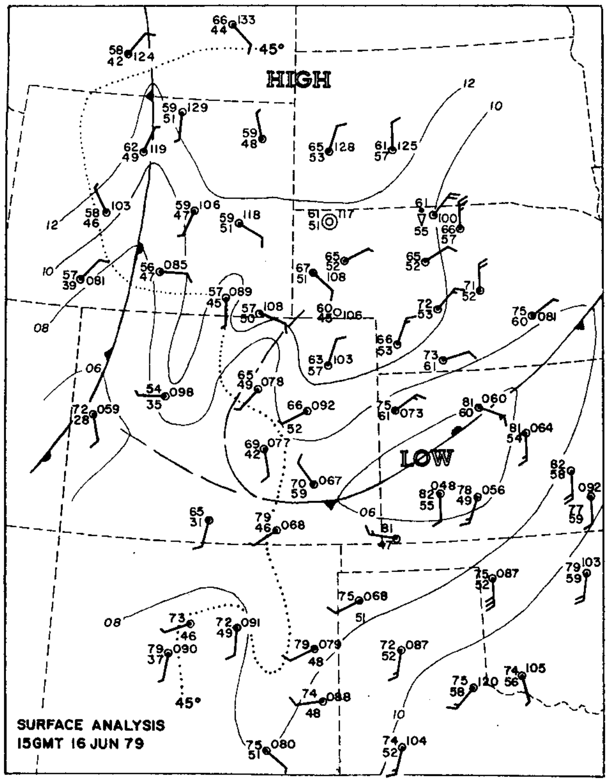

FIG. 4. Surface analysis valid at 1500 GMT, 16 June 1979. Symbols are conventional. Winds shown are peak gusts, when applicable. Dotted line denotes isodrosotherms (°F).

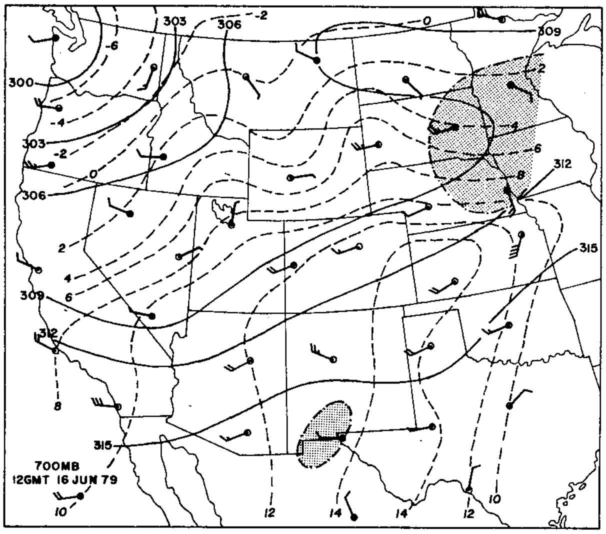

FIG. 5. 700 mb analysis valid at 1200 GMT, 16 June 1979. Solid lines are isohypes (dam), dashed lines are isotherms (°C), and stippling indicates 700 mb dewpoints greater than 0°C.

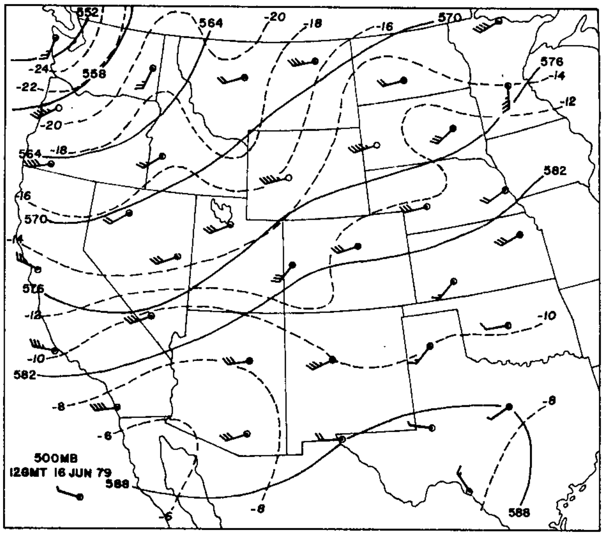

FIG. 6. As in Fig. 5, except for 500 mb.

easterlies at low levels and moderately strong westerlies aloft, suggests an environment with substantial vector wind shear. It should be noted that an alternate upper wind structure (above 500 mb) has occasionally been seen in the sample. This alternate includes two jet stream axes: one curving anticyclonically, south of the threat area, while the second arcs cyclonically, north of the threat area. This results in a diffluent jet structure over the region of severe thunderstorm occurrence (see Whitney, 1977).

The impression of strong shear is substantiated by the rawinsonde data. While Doswell and Lemon (1979) have suggested that Great Plains severe thunderstorms occur frequently with cloud-bearing layer (1.5 km AGL to tropopause) mean shears below 2.5×10^{-3} s^{-1}, values less than that are relatively uncommon with High Plains severe weather. Further, the subcloud layer (surface to 1.5 km AGL) mean shears in the High Plains are usually less than 2.5×10^{-3} s^{-1}, in strong contrast with the Great Plains environment, where subcloud shears have been found to exceed 7.0×10^{-3} s^{-1} for many severe storm events. Reasons for this latter result are not clear, but one suggestion is that the easterly flow is relatively shallow, so that a 1.5 km averaging depth is dominated by weaker vector shears above the shallow inflow layer.

