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SYNOPTIC-SCALE REGIMES MOST CONDUCIVE TO TORNADOES IN EASTERN WYOMING — A LINK BETWEEN THE NORTHERN HEMISPHERIC SCALE CIRCULATION AND CONVECTIVE-SCALE DYNAMICS

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Abstract. During 1979, 41 tornadoes were reported in Wyoming, well above the nine per year average. As a result, 1979 was used to help understand the causes of the synoptic scale environment that resulted in so many tornadoes over Wyoming during that year. Seventeen cases were extracted from the summer (June, July, and August) and composite maps for the surface and selected constant pressure surfaces (850, 700, 500, and 300 mb) were constructed.

A contrast is made between northwest (NW) and southwest (SW) flows observed during the summer of 1979. Twenty-six of the 38 tornadoes reported in Wyoming during the summer occurred in a NW flow regime. A fairly persistent and anomalously strong middle and upper tropospheric full-latitude ridge in the height field became established west of eastern Wyoming for the tornado days of July and August. Thus, the Northern Hemispheric scale circulation was believed to be important for the large number of Wyoming tornadoes during the summer of 1979.

Two "super composites" are resolved from the data: one favoring Doswell's (1980) SW flow regime, and the other favoring a NW flow regime. The NW flow regime was characterized by an environment with moist upslope easterly winds and significant directional lower tropospheric vertical wind shear (wind velocity vector veering nearly 90° with increasing elevation) over eastern Wyoming. Additionally, there was warm advection, cyclonic vorticity advection, and frontogenesis.

The principle of the "forecast funnel" technique of focusing first on the Northern Hemispheric scale dynamics and then steeping down to the smaller scales of motion is highlighted in this work. The NW flow regime was believed to be important to the unusually high number of Wyoming tornadoes during the summer of 1979, demonstrating a link between the Northern Hemispheric scale circulation and convective scale dynamics.

1. Introduction

Wyoming tornadoes, for the most part, tend to be generally weak but can, on occasion, become quite strong and cause extensive damage as occurred with the Cheyenne tornado of July 16, 1979 (Parker and Hickey, 1980). Prior to that, the most destructive tornado reported in Wyoming occurred at Midwest, Wyoming, in 1928 (Beebe, 1978). While national studies show that tornadoes, especially the more destructive ones, are rare in Wyoming compared with the Midwest and Plains states, the importance of tornadoes in Wyoming should not be overlooked (Martiner, 1986). This lack of frequent destruction has prompted many people to downplay the significance of tornadoes in Wyoming — a response which is far from valid.

Figure 1 illustrates the distribution of reported tornadoes in Wyoming by county. Most striking is the fact that certain sections of the state, namely the eastern counties, are significantly more prone to tornado occurrence. This result is due primarily to the protective barrier afforded by the Laramie Range which acts to retard westward incursions of moisture into other portions of the state.

When viewed chronologically, shown in Figure 2, the historical record of tornadoes reported in Wyoming from 1950 to 1982 by year is also revealing. While an upward trend in tornado reports is readily apparent (a result which is due in part to better reporting, improved communications, and a growing population), one year stands out as being highly significant — 1979.

During this one year, 41 tornadoes were reported which is well above the nine per year average (38 occurred during the summer; i.e., June, July and August) (Storm Data, 1979). In fact, this result suggested that during 1979 a synoptic scale environment unusually favorable for the development of tornadoes was created. This was especially true along the eastern counties.

This study is an attempt to identify the conditions that occurred during 1979. Seventeen cases, shown in Table 1, were extracted from the months of June, July and August 1979, and composite maps were constructed of the surface and for selected constant pressure surfaces (850, 700, 500, and 300 mb). In addition, various severe weather parameters based on composite data were examined to further aid in this analysis. In essence, the attempt was to use the 1979 severe weather season in Wyoming to develop a more precise model of the tornadic environment.

A previous study using composite maps was done by Doswell (1980) to identify High Plains severe weather events (tornadoes and severe thunderstorms together). This study expands on Doswell's earlier effort by focusing only on tornado occurrences in Wyoming. The goal of this work is to gain a better understanding of the environment most conducive to tornadoes in Wyoming, and to have these results help expand operational forecasting capabilities.

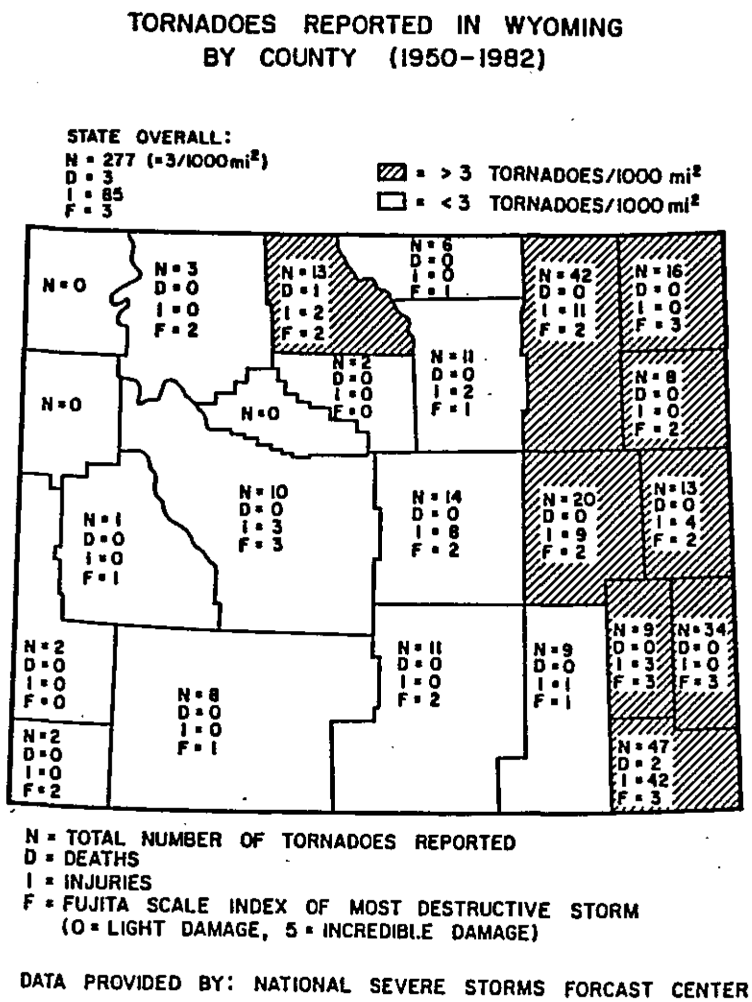

Figure 1. Tornado statistics by county for Wyoming for a 33-year period. Shading indicates counties where tornadoes are most prevalent (from Martiner, 1986).

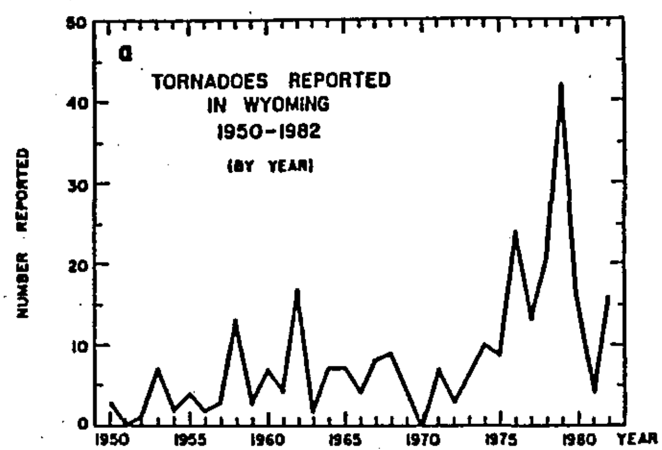

Figure 2. Annual distribution of tornadoes in Wyoming during a 33-year period (from Martiner, 1986).

TABLE 1.

Tornado occurrences in Wyoming for June, July and August, 1979. Seventeen cases were used representing a total of 38 tornadoes. (41 tornadoes were actually reported during the 1979 severe weather season in Wyoming.) Each case is also identified as being either a southwest (SW) or northwest (NW) flow situation. (Storm Data: 1979)

JUNE 1979

Date	# of Tornadoes	Flow
14	1	SW
15	1	SW
16	1	SW
18	3	SW
26	1	NW
27	2	NW
28	4	NW
	13	

JULY 1979

Date	# of Tornadoes	Flow
4	1	SW
16	2	NW
22	1	SW
26	4	NW
27	5	NW
28	3	NW
30	2	NW
	18	

AUGUST 1979

Date	# of Tornadoes	Flow
1	1	NW
14	4	SW
28	2	NW
	7	

Other months not considered:
May 1 tornado
Sept. 2 tornadoes

2. Discussion

A. Hemispheric Overview

The summer of 1979 was in some aspects an unusual period for many areas of the continental United States. During June a ridge intensified over Alaska with flow across the continental United States rather flat and wave lengths generally short. An important feature which would prove significant later in the summer was a trough in eastern Canada deepening southward over the Great Lakes. In addition, stronger than normal ridges prevailed over the Rocky Mountains. Consequently, higher than normal temperatures resulted in June across the northern half of the country and extended into portions of the southwest where the 700 mb flow was southwesterly. Most significant, however, was the occurrence of several strong and persistent cold air outbreaks which led to lower than normal temperatures across much of the remainder of the country -- a fact that would persist throughout much of the summer (Taubensee, 1979).

July was characterized by the progression of a high-latitude ridge from Alaska to northwest Canada. In fact, by mid-month a strong full-latitude ridge extended northwestward from the Great Basin to the Beaufort Sea north of Alaska. Mean 700 mb height changes from the first half to the second half of July indicated a +113 meter anomaly centered just to the west of Puget Sound in the east Pacific with a -173 meter anomaly over northern Hudson Bay. The result was record low temperatures over much of the northeastern quadrant of the continental United States, and above normal temperatures for the northern Great Plains and Alaska. In fact, by mid-July temperatures were below normal in the middle third of the United States due in part to northwesterly flow bringing cool Canadian air into the north central states. Similarly, a building 700 mb ridge over the west caused extremely high temperatures in the northwest, and the onset of the southwest summer rainy season was about two weeks later than normal (Wagner, 1979).

By August, the trough in eastern Canada and the mean ridge over Alaska were of exceptional strength and were resulting in major temperatures anomalies. Below normal mean temperatures continued to persist over much of the country east of the Continental Divide with mean temperatures well above normal for much of the west and extending northward under the strong Alaskan ridge. Only in the last week in August did the circulation pattern, which dominated much of the summer, begin to de-amplify marking an end to a rather anomalous summer (Dickson, 1979).

In total, the strong and persistent full latitude ridge over the western portions of the continent produced significant changes in the weather for 1979 over many areas of the continental United States, and one area in particular, eastern Wyoming, was strongly influenced by these large scale activities.

B. Constant Pressure Composites

In this study a contrast is made between NW and SW flow situations. Specifically, a NW (SW) flow event is when the direction of the middle and upper tropospheric velocity field is directed from northwest to southeast (southwest to northeast) over eastern Wyoming. The distinction is made because the results described later in this paper suggest that tornado formation during the 1979 severe weather season in Wyoming can be separated into two major groups: one group favoring the severe weather composite described by Doswell, and the other representing a similar, yet inherently different set of conditions. In effect, the importance of NW flow was revealed in 1979 as Wyoming was dominated by this flow pattern aloft during the latter portions of the severe weather season -- a result suggesting that Northern Hemispheric-scale forcing was primarily responsible for the unusually high occurrence of tornadoes in Wyoming.

Figures 3 through 6 illustrate the composite constant pressure analyses for all 17 tornado cases during the summer of 1979. These charts include the 850, 700, 500, and 300 mb composites and combine both the NW and SW flow cases. These composites were obtained by averaging gridded height data of the constant pressure surfaces. The gridded data was obtained by manually interpolating the objective analyses of the constant pressure surfaces onto grid points for all 17 tornado cases. The grid spacing used was 5° latitude by 5° longitude.

The 850 mb composite in Figure 3 indicates lower heights southwest of Wyoming with the highest heights to the west and east. The most significant feature of this composite was the presence of a southeasterly gradient wind over eastern Wyoming (keeping in mind that the 850 mb level is below the surface for this area). This result implied that upslope flow was a dominate factor in the composite and was a reflection of climatology (Table 2). The effect of upslope flow in this region is that the surface winds are forced to move up the lee slopes of the Rocky Mountains -- a significant factor for thunderstorm development in eastern Wyoming.

At 700 mb, Figure 4, the composite representation placed a trough at roughly 125° west longitude and a low amplitude ridge from near 110° west extending north-northeast into the Central Plains. The obvious feature at this level was the winds over eastern Wyoming were from the west and southwest which is suggestive of strong directional vertical wind shear in the low levels (Johns, 1982 and 1984). The significance of this result was the contribution made to creating a tornadic environment (Maddox, 1976; Weisman and Klemp, 1986; Klemp and Wilhelmson, 1978; Rotunno and Klemp, 1982 and 1985).

In the middle troposphere a ridge, stronger than indicated in climatology (Crutcher and Meserve, 1977), was apparent at the 500 mb level from 105 to 110° west, and troughing was indicated off the West Coast. Comparing the 500 mb level to 850 mb level, it is important to note that the upper-level ridge was above the 850 mb trough.

Figure 6 illustrated the distribution of the composite height at 300 mb. It was similar to the 500 mb level.

To further illustrate the magnitude of both the speed and directional vertical wind shear, the actual 850 mb wind vector was subtracted from the 500 mb wind vector for selected locations. These results are displayed in Table 3. Most important was the result that twice as much directional and more speed vertical wind shear was observed in NW flow situations than SW flow.