The thermodynamic stratification can be measured by a modified lifted index (MLI) based on the maximum wet-bulb potential temperature (θ_w) in the lowest 300 mb. The MLI is the difference between the ambient 500 mb temperature and that of a parcel with this θ_w value lifted to 500 mb. Such a parameter is strongly influenced by diurnal changes. Along the lee slopes its variation is often even larger than the average diurnal decrease of 2.4°C noted by Doswell and Lemon (1979) in association with Great Plains severe weather. In this study, storm reports were generally not well correlated (subjectively) with the most unstably stratified areas. Many of the severe reports occurred in areas where the MLI was only slightly negative (1–3°C buoyancy at 500 mb), even at 0000. Naturally, some ambiguity remains, since the only routine sounding site actually on

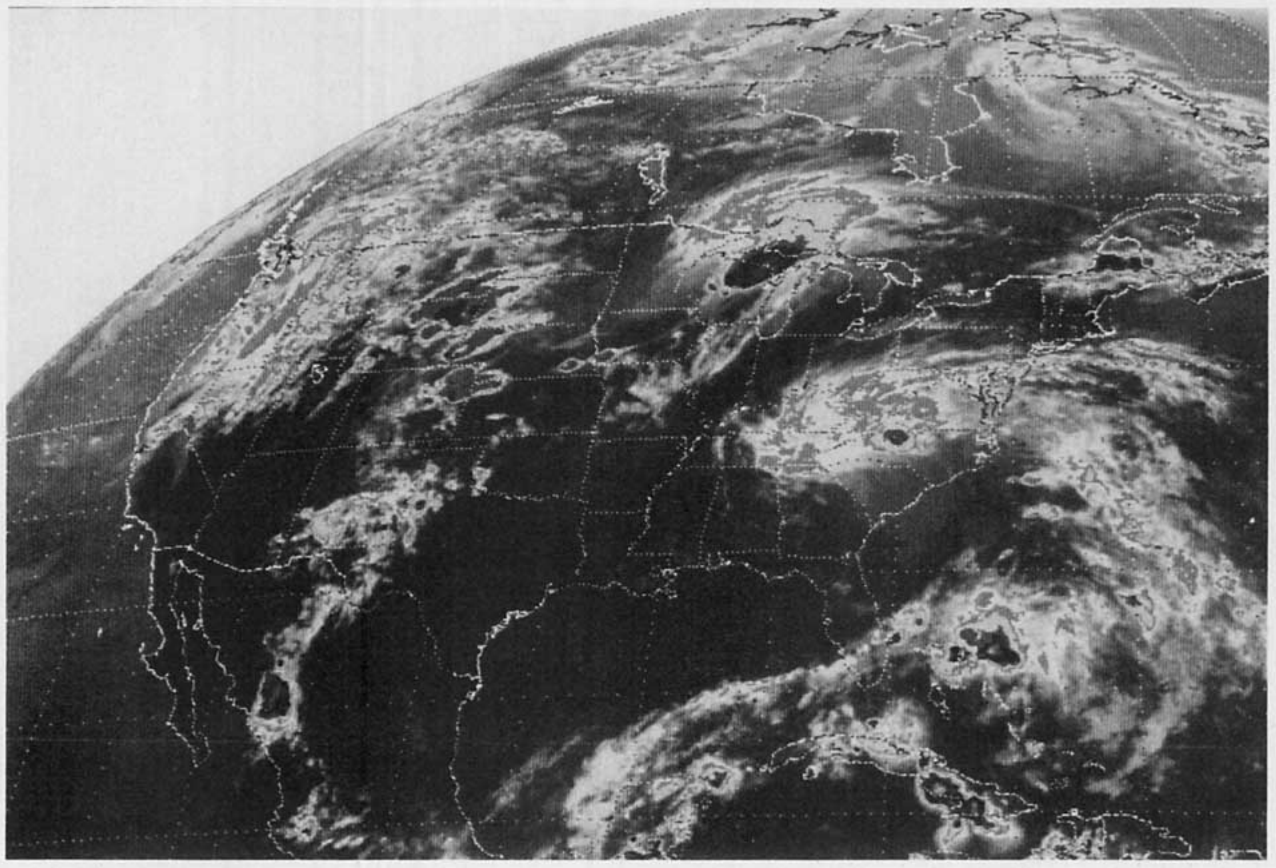

FIG. 7. As in Fig. 3, except at 2345 GMT.

the High Plains is Denver. From a forecast viewpoint then, knowing where the most unstably stratified air is at 0000 is not too valuable, since severe weather is not always located in the most unstable MLI region.

Moving on with the sequence of events, after the first day in an episode of High Plains severe weather, the basic pattern shown by the composite remains in place for the duration of the episode. Naturally, there are minor day-to-day variations and the threat area may move northward or southward with the frontal boundary. The convection may also influence the day-to-day events, as we shall see. However, the same basic elements of upslope flow, moderate westerly winds aloft, marginal instability, and moisture continue to produce severe thunderstorms.

The end of an episode can come about in a variety of ways, but there are two main types. The first pattern associated with the termination of severe weather is characterized by an amplification of the long-wave ridge, which decreases the winds aloft and acts to reduce moisture through subsidence and an end to upslope flow as the frontal boundary dissipates. The second, somewhat surprising terminator to High Plains severe storms is the passage of a vigorous short-wave trough through the area. Such a trough is not likely to be accompanied by severe weather, owing to the marginal severe weather parameters, unless its timing puts its upward vertical motion over the High Plains at or near the time of maximum heating. Usually it sweeps the moisture eastward away from the slopes and stabilizes the stratification beyond the point where severe thunderstorms are possible. Also, the upslope flow ceases and severe weather forecasting can revert to more conventional parameters. No composite is presented for the termination of an episode, since the two types of terminating weather systems are so synoptically dissimilar.

Features shown on the composite chart are consistent with those described in the literature on High Plains severe convection. Since the diurnal tendency for afternoon upslope flow augments the synoptic-scale pattern, the increasing easterly flow prior to severe convection described by Modahl (1979) is easily understood. Mahrt (1977), in addition to noting the importance of easterly low-level flow, has suggested that the low-level inversion is significant on hail days in northeast Colorado. An inversion associated with the frontal surface over the threat area may well be that described by Mahrt. Foote and Fankhauser (1973) present a case study consistent with the findings of this study, as do Ellrod and

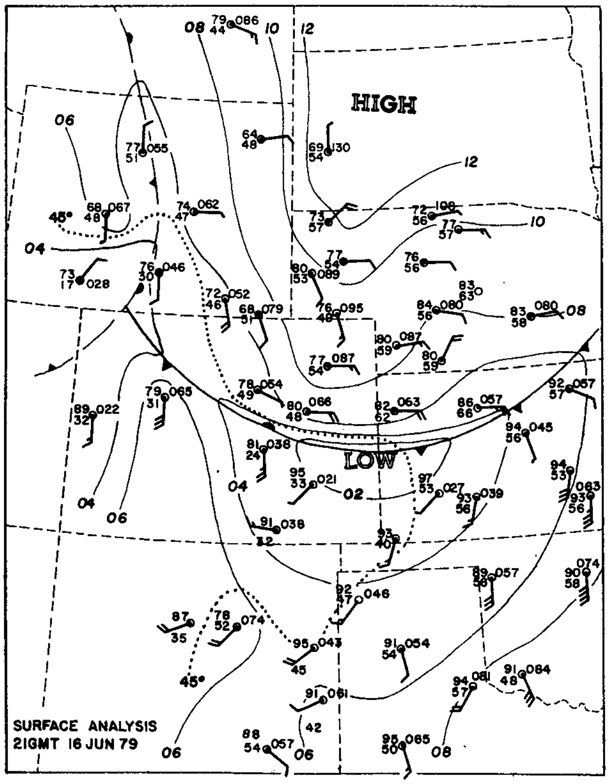

FIG. 8. As in Fig. 4, except at 2100 GMT.

Marwitz (1976). Finally, the synoptic climatology of Henz (1973) shows that this surface pattern is associated with the majority of severe storms over the High Plains.

New features developed in this study include: The apparent necessity for 10 m s^{-1} or stronger 500 mb winds, the poor relationship between High Plains severe weather and strong thermal buoyancy, and the tendency for severe weather to develop in episodes of four to five days in length. The overall appearance of the synoptic pattern is relatively benign in terms of classical severe weather parameters. Upper-air features are poorly defined, as seen by examination of the mean divergence

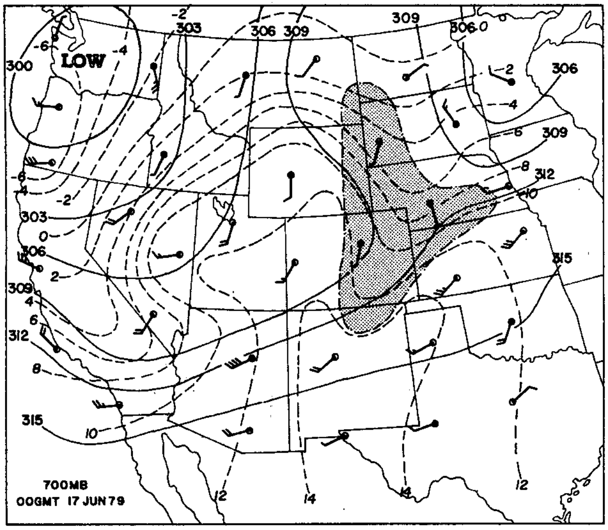

FIG. 9. As in Fig. 5, except at 0000 GMT, 17 June 1979.

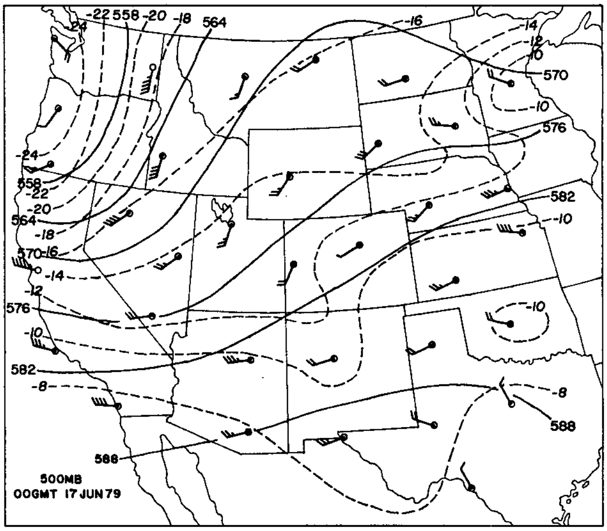

FIG. 10. As in Fig. 6, except at 0000 GMT, 17 June 1979.

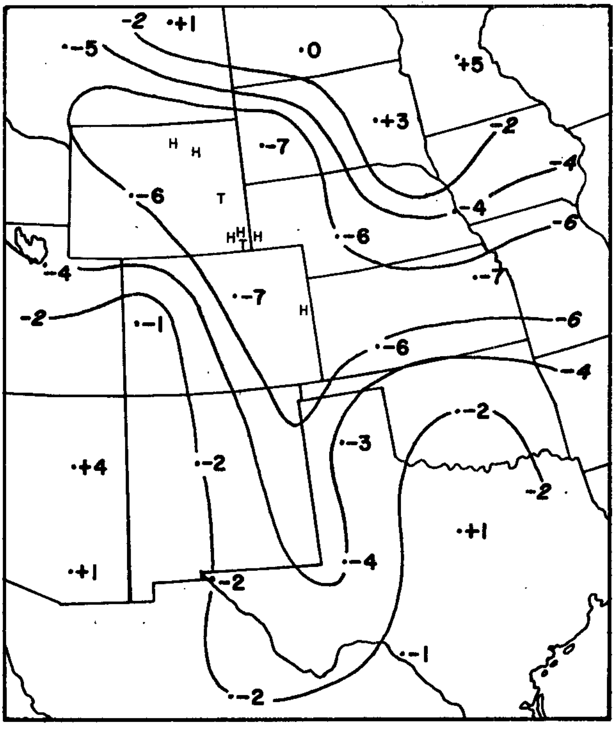

FIG. 11. Modified Lifted Index analysis at 0000 GMT, 17 June 1979. Also shown are High Plains severe weather reports, denoted as in Fig. 1.