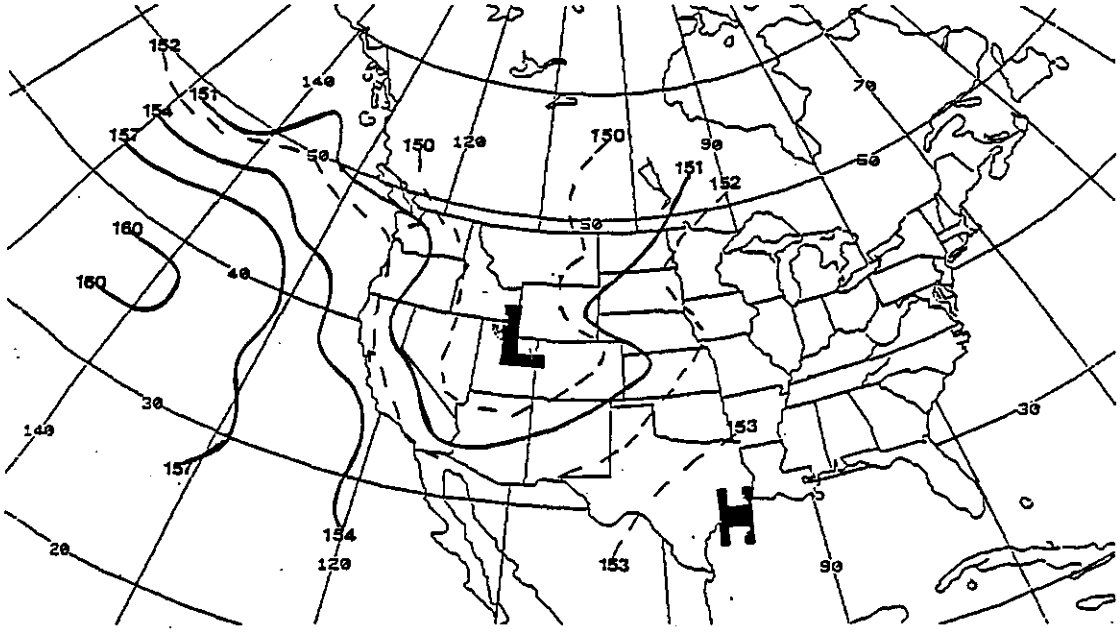

Figure 3. 850 mb Composite (17 cases). Units in whole decameters (dm). Note that all other upper level charts use the same units.

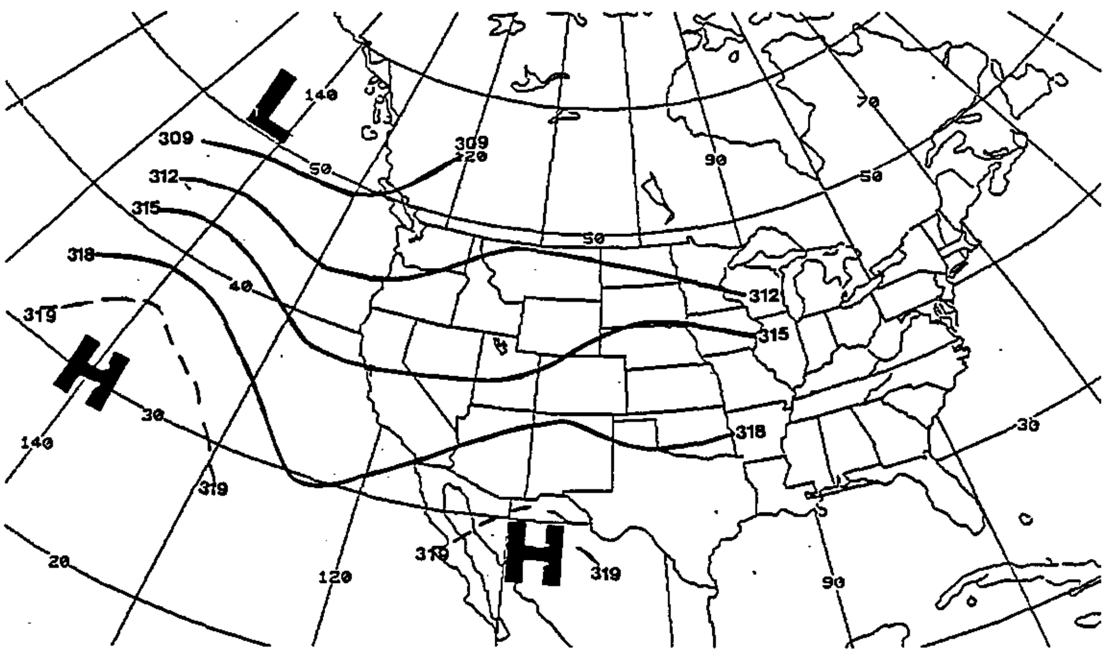

Figure 4. 700 mb Composite (17 cases).

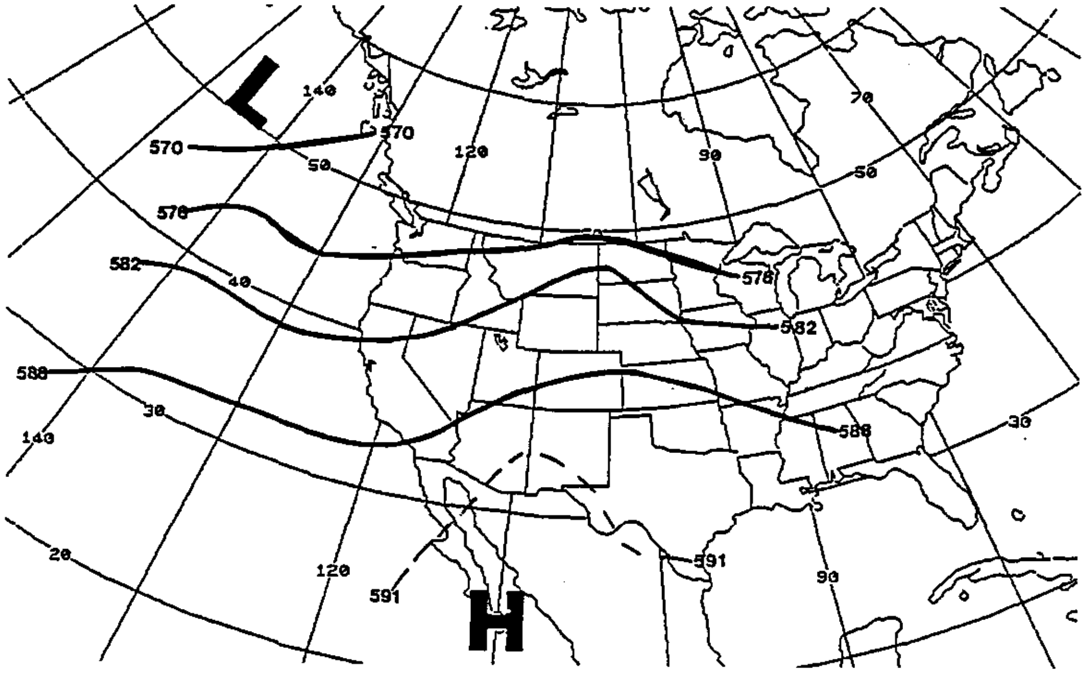

Figure 5. 500 mb Composite (17 cases).

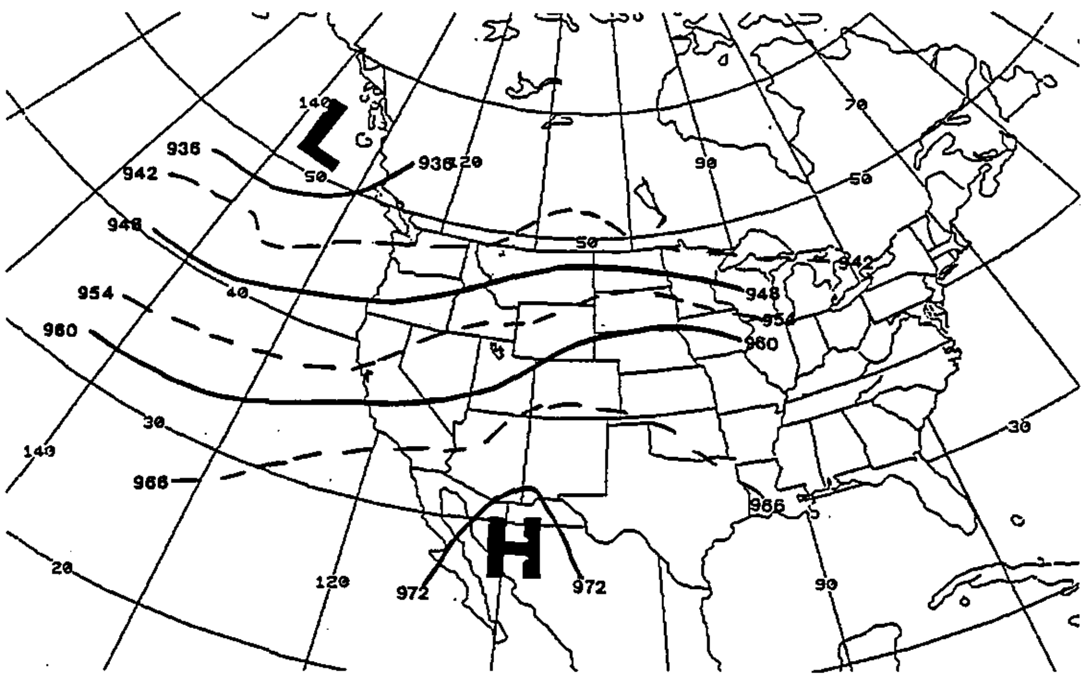

Figure 6. 300 mb Composite (17 cases).

CHEYENNE MUNICIPAL AIRPORT

PREDOMINANT HOURLY WIND DIRECTION

SPANNING 1951 - 1984

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1	WNW	WNW	WNW	WNW	WNW	W	W	W	W	WNW	WNW	WNW	WNW
2	WNW	WNW	WNW	WNW	WNW	WNW	WNW	W	W	WNW	WNW	WNW	WNW
3	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	W	W	WNW	WNW	WNW
4	WNW	WNW	WNW	WNW	WNW	WNW	WNW	W	W	WNW	WNW	WNW	WNW
5	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	W	WNW	WNW	WNW	WNW
6	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW
7	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW
8	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW
9	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW
10	WNW	WNW	WNW	WNW	WNW	SSE	WNW	WNW	WNW	WNW	WNW	WNW	WNW
11	WNW	WNW	NW	WNW	WNW	SSE	SSE	WNW	WNW	WNW	WNW	WNW	WNW
12	WNW	WNW	NW	WNW	SSE	SSE	SSE	WNW	WNW	WNW	WNW	WNW	WNW
13	WNW	WNW	NW	NW	SSE	SSE	SSE	WNW	WNW	WNW	WNW	WNW	WNW
14	WNW	WNW	NW	NW	SSE	SSE	SSE	SSE	WNW	WNW	WNW	WNW	WNW
15	WNW	WNW	NW	WNW	WNW	SSE	SE	SSE	S	WNW	WNW	WNW	WNW
16	WNW	NW	NW	WNW	SSE	SSE	SSE	SSE	SSE	WNW	WNW	WNW	WNW
17	WNW	WNW	NNW	WNW	SSE	SSE	SE	SE	SSE	WNW	WNW	WNW	WNW
18	WNW	WNW	NW	WNW	SSE	SSE	SE	SSW	S	WNW	WNW	WNW	WNW
19	WNW	WNW	NW	WNW	SSE	SE	SE	S	SSW	WNW	WNW	WNW	WNW
20	WNW	WNW	NW	WNW	SE	SSE	SSW	SSW	SW	WNW	WNW	WNW	WNW
21	WNW	WNW	WNW	WNW	SE	SSE	SSE	SW	WNW	WNW	WNW	WNW	WNW
22	WNW	WNW	W	WNW	WNW	WNW	SSE	WNW	W	WNW	WNW	WNW	WNW
23	WNW	WNW	WNW	WNW	WNW	WNW	WNW	W	W	WNW	WNW	WNW	WNW
24	WNW	WNW	W	WNW	WNW	WNW	WNW	WNW	W	WNW	WNW	WNW	WNW
MONTHLY	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW	WNW

Table 2. Average predominant wind direction as a function of hour of day and month at Cheyenne. (from Martiner: 1986)

Table 3. Directional and speed vertical wind shears. Units are whole degrees for directional shear and whole knots for speed shear. Shear was computed by subtracting the actual 850 MB wind vector from the 500 MB wind vector. Positive (negative) numbers mean the direction of the wind velocity vector veers (backs) with its magnitude increasing (decreasing) with increasing elevation. The data are displayed for the northwest flow/southwest flow cases (NW/SW).

LOCATION	DIRECTIONAL SHEAR (Degrees)	SPEED SHEAR (Knots)
	NW/ SW	NW/ SW
RAPID CITY, SD	53/ 8	18/ 15
NORTH PLATTE, NE	90/ 136	12/ -4
GRAND JUNCTION, CO	111/ 82	12/ 24
DENVER, CO	82/ 12	12/ 7
LANDER, WY	36/ -5	28/ 13
CHEYENNE, WY	136/ 32	18/ 10
CASPER, WY	110/ 42	20/ 9
AVERAGE FOR ALL 7 SITES	88/ 44	17/ 11

As a group, the composite charts of the 17 cases and Table 3 represented a vertical structure of the atmosphere over Wyoming which had some significant features believed to be important for a tornadic environment along the front range:

(1) The velocity vector veered and strengthened with increasing height suggesting warm air advection (Holton, 1979) and low level directional vertical wind shear.

(2) Upslope flow was a dominate surface feature in eastern Wyoming.

C. SW/NW Constant Pressure Composite Cases

Of the 17 severe weather cases chosen in this study, ten of these cases were classified as NW flow events and seven were SW flow (subjectively determined by the authors). It is also important to note that June was represented primarily by SW flow events, whereas July and August were dominated by NW flow events (Table 1).

Figures 7 through 18 represent composite upper air charts for each month. Comparing the June composites to July and August, obvious differences emerged. In June, for example, for the 700 mb level and above, a trough along 120° west longitude and a ridge near 100° west was present. For July and August, however, the shift of the ridge was westward and the amplitude had increased.

At the 850 mb level in June, the lowest heights were over northeast Utah and a trough in the height field was situated along 110° west longitude. It is important to note that while there was a ridge in the height field positioned over the Plains states for all three months, by July and August a cyclonic circulation (closed low) developed in the Rockies thus enhancing the southeasterly gradient flow over eastern Wyoming.

In effect, by reviewing the composite charts for all 17 cases and for each month individually, a conceptual model of the atmosphere using basic principles of atmospheric dynamics and quasi-geostrophic theory could be developed to relate the horizontal and vertical structure of the synoptic-scale regime which was so important to tornado development in Wyoming in 1979 (Holton, 1979; Palmen and Newton, 1948). During June, with SW flow a dominate factor (even though the latter portion of June was shifting to NW flow), the trough in the Rockies at 850 mb was a result of dynamic forcing (a process explained largely in terms of vorticity and temperature advection). The closed low which developed over northeast Utah in July and August, however, was caused at least in part through diabatic heating -- a result of the positioning of the middle and upper tropospheric ridge.

In comparing the composite charts developed in this study to Doswell's findings, some interesting commonalities and differences resulted. In Figure 19, Doswell indicated that upper level SW flow was a factor in severe weather development for the intermountain region. Similarly, the 500 mb composite for June 1979 (Figure 13) indicated this result. However, for July and August 1979, NW flow was present.