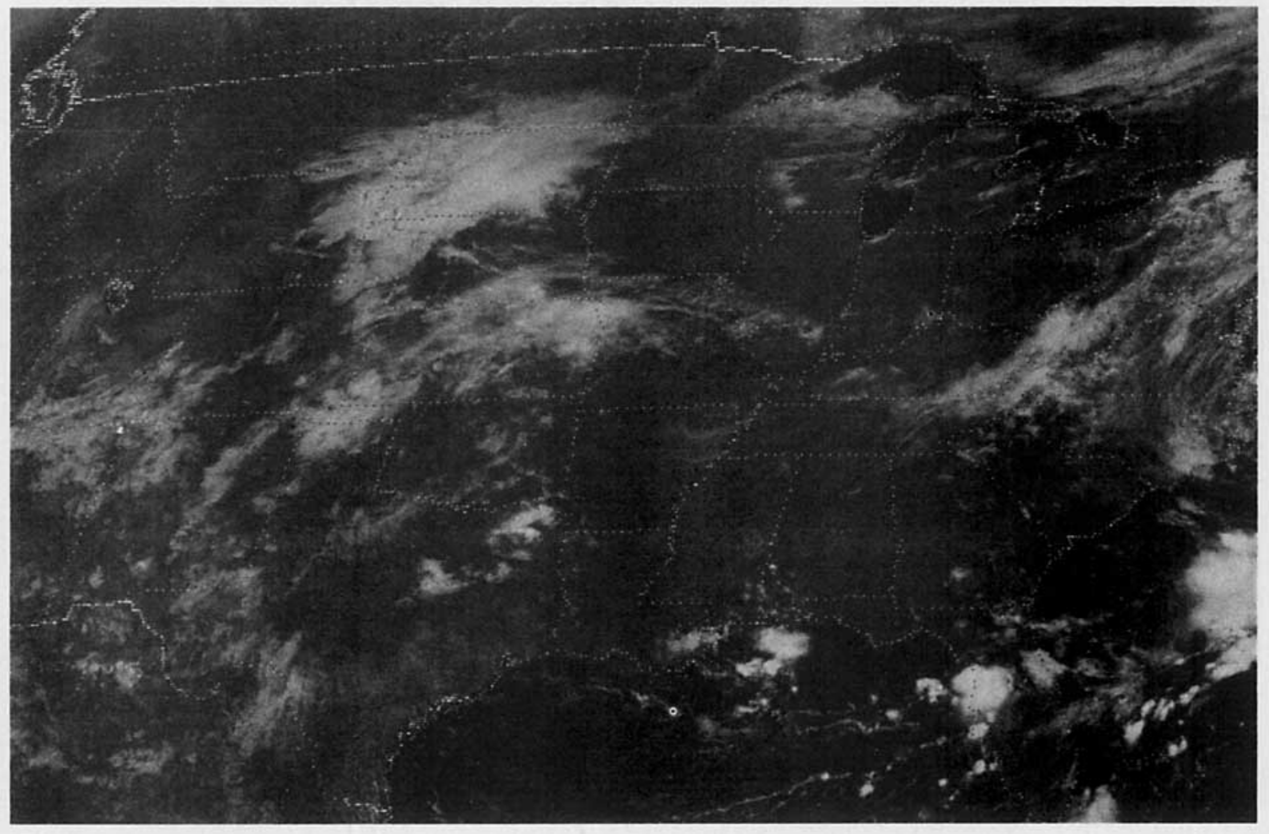

FIG. 12. Visible GOES image at 1501 GMT, 16 July 1979.

in the 300–200 mb layer (not shown). In the High Plains cases examined, severe weather occurred many times in regions of weak convergence. The suggestion is that there may not be any easily identifiable upper-air feature, even at levels well above 500 mb. Large-scale lifting is usually weak and may be difficult to separate from the effects of convection. Nevertheless, the existence of a repetitive pattern of events associated with High Plains severe weather is unmistakable. Such storms are not random "air mass" type events.

4. Case studies

In order to illustrate some of the features in the composite, as well as some of the departures from it, two cases are presented. One, that of 16 June 1979, closely resembles the composite. The other, on 16 July 1979, shows how large mesoscale systems resulting from prior convection can affect the subsequent severe weather occurrences.

a. Case of 16 June 1979

In this case, the morning satellite photograph at 1215 (Fig. 3) shows that strong thunderstorms are occurring in the Dakotas and Nebraska. These storms have their origin in activity that developed over the High Plains during the afternoon and evening of the 15th. In fact, the severe weather in the High Plains on the 15th was associated with these storms. It is not uncommon for storms developing over the High Plains to continue through the night, moving out over the Great Plains as mesoscale convective complexes (Maddox, 1980).

Surface flow at 1500 (Fig. 4) is easterly behind the front and 45°F dew points have reached the Continental Divide. The small surface low in western Kansas has a well-defined circulation[1], suggesting moisture convergence to its northeast and a threat of severe thunderstorms in northern Kansas (Doswell, 1977). At 700 mb (Fig. 5) a thermal ridge extends eastward from Colorado and significant 700 mb moisture is absent over the High Plains. The basic flow at 500 mb is southwesterly (Fig. 6) and the pattern is not well organized at any upper level. A short-wave ridge is present in western Colorado into central Wyoming.

By 2345, developing High Plains storms (Fig. 7) have already produced large hail in Wyoming. Also, some

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[1] Note that plotted surface winds are peak gusts, when applicable.

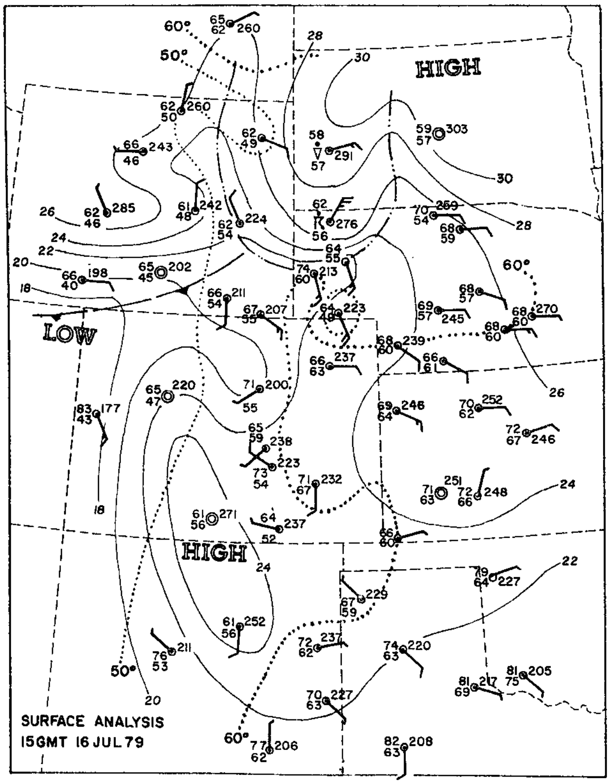

FIG. 13. As in Fig. 4, except on 16 July 1979.