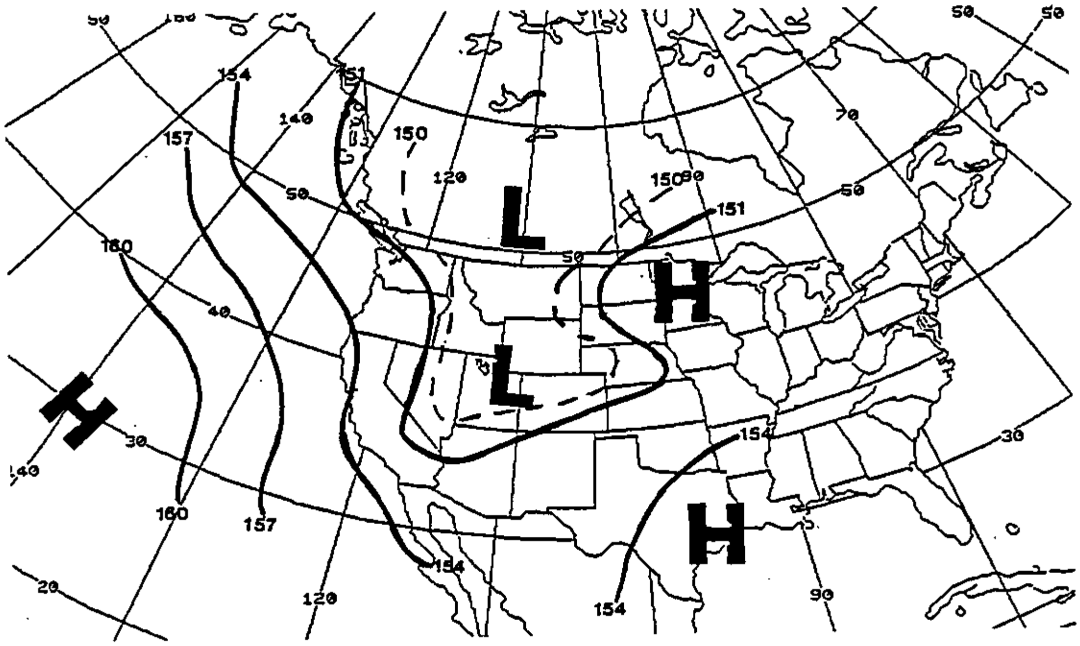

Figure 7. 850 mb Composite for June (seven cases).

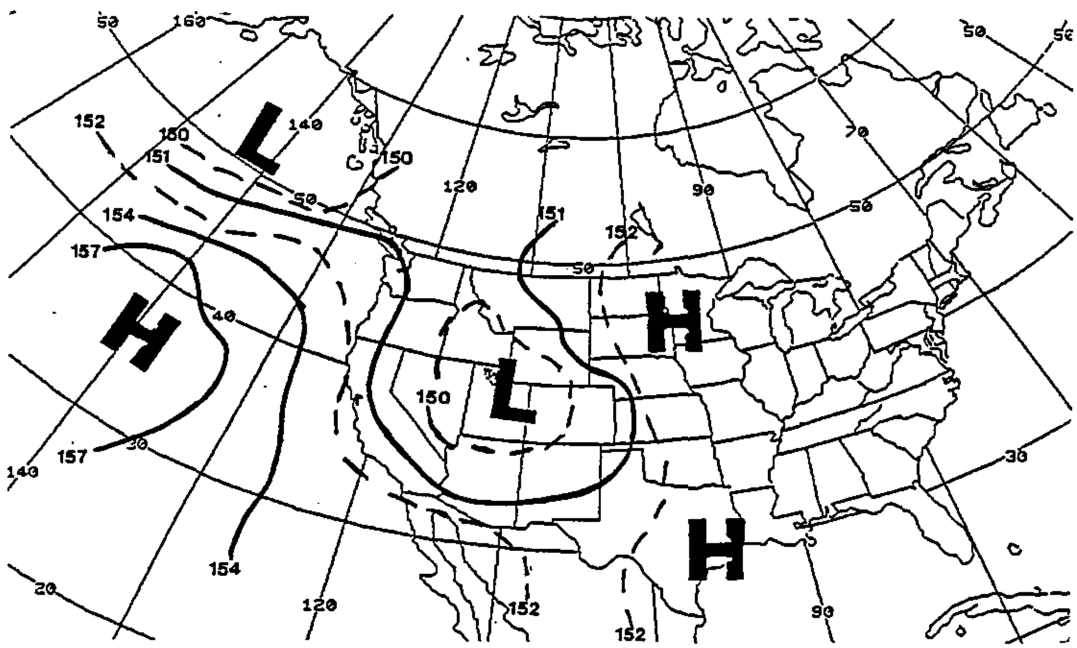

Figure 8. 850 mb Composite for July (seven cases).

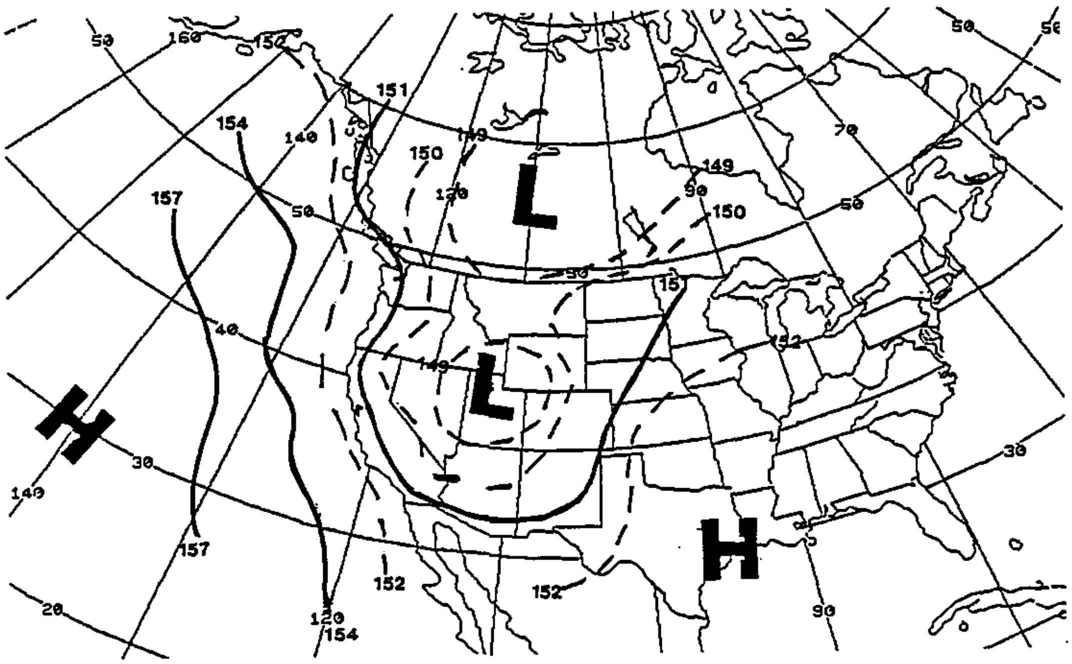

Figure 9. 850 mb Composite for August (seven cases).

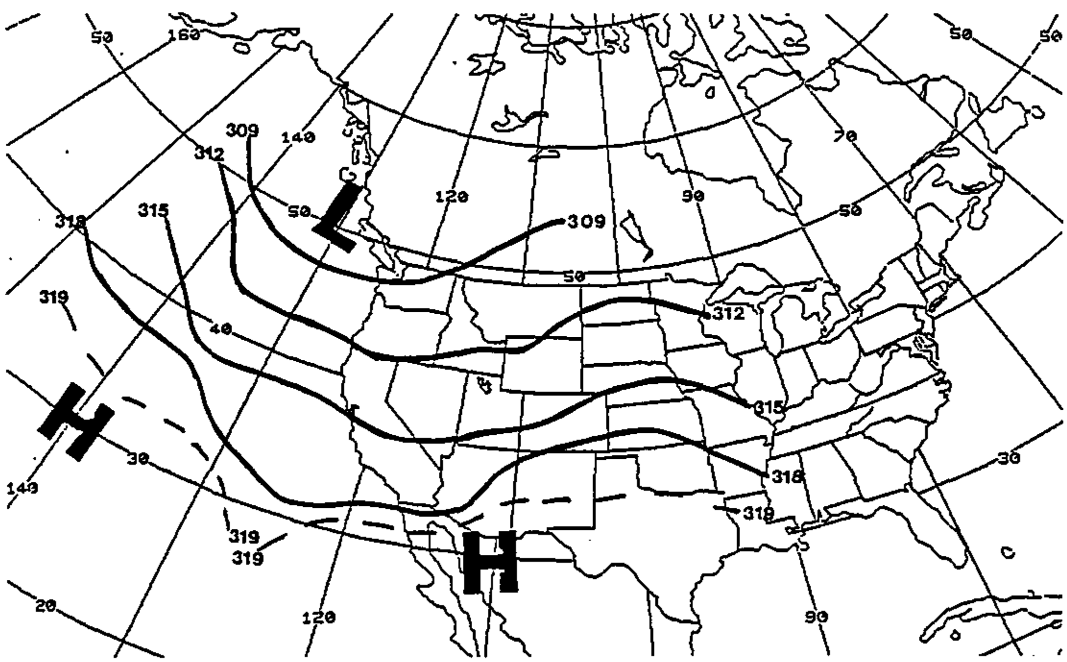

Figure 10. 700 mb Composite for June (seven cases).

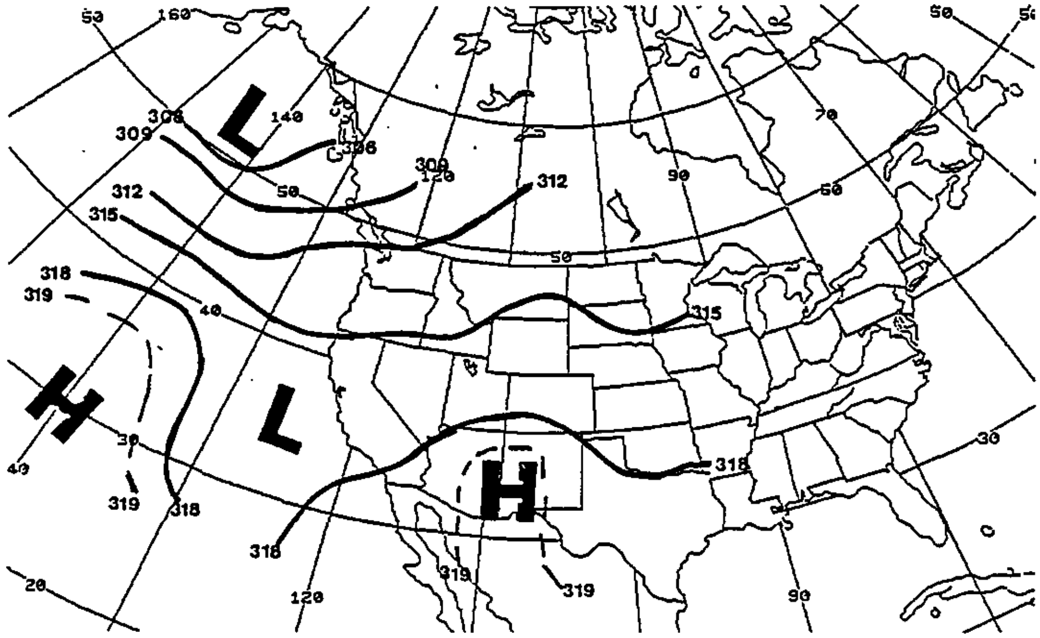

Figure 11. 700 mb Composite for July (seven cases).

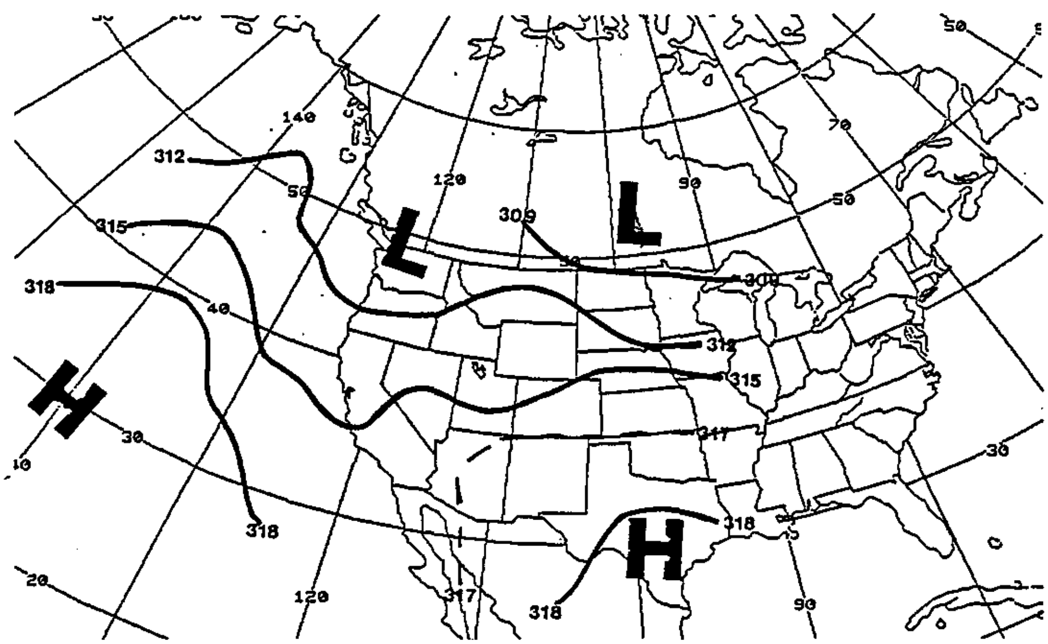

Figure 12. 700 mb Composite for August (seven cases).

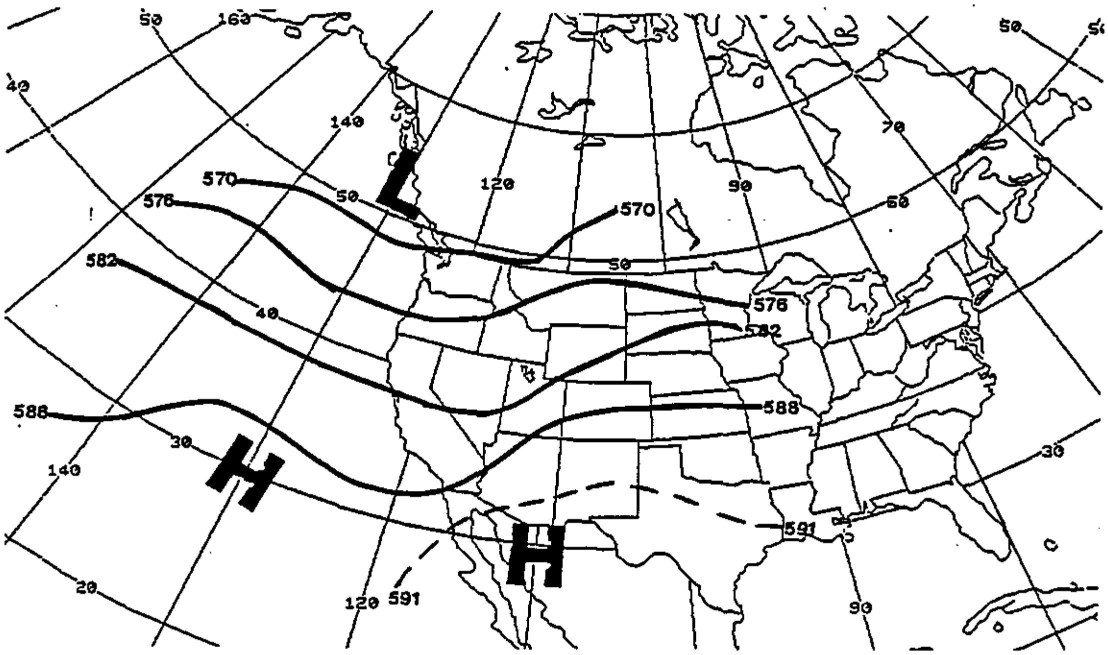

Figure 13. 500 mb Composite for June (seven cases).