nonsevere storms have developed in southeastern Nebraska and western Iowa. At 2100 (Fig. 8), the surface low had shifted westward into eastern Colorado, and easterly flow north of the front increased. Note the strong southerly flow in Oklahoma and southern Kansas, despite which the storms in Nebraska and Iowa never became severe. The early storms with the system in the Northern Plains had reached Wisconsin by 0000 on the 17th, and were responsible for quite a bit of severe weather in Minnesota and Wisconsin. The increase in 700 mb moisture along the lee slopes (Fig. 9) is associated with the convection. This moisture increase could be the result of large-scale lifting or it could be a reflection of the widespread convection. As has often been lamented, the time and space scales of the standard rawinsonde network do not allow an unambiguous answer to the "chicken and egg" problem. Severe weather reports continued on beyond 0000, with the last report being baseball-sized hail in the Nebraska panhandle at 0345. At 500 mb (Fig. 10), the short-wave ridge has progressed into the western Dakotas as it approaches the quasi-stationary long-wave ridge position, with a weak short-wave trough suggested in Utah and New Mexico. The movement of a short-wave ridge through the region during the day suggests that large-scale ascent may not be the source of the 700 mb moisture increase. As discussed, however, this issue is not certain.

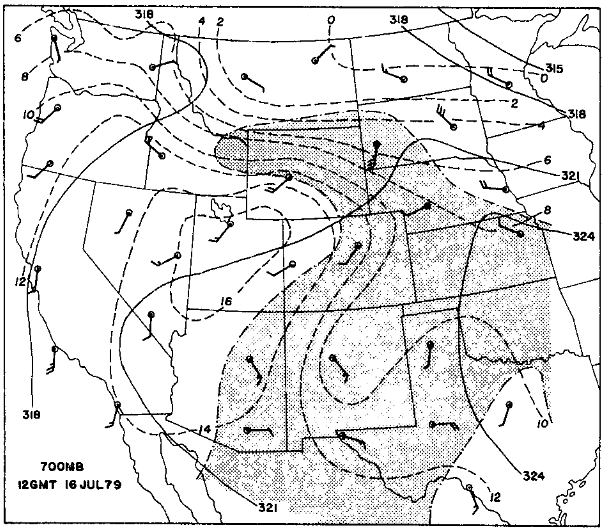

FIG. 14. As in Fig. 5, except on 16 July 1979.

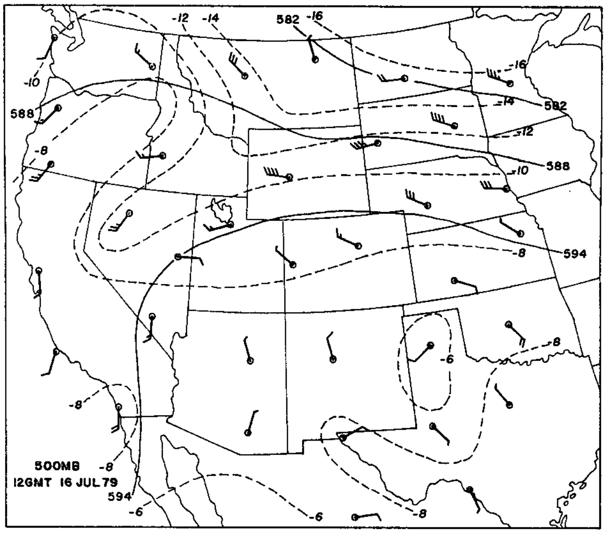

FIG. 15. As in Fig. 6, except on 16 July 1979.

It is noteworthy that the morning MLIs in the area of the severe weather on the High Plains were in the range of −2 to −3, while by 0000 they had destabilized to −6 or −7. In this case, the severe weather was within the region of strong unstable stratification at 0000, but the unstable region encompassed a much broader area than that in which severe weather was reported, extending well out into the Great Plains (Fig. 11).

Altogether, for this case there were eight reports of severe thunderstorms, including two tornadoes in Wyoming: one 20 n.mi. east of Douglas at 0200 and the second 46 n.mi. east-northeast of Cheyenne at 0300.