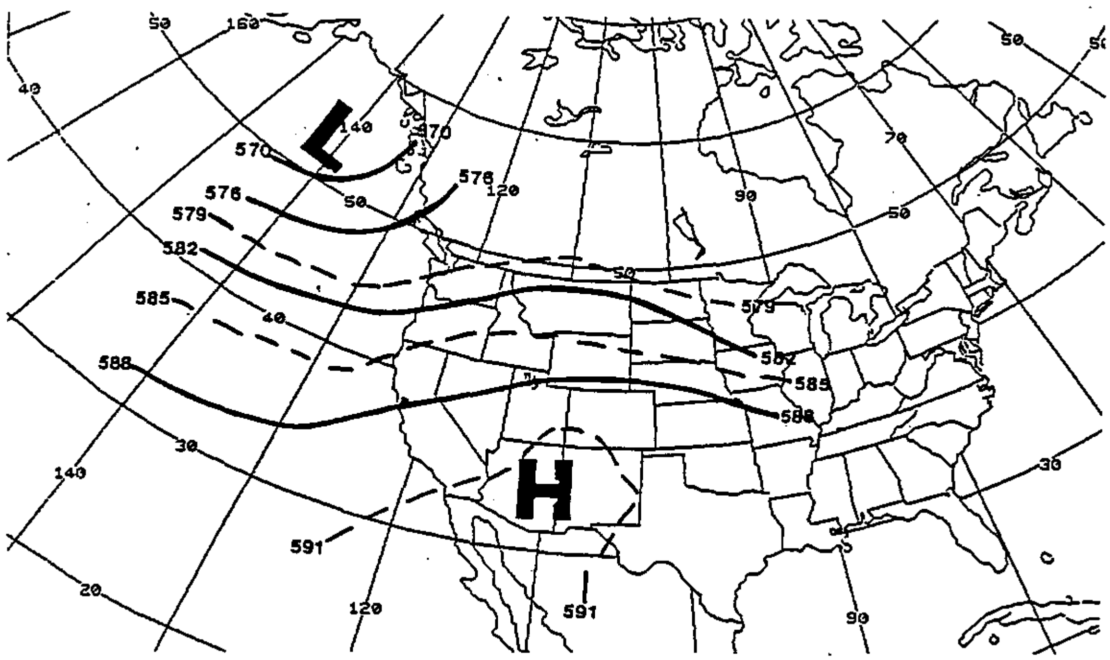

Figure 14. 500 mb Composite for July (seven cases).

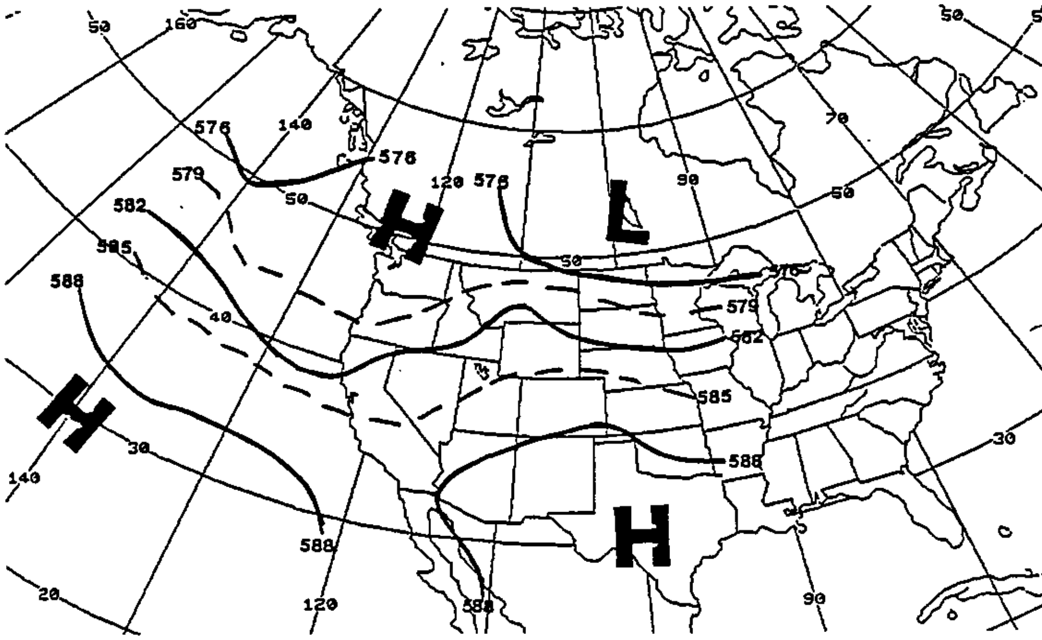

Figure 15. 500 mb Composite for August (seven cases).

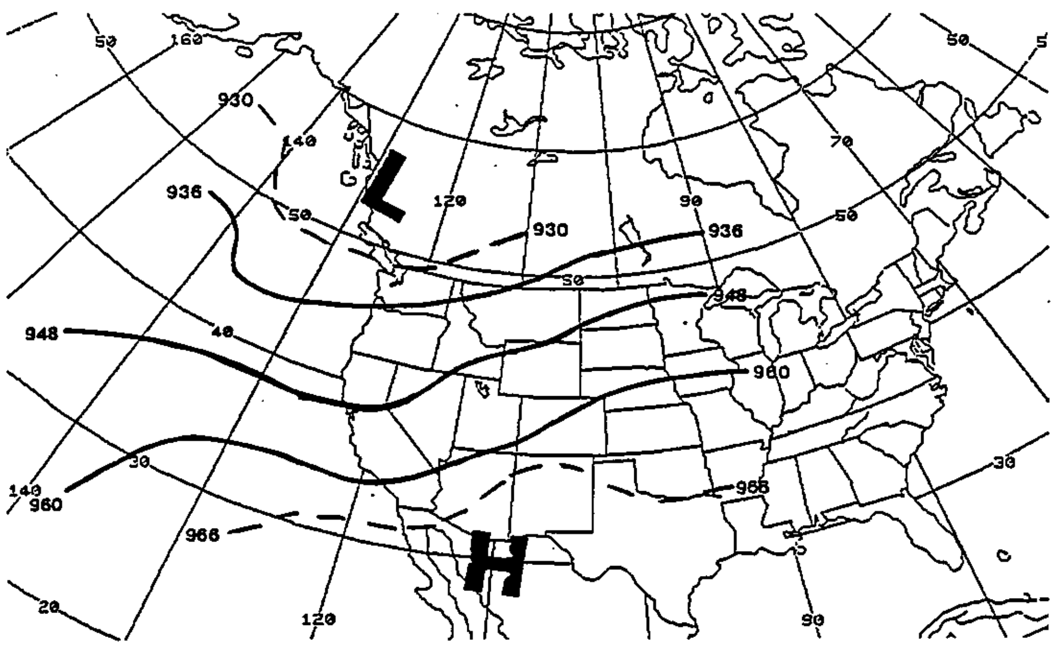

Figure 16. 300 mb Composite for June (seven cases).

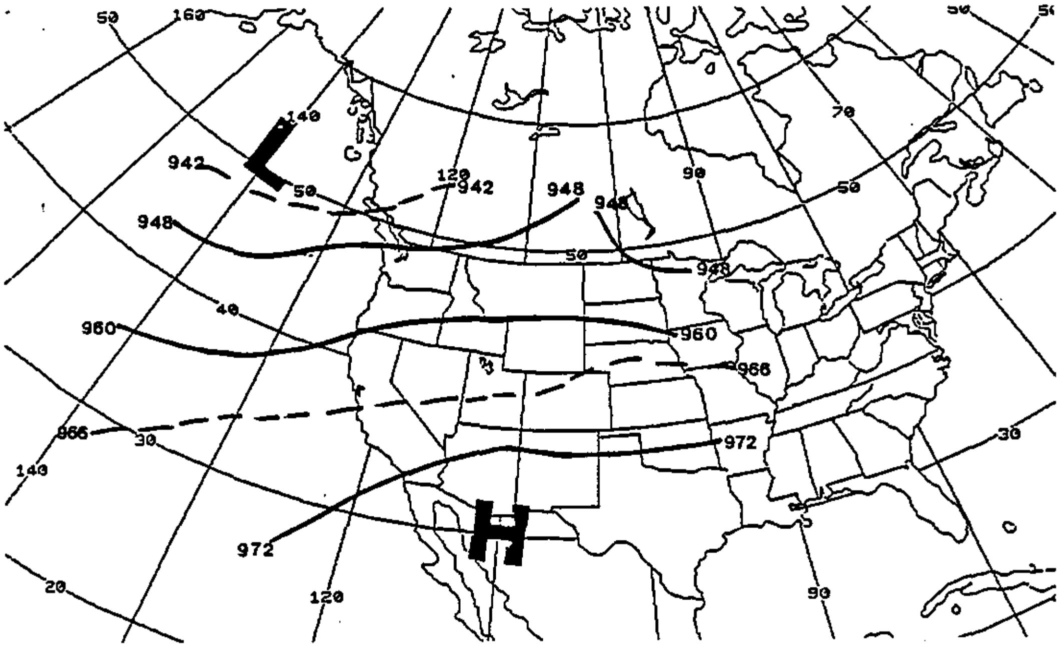

Figure 17. 300 mb Composite for July (seven cases).

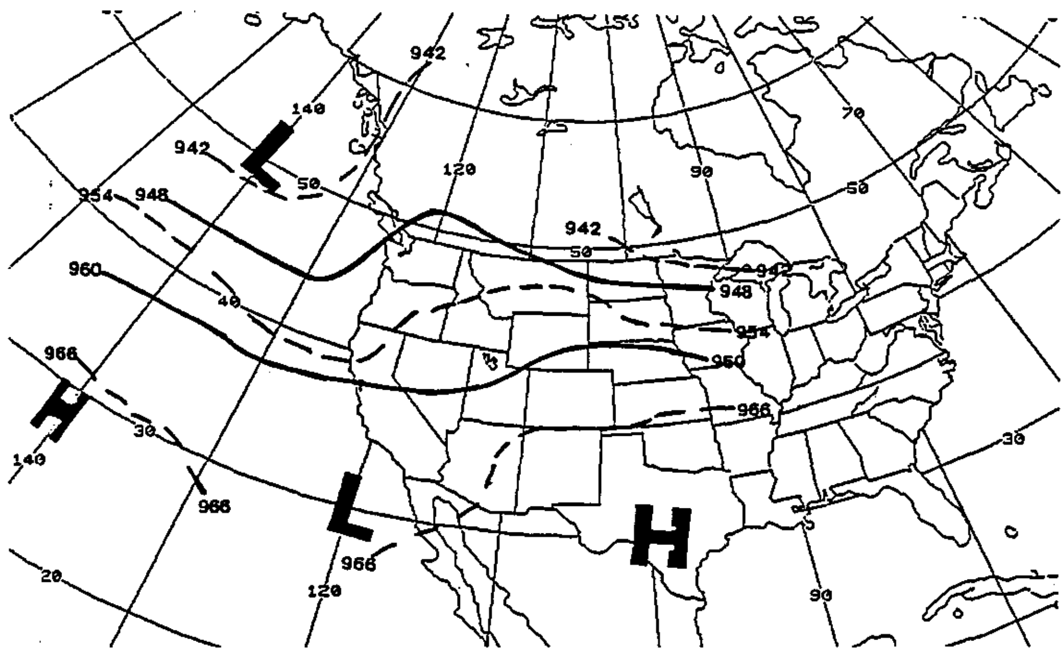

Figure 18. 300 mb Composite for August (seven cases).

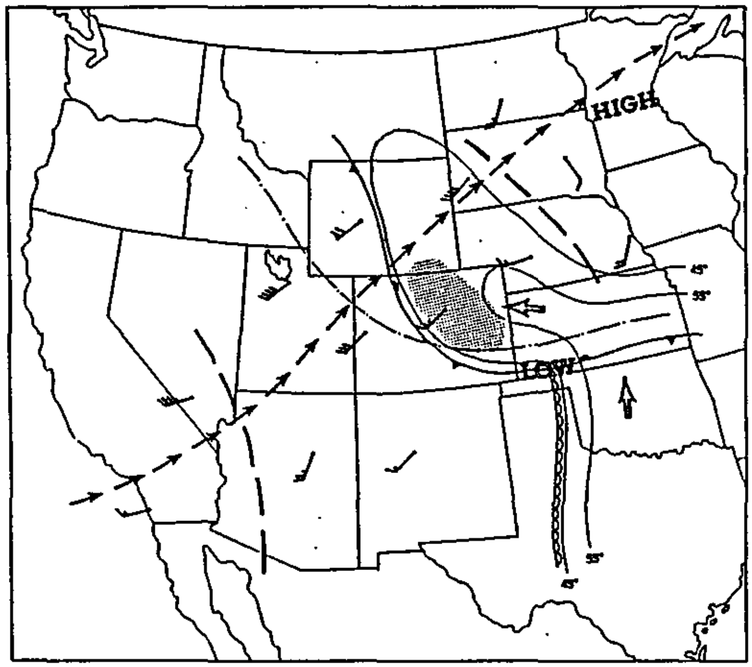

Figure 19. Composite High Plains severe thunderstorm parameter chart. Frontal symbols are conventional, surface isodrosotherms (°F) denoted by fine lines, scalloped line indicates surface dryline, large arrows depict surface flow, and "High" and "Low" refer to surface pressure centers. Dash-dot line 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 (from Doswell, 1980).

Figures 20 through 22 show the distribution of reported tornadoes by county for the 17 cases used in this study. It was interesting to note that of the 38 tornadoes reported in the eastern part of the state, 26 (68 percent) occurred in NW flow situations.

D. Surface Composites

Along with the tropospheric constant pressure composites, surface composites for 1979 were developed. Figures 23 through 25 show the analyses for all cases, the SW and NW flow situations, respectively.