b. Case of 16 July 1979

This day's events are dominated by relatively low-level

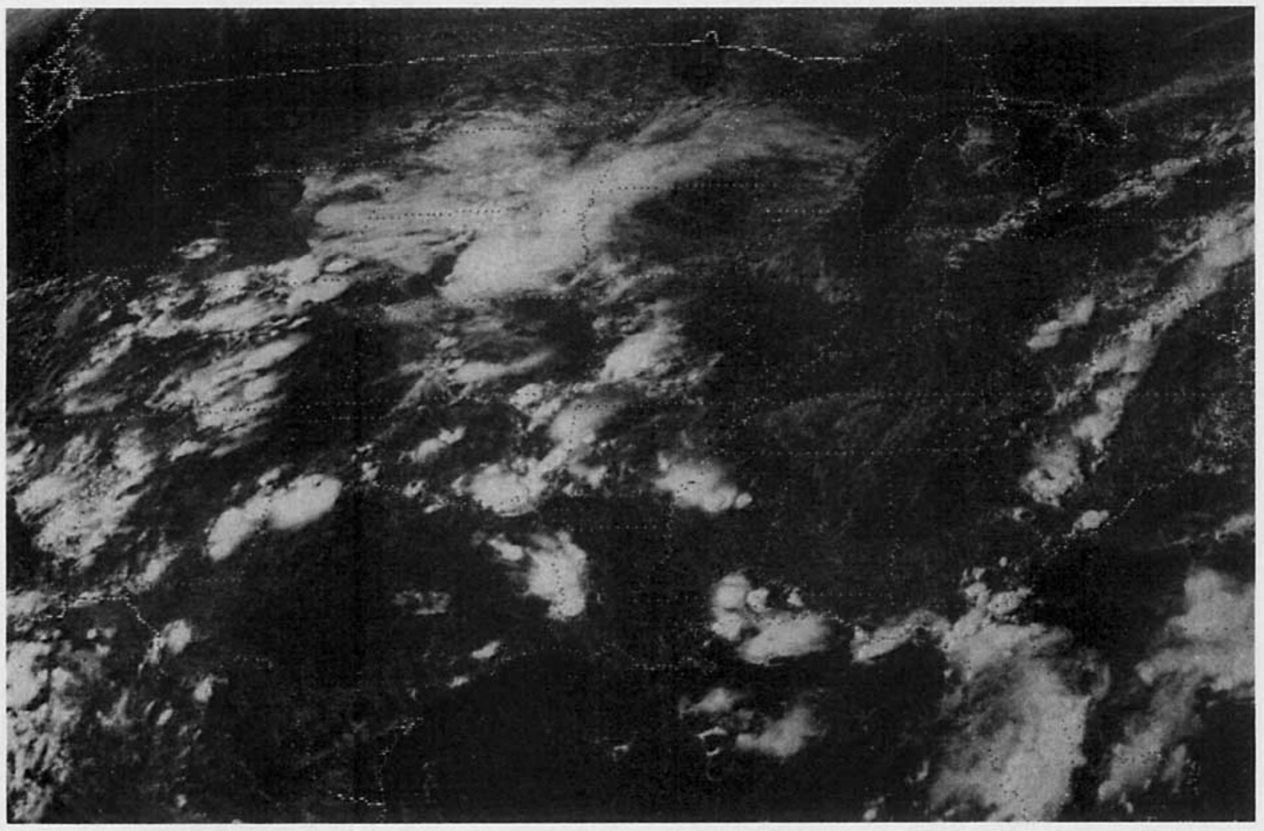

FIG. 16. As in Fig. 12, except at 2101 GMT.

features. Of greatest importance is the morning thunderstorm activity (nonsevere) seen in northwest Nebraska at 1501 (Fig. 12). These thunderstorms developed in northwestern South Dakota shortly after midnight and had been moving southeastward without any reports of severe weather. Unlike the 16 June case, these morning storms were not the continuation of High Plains severe storms from the previous day. This activity had produced an outflow boundary and "bubble" ridge at the surface (Fig. 13). The surface easterly flow extends well south of Colorado, indicative of a frontal passage several days before, with weak upslope flow developing in its wake. The surface system is much weaker and surface pressures are higher than on 16 June. The 500 and 700 mb heights and temperatures are also higher.

The 700 mb analysis (Fig. 14), shows that the low-level moisture seen in Fig. 13 is rather deep and extensive. The thermal pattern suggests a weak frontal boundary well south of the region in central Texas, with a second thermal ridge developing in northern Colorado and southern Wyoming. Warm advection in the High Plains extending into western South Dakota suggests some larger-scale lifting may be helping to enhance the 700 mb moisture. In contrast to the 16 June example, the basic 500 mb flow east of the Divide is northwesterly (Fig. 15). A weak short-wave trough is moving east-southeastward from eastern Montana.

At 2100, the outflow boundary left behind by the morning activity (which has continued into eastern Nebraska) can be seen in the satellite data (Fig. 16) and the surface analysis (Fig. 17). New storms developing along the Continental Divide seem to be creating a second outflow boundary, which intersects the old boundary near Cheyenne.

The 0000 upper-air patterns show the progression of the weak features seen at 1200. At 700 mb (Fig. 18), the warm advection pattern has disappeared. Note that the east-west thermal ridge has moved southward into central Colorado and now extends into northwest Missouri. Although a 500 mb thermal trough (Fig. 19) is now present over the threat area, the actual temperature at that level has not changed significantly. However, the 500 mb wind speed at Denver has roughly doubled with the passage of the short-wave trough mentioned earlier.

Four tornadoes were reported on this day, but the one in Cheyenne was by far the most significant. It touched down about 30 min after the satellite photograph at 2101. It seems clear that the effect of the morning storm was the controlling factor, augmenting the preexisting upslope flow and acting to localize the low-level forcing, as described by Maddox *et al.* (1980). This day is one with only modestly unstable MLI values throughout the period, with -2 to -3 characteristic values at both 1200 and 0000 (Fig. 20).

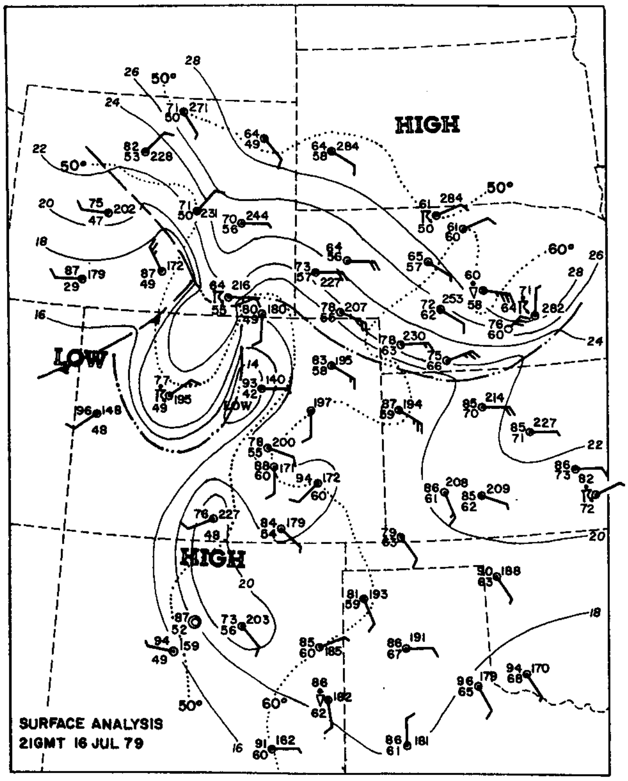

FIG. 17. As in Fig. 8, except on 16 July 1979.