When all of the cases in 1979 were combined (Figure 23), the composite surface chart indicated the presence of a "significant" stationary front along the Laramie Range northward into central Wyoming. Easterly upslope flow was also present over eastern Wyoming, and the "mean" position of the front represented an important boundary because of the separation of moist air to the east from drier air to the west. Significant wind and moisture convergence were also evident. The results were generally consistent with Doswell's findings in Figure 19, except that the surface wind gradient was enhanced by the presence of high pressure in the Dakotas and low pressure in western Colorado.

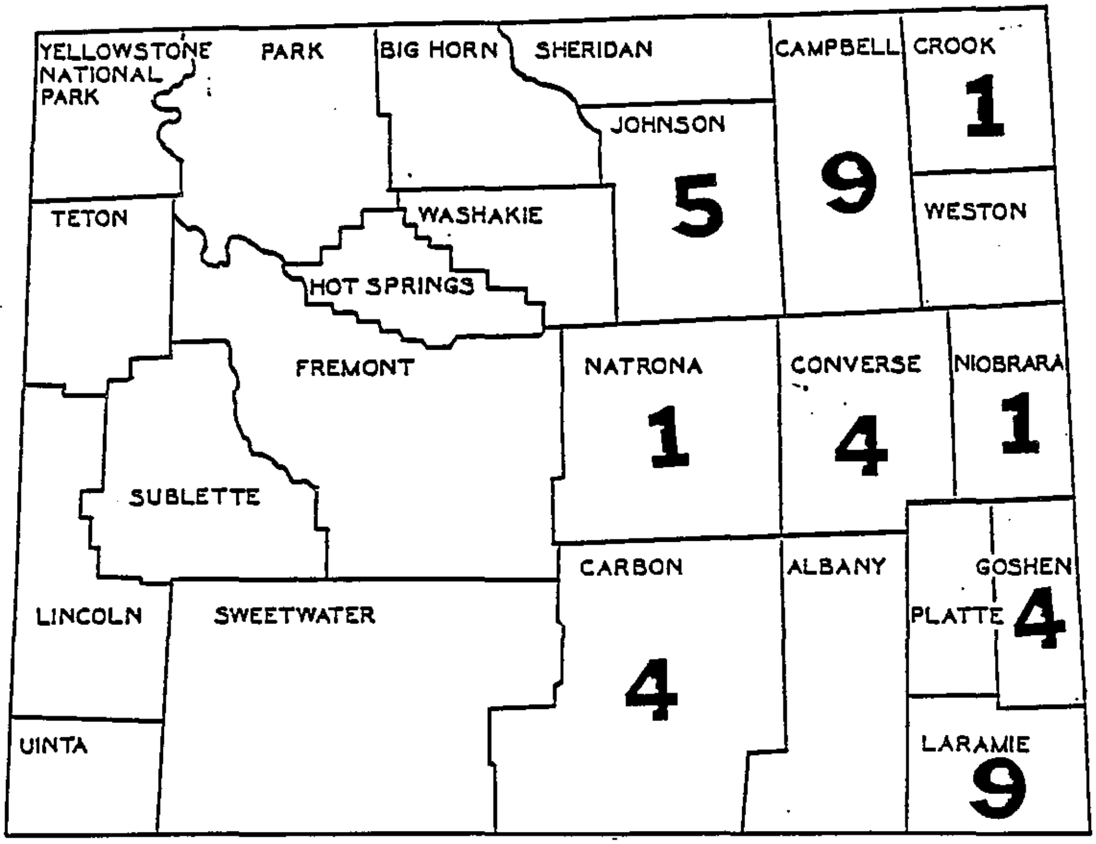

Figure 20. Total number of tornadoes reported by county for all 17 cases.

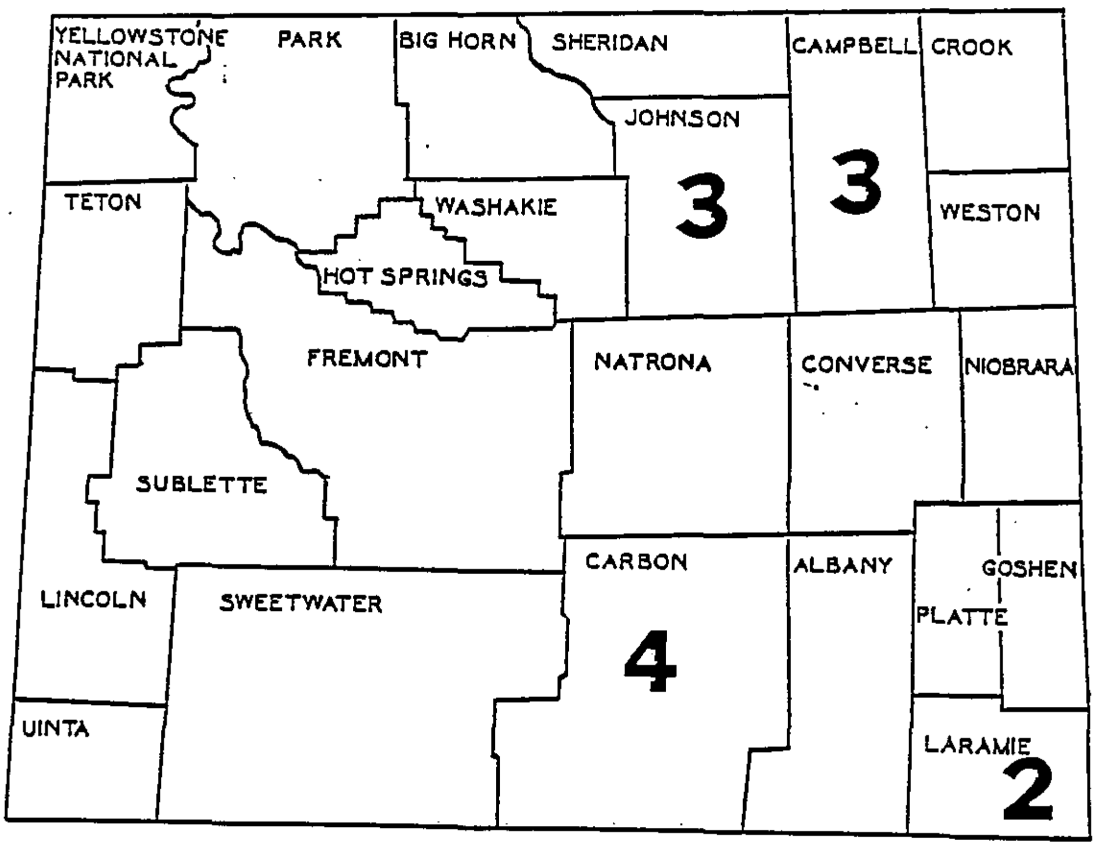

Figure 21. Total number of tornadoes reported by county for only the southwest (SW) flow cases (seven cases).

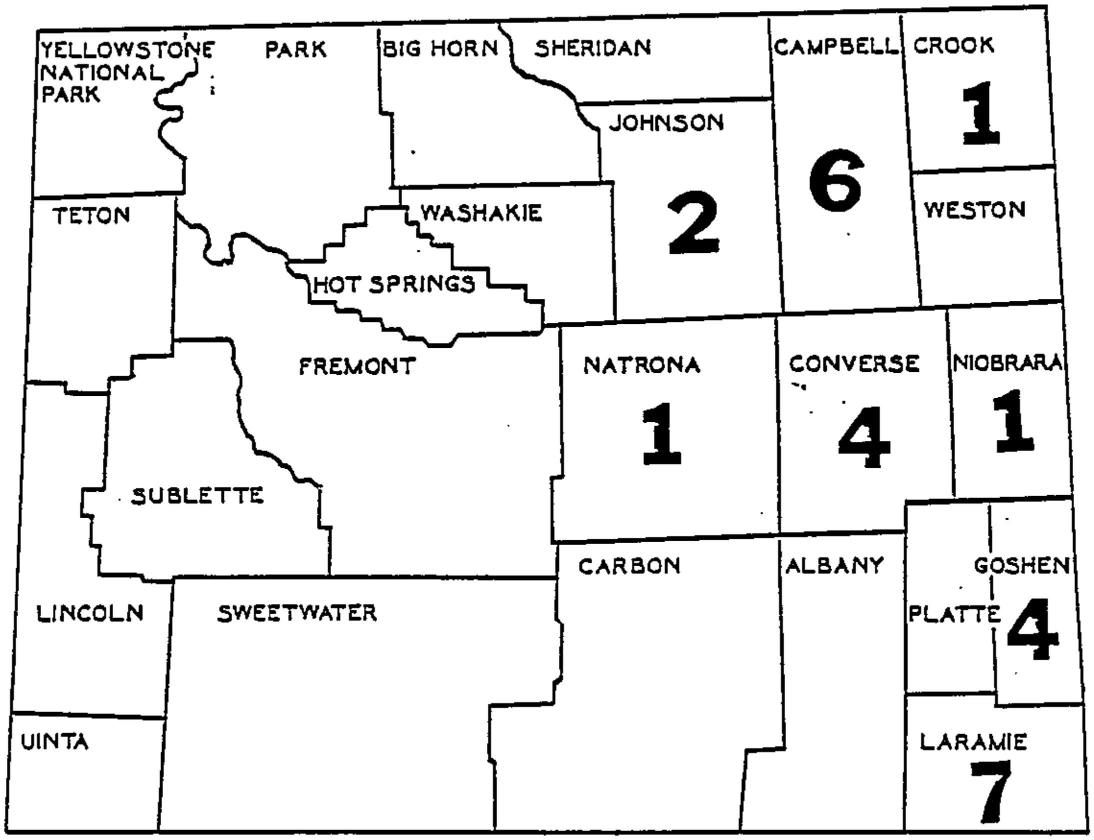

Figure 22. Total number of tornadoes reported by county for the northwest (NW) flow cases (ten cases).

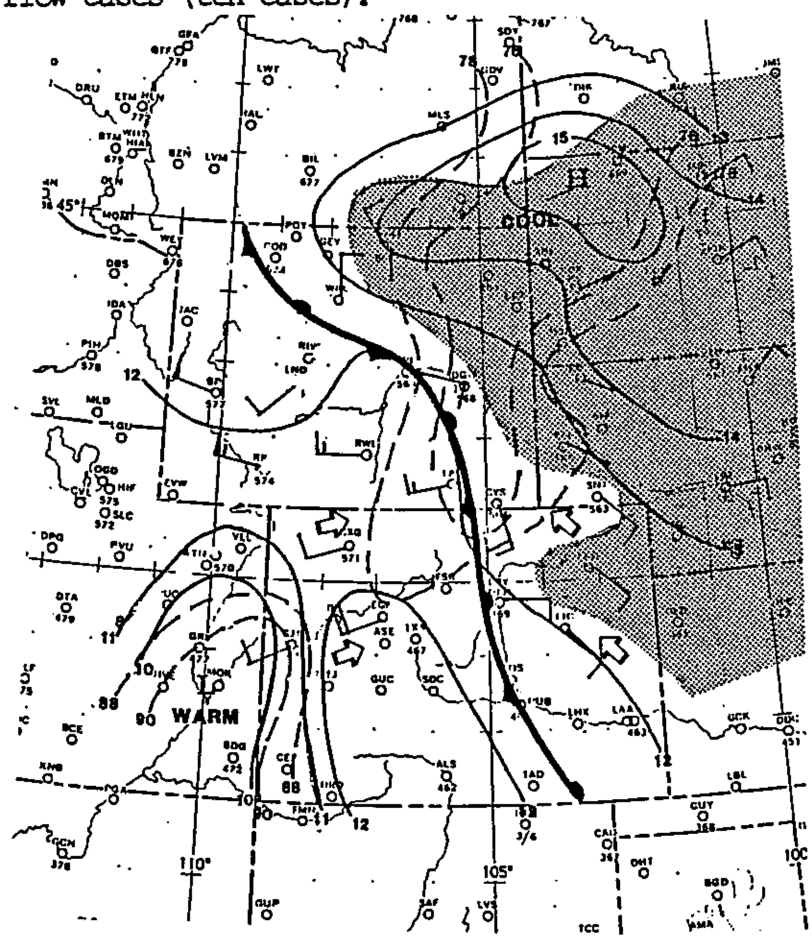

Figure 23. Surface composite for all 17 cases. Frontal symbols are conventional, surface isotherms denoted by dashed lines, isobars indicated by solid lines (mb - 1000), "H" and "L" refer to surface pressure centers, wind barbs show surface composite wind for a particular station (standard plotting convention), and stippled area denotes areas of dew point temperatures equal to or greater than 50°F. Large arrows indicate suggested stream flow. (Figures 24 and 25 follow the same plotting format.)

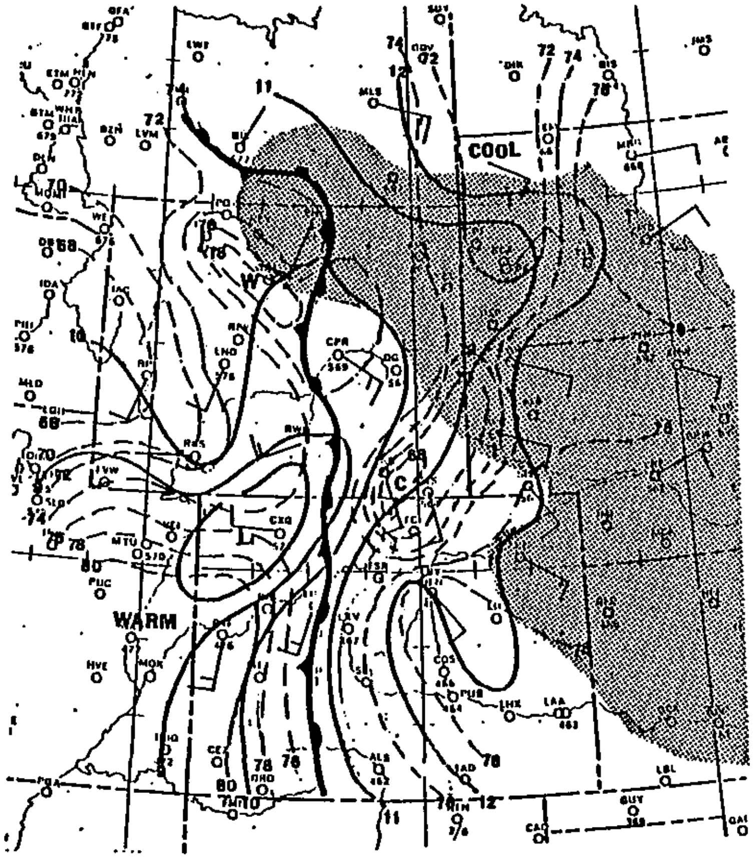

Figure 24. Surface composite for southwest (SW) flow cases (seven cases total). See Figure 23 for plotting format.

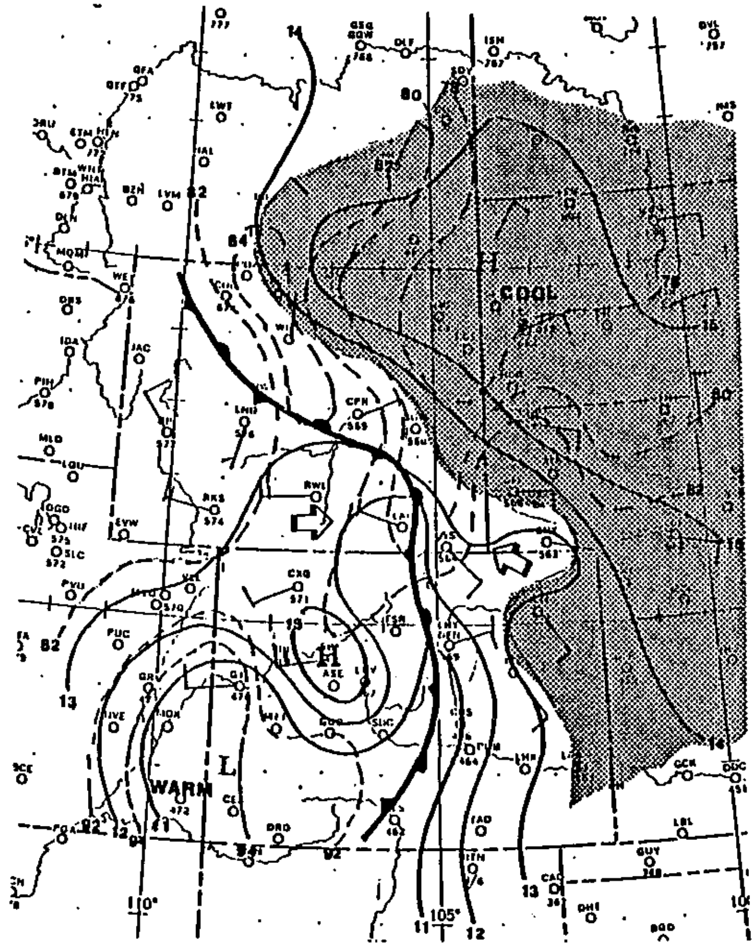

Figure 25. Surface composite for northwest (NW) flow cases (ten cases total). See Figure 23 for plotting format.

Figure 24 shows the composite surface chart for only the SW flow cases. Like the surface composite constructed using all 17 cases, the SW flow surface composite showed some similarity to Doswell's representation in Figure 19. However, in Figure 25, the surface composite chart using only NW flow cases, some significant departures from Doswell's composite resulted. The position of the surface low in southwestern Colorado was farther west and deeper; and the position of the high over extreme northeast Wyoming was farther west and more intense. The results were not really surprising, given the distribution of height in the middle and upper troposphere. With a middle and upper tropospheric ridge over the western and central Rockies, quasi-geostrophically, subsidence and therefore surface high pressure would be expected over the Plains. Furthermore, low pressure in southwestern Colorado would be expected to intensify due to radiational warming. Thus what resulted was moist easterly to southeasterly upslope flow over eastern Wyoming.

The magnitude of selected surface derived quantities for SW and NW flow is illustrated in Figures 26 through 31, and were obtained from the composite data. Moisture and surface convergence, as well as the surface potential temperature, using Bothwell's "severe SAO" program (1980), are presented. The results indicated that significant values of these quantities were aligned with the stationary front (and the Laramie Range), as would be expected. (NOTE: The surface convergence results were positioned farther west as a result of data resolution in the program.) A significant feature from these analyses was the increased magnitude of surface wind convergence in the east portions of the state during NW flow situations. Additionally, the surface potential temperature analysis revealed a stronger gradient parallel to the front. From comparison of the NW and SW flow surface composites, it appeared that the surface gradients of the selected derived quantities were greater in a NW flow regime.

E. Building an Overall Composite

Clearly, two composites appeared to be resolved from the data. These were the Doswell composite (Figure 19), which was consistent with the SW flow situation, and a NW flow composite (Figure 32) that had been developed from this study for the tornado days during the summer of 1979 when there was NW middle and upper tropospheric flow.

One major difference between these two composites was that the NW flow chart, Figure 32, showed the position of the surface cyclone to the southwest of Wyoming and the position of the surface anticyclone closer to northeast Wyoming with possibly greater magnitude. Additionally, the position of the 500 mb ridge was considerably farther west — a result of the circulation of the westerlies around the entire Northern Hemisphere for the summer of 1979. Recalling Figure 19, Doswell showed the surface cyclone over extreme southwest Kansas and the surface anticyclone in northern Minnesota, considerably farther east than for the NW flow composite.

The NW flow situation for the summer of 1979 was believed to be significant because of the positioning of the full-latitude middle- and upper-tropospheric ridge along 115° west with its greatest amplitude in its northern portion and the strongest westerlies north of Wyoming (Taubensee, Wagner, and Dickson, 1979). This resulted in the location of a "thermal low" in southwestern

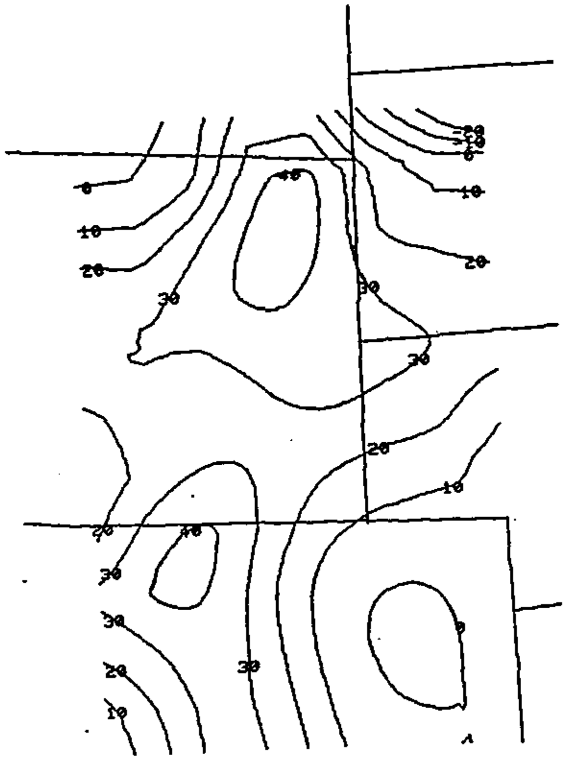

Figure 26. Composite chart for southwest (SW) flow wind convergence. Units are 10^{-6} sec^{-1} (Bothwell, 1985).

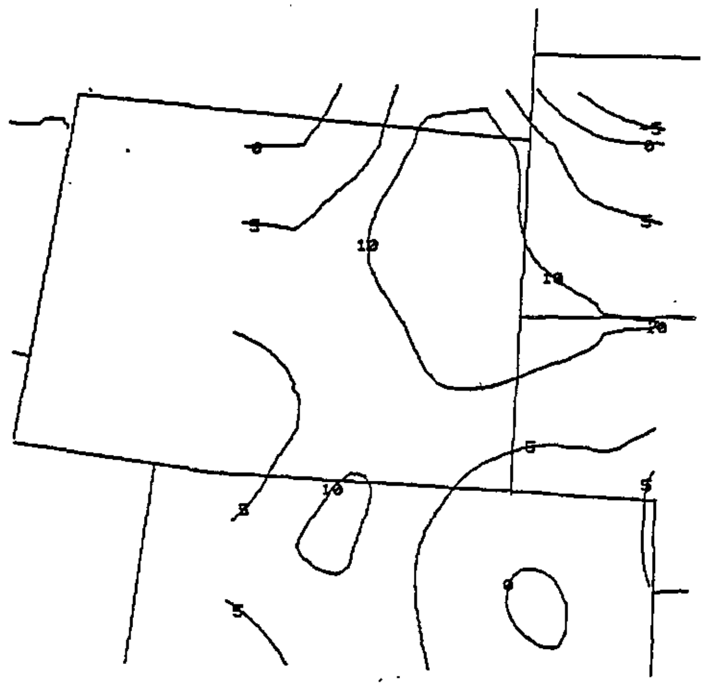

Figure 27. Composite chart for southwest (SW) flow moisture convergence. Units are g kg^{-1} hr^{-1} x 10 (Bothwell, 1985).

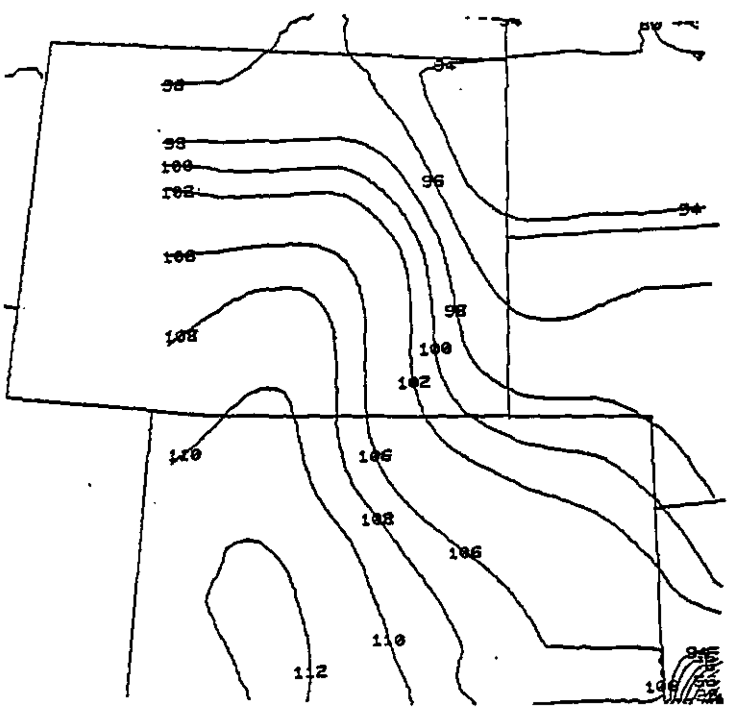

Figure 28. Composite chart for southwest (SW) flow potential temperature. Units are ^{o}F (Bothwell, 1985).

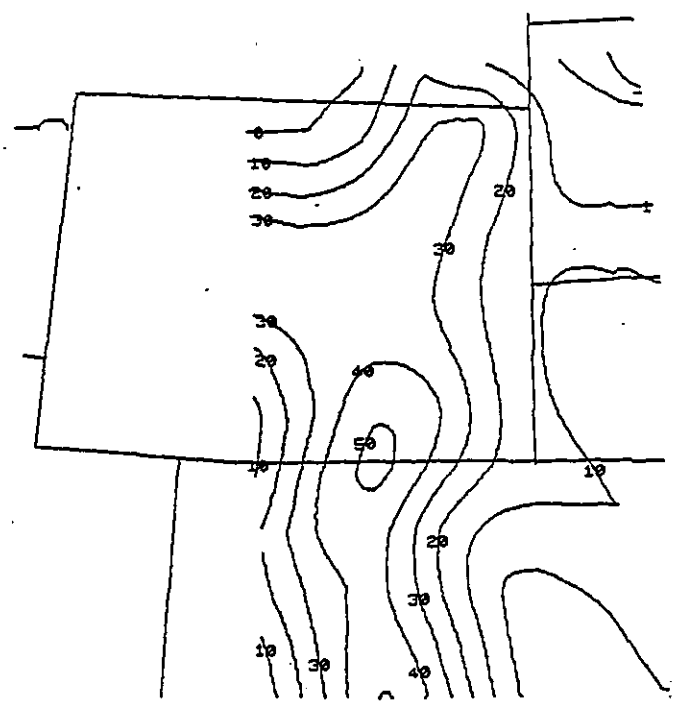

Figure 29. Composite chart for northwest (NW) flow wind convergence. Units are 10^{-6} sec^{-1} (Bothwell, 1985).

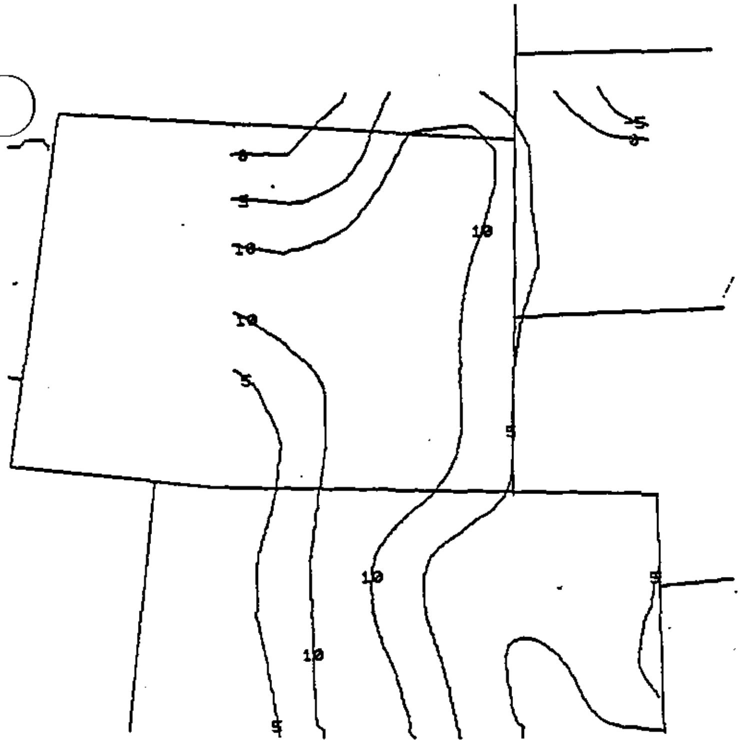

Figure 30. Composite chart for northwest (NW) flow moisture convergence. Units are g kg^{-1} hr^{-1} x 10 (Bothwell, 1985).

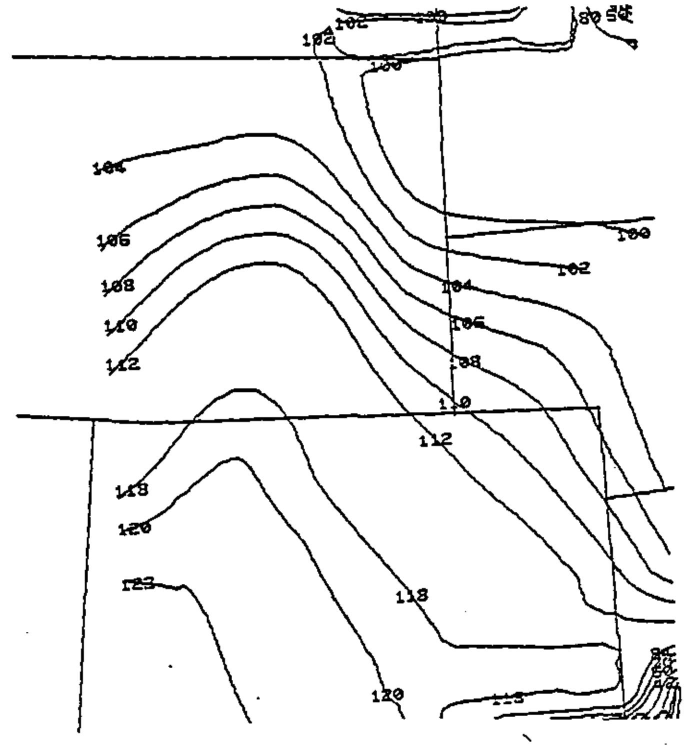

Figure 31. Composite chart for northwest (NW) flow potential temperature. Units are ^{o}F (Bothwell, 1985).