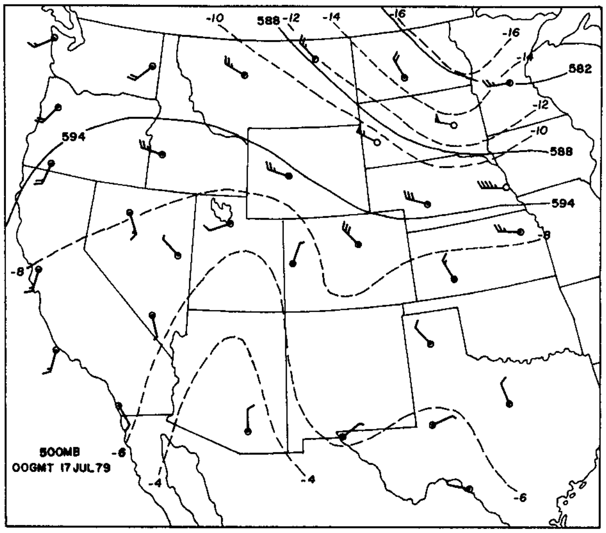

FIG. 19. As in Fig. 10, except on 17 July 1979.

5. Summary and concluding remarks

This study's results indicate that High Plains severe thunderstorms are frequently associated with a specific synoptic-scale pattern. This pattern is somewhat similar to that found during heavy convective rainfall. However, the stratification may not be as unstable as in flash flood situations, and the upper flow is stronger, with stronger vertical shear a direct result. Since severe thunderstorms in the High Plains occur most frequently in the summer months, the patterns are slow to evolve and the potential for severe weather may linger over the lee slopes for several days. Thus, severe storms tend to occur on several consecutive days, until the passage of a major upper-level system sweeps the moisture out of the area and builds a stronger ridge (with weaker winds

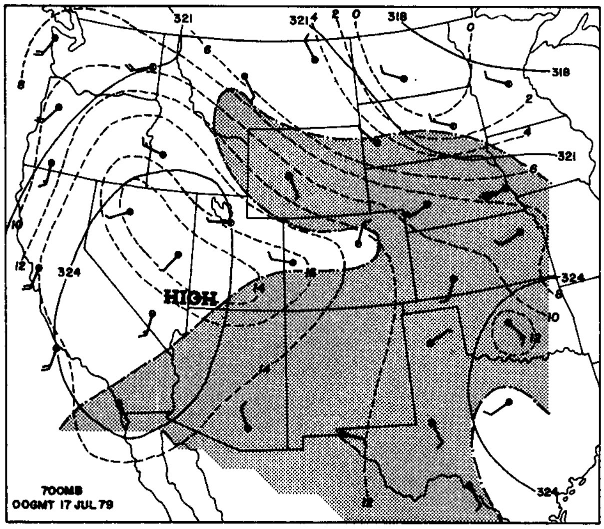

FIG. 18. As in Fig. 9, except on 17 July 1979.

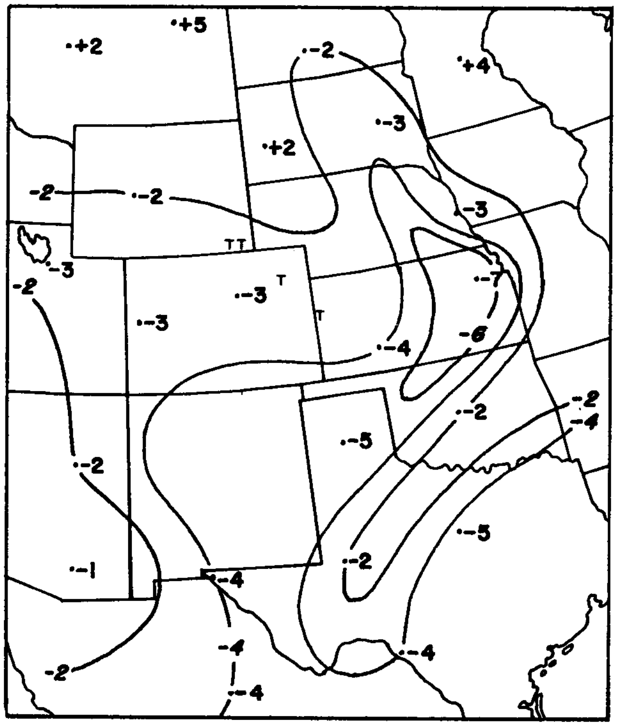

FIG. 20. As in Fig. 11, except on 17 July 1979.

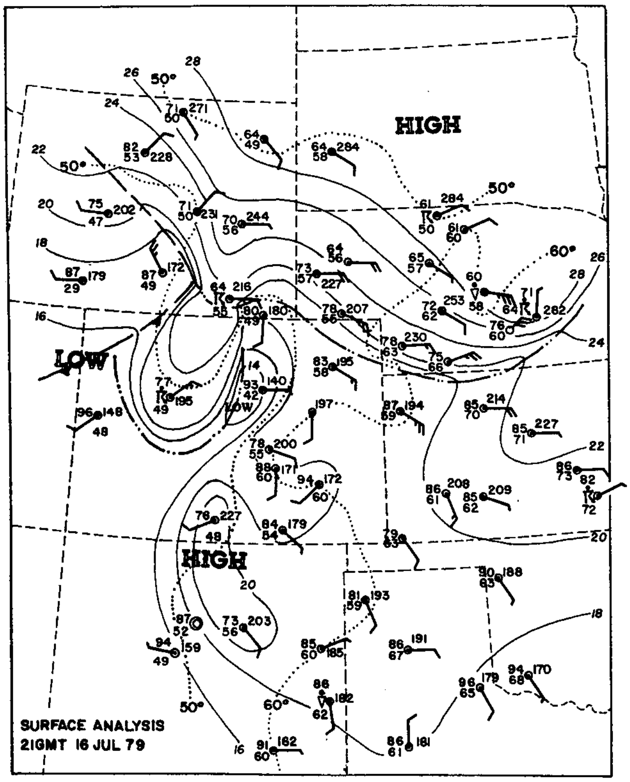

FIG. 17. As in Fig. 8, except on 16 July 1979.

5. Summary and concluding remarks

This study's results indicate that High Plains severe thunderstorms are frequently associated with a specific synoptic-scale pattern. This pattern is somewhat similar to that found during heavy convective rainfall. However, the stratification may not be as unstable as in flash flood situations, and the upper flow is stronger, with stronger vertical shear a direct result. Since severe thunderstorms in the High Plains occur most frequently in the summer months, the patterns are slow to evolve and the potential for severe weather may linger over the lee slopes for several days. Thus, severe storms tend to occur on several consecutive days, until the passage of a major upper-level system sweeps the moisture out of the area and builds a stronger ridge (with weaker winds

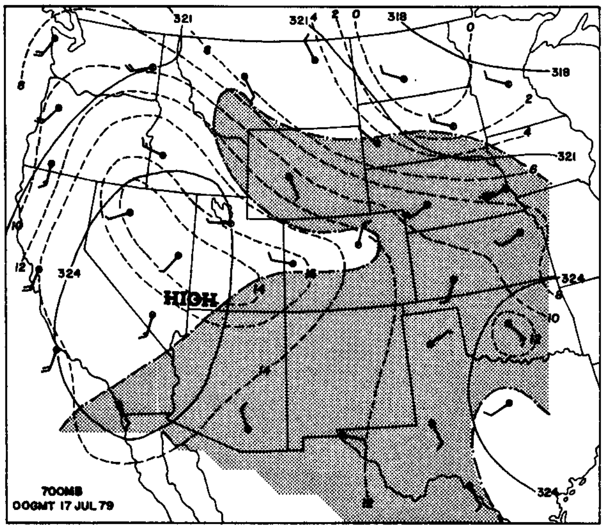

FIG. 18. As in Fig. 9, except on 17 July 1979.

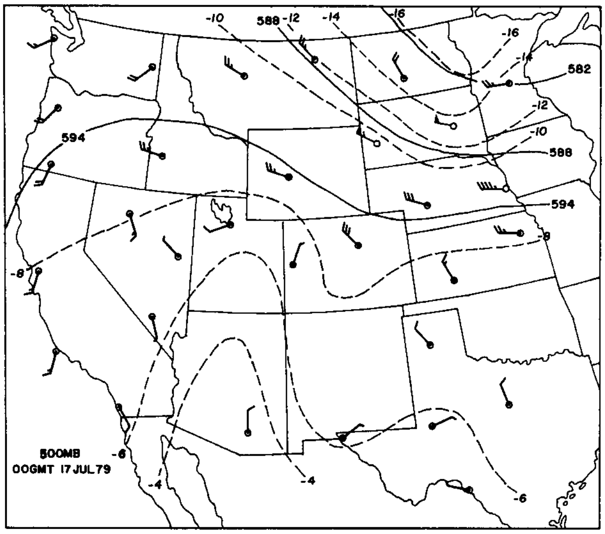

FIG. 19. As in Fig. 10, except on 17 July 1979.

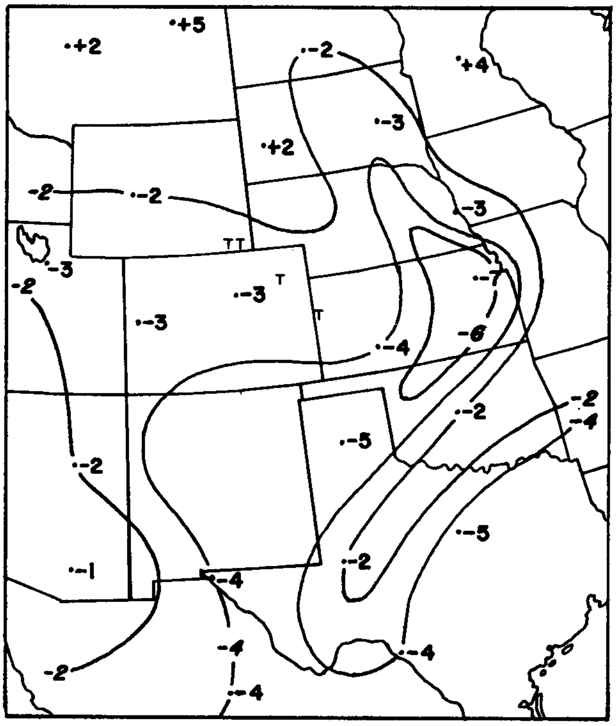

FIG. 20. As in Fig. 11, except on 17 July 1979.

aloft) over the region. Such an occurrence is a signal to the forecaster that the severe weather episode is over.

The main forecast problem is to predict the first of what is likely to be a series of severe weather days. The return of 45°F dewpoints (or higher) to the Continental Divide, coupled with 10 m s^{-1} (or greater) 500 mb flow and the presence of a frontal boundary to the south seems to be a starting point for a pattern-recognition approach. The convection appears in many cases to be forced by the low-level flow, because of the modest instabilities frequently present. Further, the frequent absence of well-defined upper-air features implies that High Plains severe thunderstorms cannot be forecast by conventional methods. Such traditional techniques heavily favor an environment that is quite unstable, as well as being forced by upper-level (500 mb and higher) features that are well defined. In this context, it is noteworthy that most of the days examined in this study that involved the passage of significant short-wave troughs were not accompanied by severe weather, the exceptions being confined to Montana.

Another forecast problem is whether or not tornadoes will occur. Unfortunately, this study has not revealed any obvious criteria for distinguishing tornado days. Table 1 suggests that on days with relatively few reports, it is unlikely that any will be tornadoes, but the Cheyenne tornado day (16 July) is certainly a striking exception. The severe weather climatology of the region indicates that tornadoes are significantly underreported, so *whenever severe weather is expected, tornadoes are a real possibility.*

As the 16 July case study shows, close monitoring of the surface data can aid the short-range severe weather forecast problem. In such cases where prior convection plays a major role, it is unlikely that numerical model output can capture the events sufficiently well to allow a useful forecast in the first 12 h. Longer-range forecasts can probably benefit from model output, provided large mesoscale events are not involved. The proposed composite model should be of value since High Plains severe thunderstorms often occur in association with synoptic-scale patterns that are not widely recognized as capable of producing severe weather. This subject is being pursued at NSSFC and application of these results will be tested in the future.

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