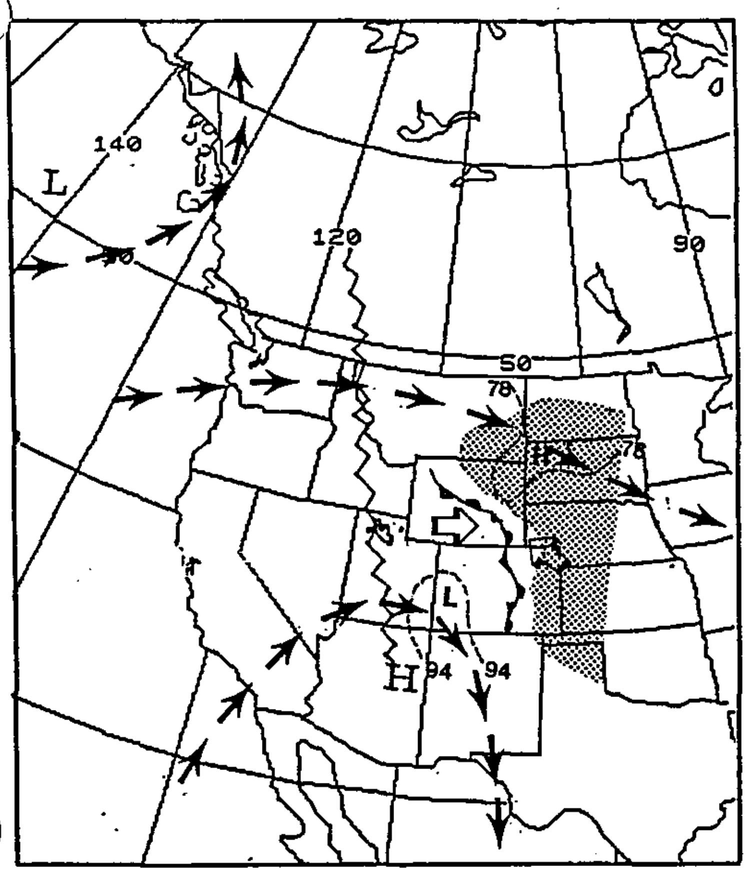

Figure 32. Composite chart illustrating the northwest (NW) flow regime for Wyoming. Large arrows indicate surface stream flow, frontal symbols are conventional, dashed line indicate surface isotherms (^{o}F), stippling indicates dew points at the surface equal to or greater than $50^{o}F$, "H" and "L" indicate pressure centers (small at the surface, large at 500 mb), jagged line indicates the upper level ridge axis, and chain of arrows indicate the mid- and upper-tropospheric wind flow.

Colorado and a surface high to the northeast of Wyoming. Hence, an environment favorable for the development of tornadoes was created -- a regime characterized by a combination of upslope surface winds, warm surface advection, frontogenesis (shown below), and cyclonic vorticity advection downstream from any short wave trough in the middle- and upper-tropospheric NW flow -- results which were similar to the findings by Johns for northwest flow situations over the Plains (Johns, 1982 and 1984). Moreover, directional vertical wind shear (Table 3) along with surface wind and moisture convergence were also present.

F. Case Studies

Two cases were extracted from 1979 to illustrate the SW and NW flow characteristics: June 18 and July 16, respectively. These cases were included to further make distinctions between these two types of regimes.

1. Case One

On June 18, 1979, a large middle- and upper-tropospheric closed cyclonic circulation was located over eastern Nevada, placing Wyoming under a southerly to southwesterly middle- and upper-tropospheric flow (Figure 33). The surface analysis at 2100 GMT, Figure 34, for that day was similar to Doswell's composite (Figure 19). The lowest surface pressures were over northern Colorado with cyclogenesis occurring along the stationary front. The "severe SAO" analyses, Figures 35 through 37, showed surface moisture and wind convergence which was significant. Additionally, the potential temperature analysis indicated a strong gradient over eastern Wyoming. A measure of static stability (Berry, 1981) was computed from the surface observations and is displayed in Figure 38. The results confirmed the presence of a strong horizontal gradient of static stability across the front and that the troposphere was unstable. On this day, three tornadoes occurred in Campbell County, believed to be of light to moderate intensity, just north of the 70-unit region on the surface velocity convergence chart shown in Figure 35.

2. Case Two

July 16, 1979, was significant in Wyoming since the most damaging tornado on record for the state hit Cheyenne. The F-scale rating was 3 (Parker and Hickey, 1980). On that day, west to northwest flow was evident in the middle- and upper-tropospheric regions over the state. In fact, Figure 39 indicated that the axis of the long wave ridge at 500 mb was west of Wyoming. Additionally, a short wave trough from about north-central Montana to extreme northwest Wyoming was embedded in the large-scale upper-level flow suggesting the possibility of cyclonic vorticity advection increasing with height (to prove this requires computation, which is planned in a continuation of this study).

At the surface, Figure 40, the 2100 GMT analysis compared well to Doswell's composite, except that the lowest surface pressures were farther northwest over northeastern Colorado. Most of eastern Wyoming had surface winds predominantly from the east, and the isobars indicated that the direction of the surface gradient wind was from the east-southeast.

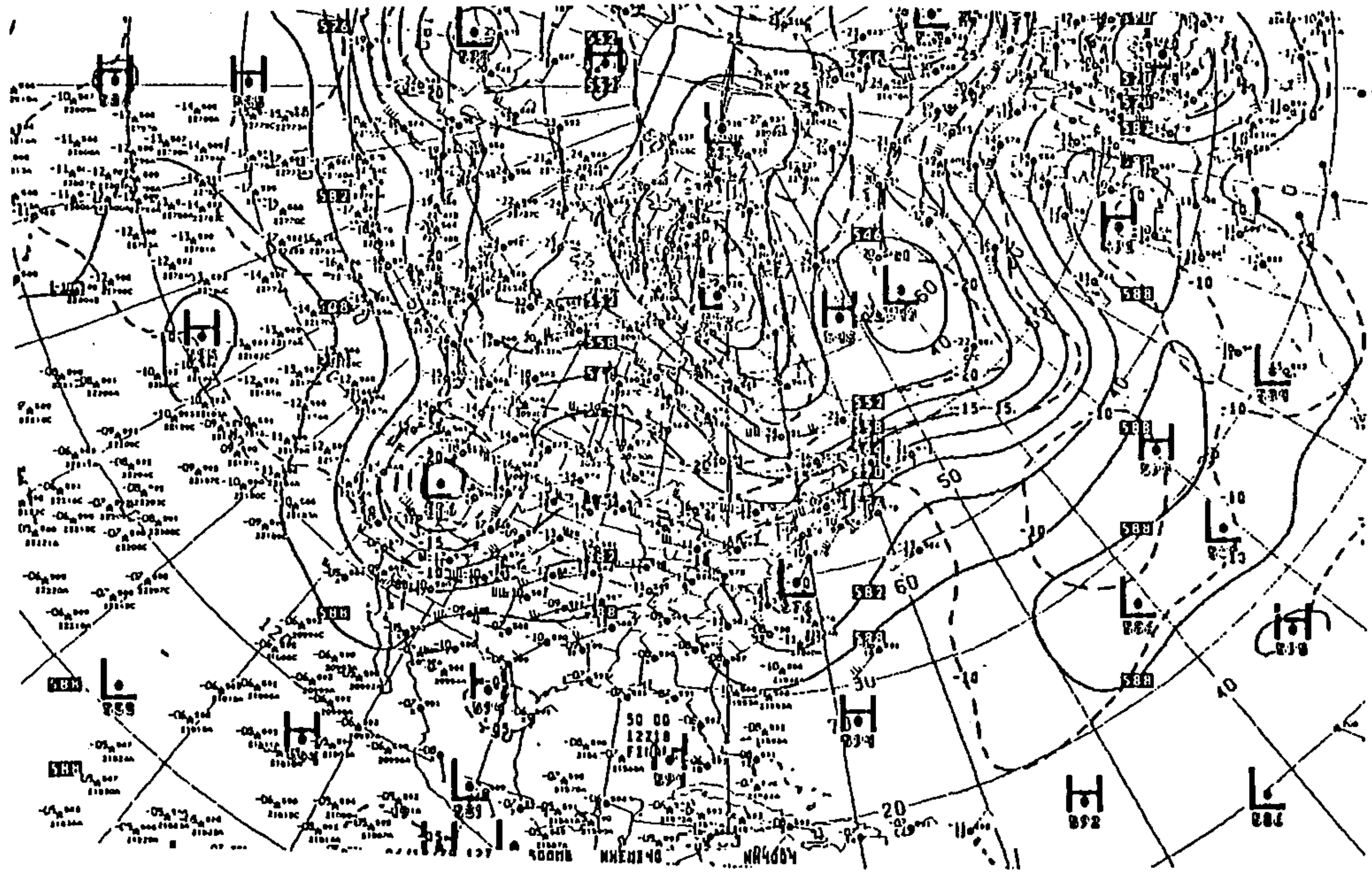

Figure 33. 500 mb Analysis for 1200 GMT, June 18, 1979.

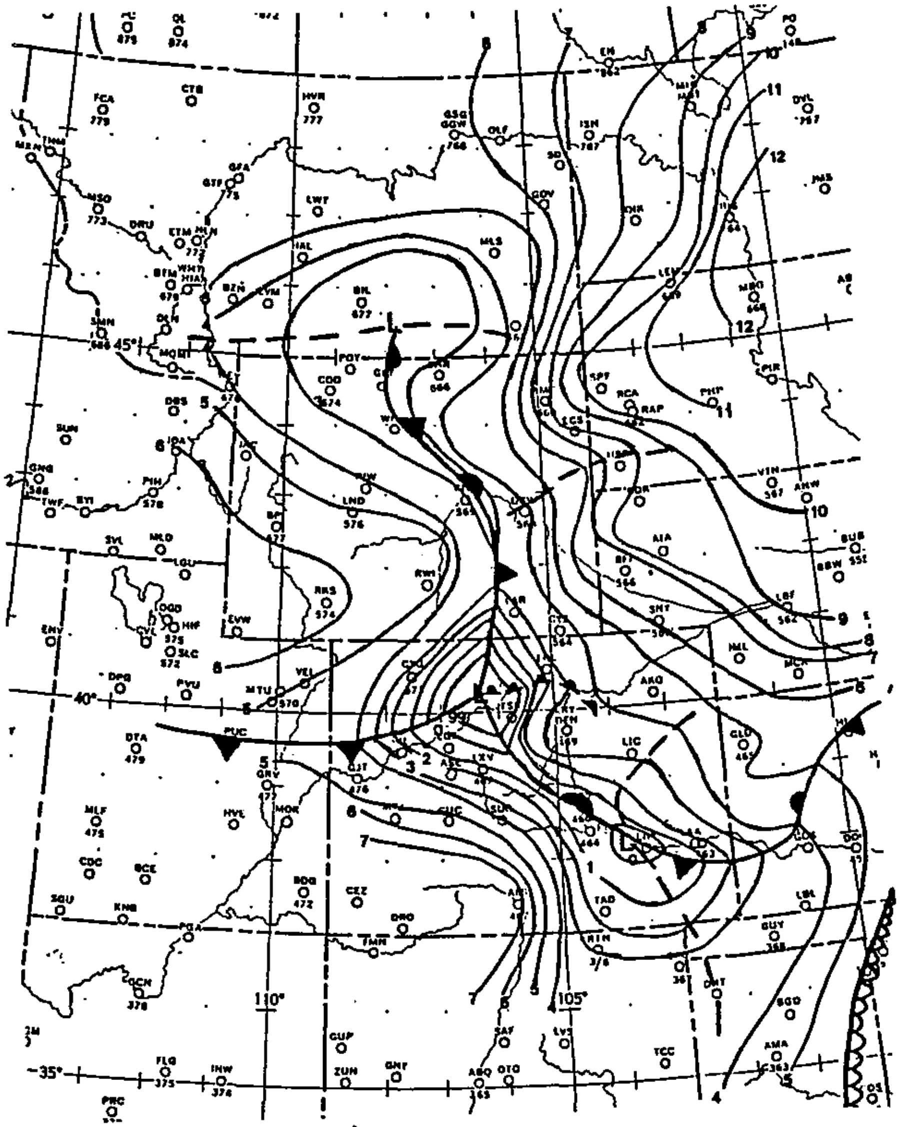

Figure 34. Surface analysis for 2100 GMT, Monday, June 18, 1979. Solid lines are isobars (mb - 1000 for values 1000 mb or greater, mb - 900 for values less than 1000 mb). Frontal symbols are conventional. Dashed lines are surface troughs, and "H" and "L" are surface pressure centers. Figure 40 uses the same plotting format.

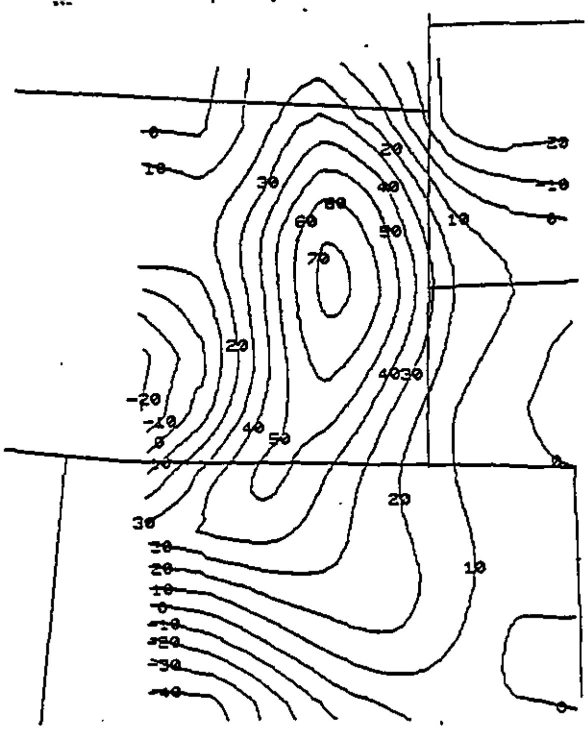

Figure 35. Wind convergence (10^{-6} sec^{-1}) for June 18, 1979, 2100 GMT (Bothwell, 1985).

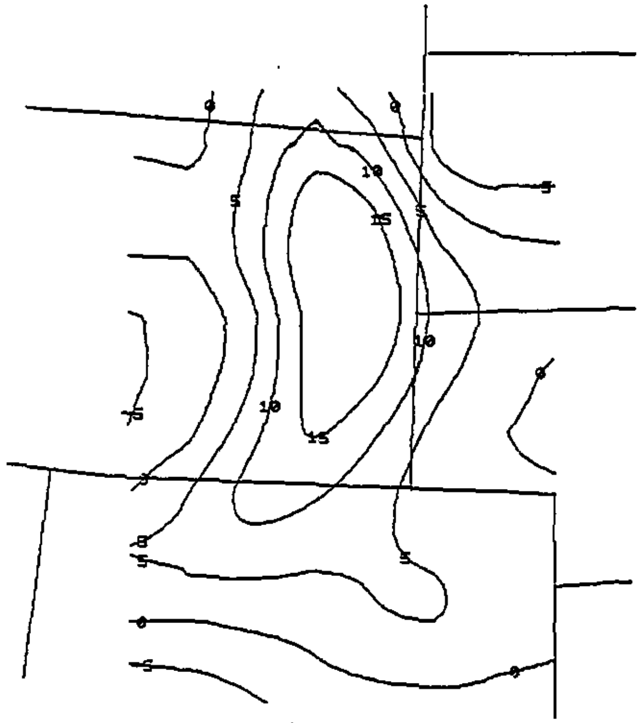

Figure 36. Moisture convergence ($g\ kg^{-1}\ hr^{-1} \times 10$) for June 18, 1979, 2100 GMT (Bothwell, 1985).

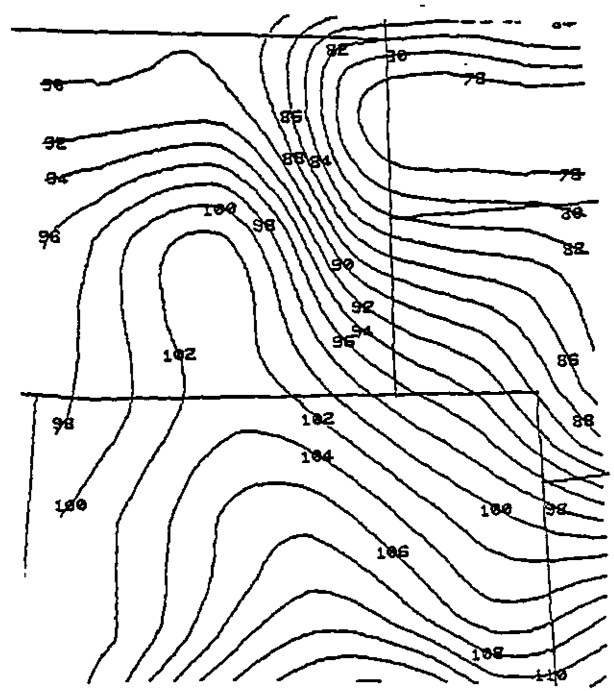

Figure 37. Potential temperature (°F) for June 18, 1979, 2100 GMT (Bothwell, 1985).

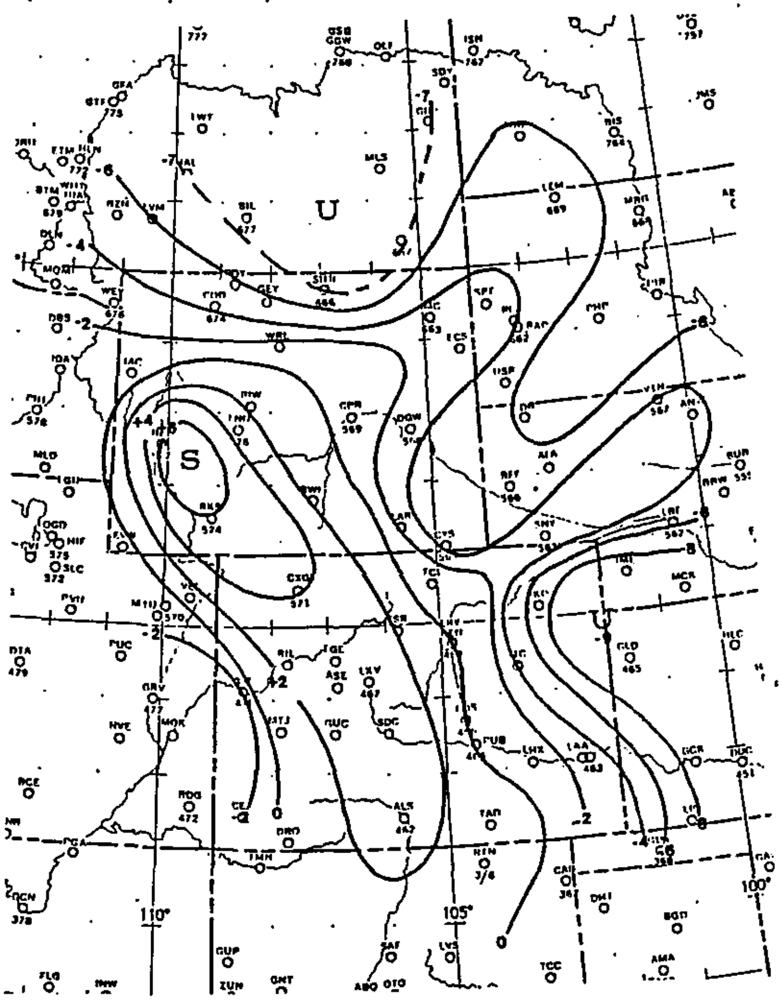

Figure 38. Surface based lifted indices for June 18, 1979 (Berry, 1981).

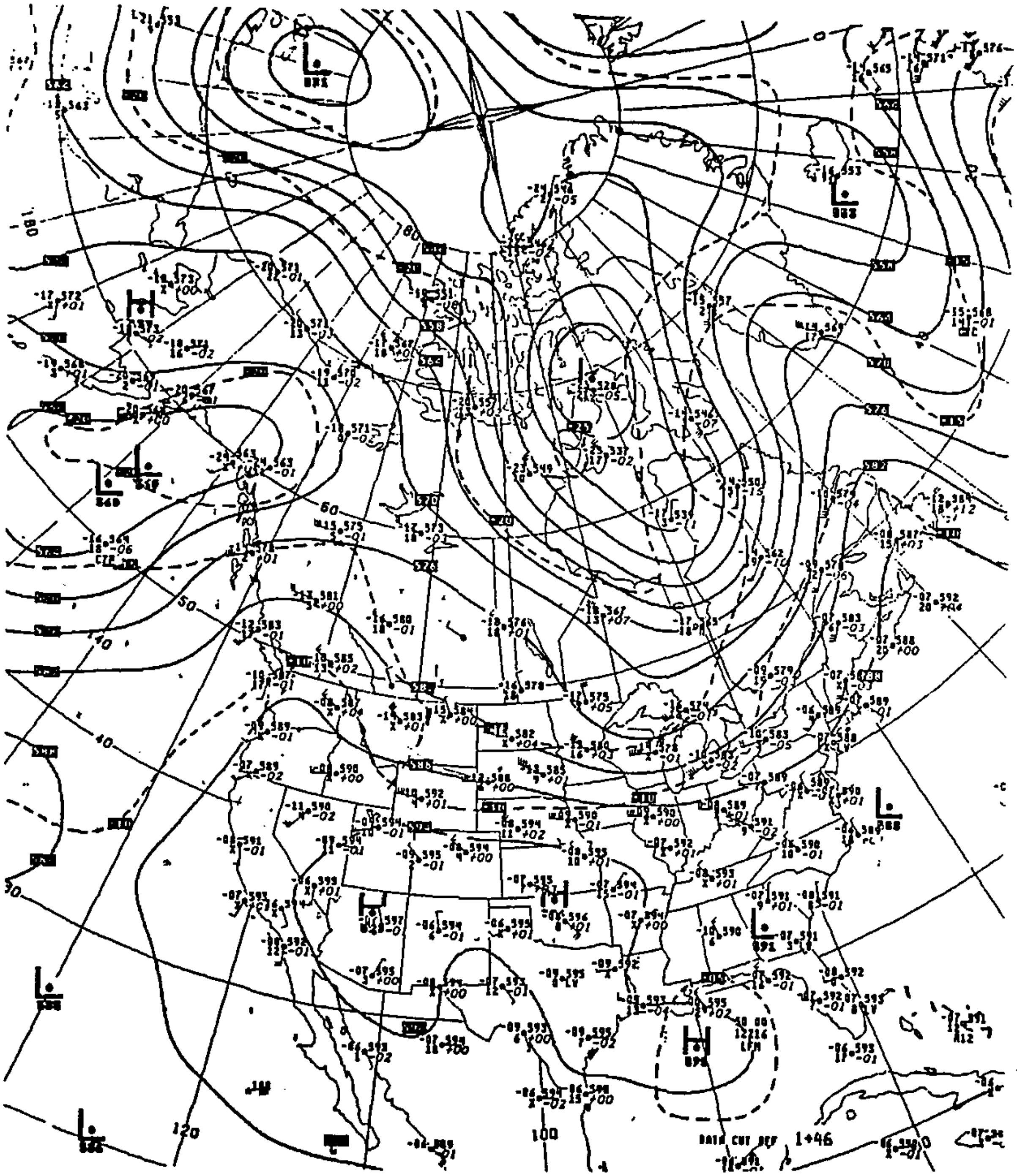

Figure 39. 500 mb Analysis for 1200 GMT, Monday, July 16, 1979.

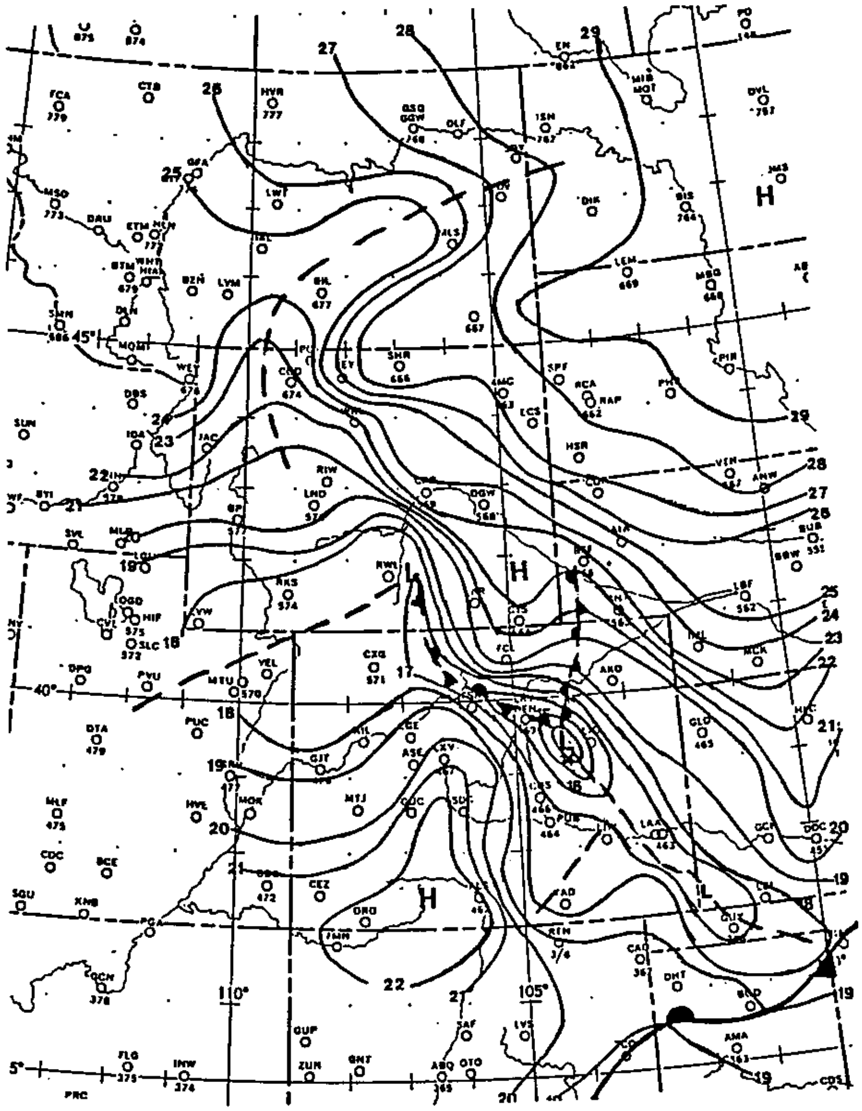

Figure 40. Surface analysis for 2100 GMT, Monday, July 16, 1979. Plotting format is the same as Figure 34.

The "severe SAO" analyses, Figures 41 through 43, similarly show a strong potential temperature gradient with its vector pointing southwest. The moisture and velocity convergence maxima were in good agreement with the surface analysis. Figure 44 shows the distribution of static stability for 2100 GMT, July 16, 1979. Even though instability was present, its gradient was not as strong as for the SW flow case. Finally, Figure 45 illustrates two soundings from Fort Collins, Colorado, for July 16, 1979.

In addition, a calculation of frontogenesis, utilizing Petterssen's two-dimensional frontogenetical function, produced significant values of 12×10^{-10} deg. m^{-1} s^{-1} (Petterssen, 1956) -- clearly indicating that rising motion was occurring over southeast Wyoming.

Table 4. Vorticity advection (VA) and temperature advection (TA) are listed for the 700 MB/ 500 MB pressure surfaces for each of the 17 cases used in this study.

C = Cyclonic vorticity advection
A = Anticyclonic vorticity advection
COLD = Cold temperature advection
WARM = Warm temperature advection
N = indicates advection was too week to determine
SW = Southwest flow
NW = Northwest flow
M = MISSING

DATE	FLOW	VA	TA
		700 MB/500 MB	700 MB/500 MB
6/26	NW	C/A	WARM/WARM
6/27	NW	C/A	WARM/COLD
6/28	NW	N/C	N/N
7/16	NW	C/C	WARM/COLD
7/26	NW	A/A	N/N
7/27	NW	A/A	WARM/COLD
7/28	NW	N/A	WARM/N
7/30	NW	N/C	N/COLD
8/1	NW	N/A	WARM/WARM
8/28	NW	N/C	N/N
6/14	SW	C/C	N/COLD
6/15	SW	C/N	WARM/N
6/16	SW	C/C	N/COLD
6/18	SW	C/M	COLD/M
7/4	SW	N/C	N/COLD
7/22	SW	C/C	COLD/N
8/14	SW	N/A	N/N

To help summarize the differences between the SW and NW flow scenarios, Table 4 was constructed. In the table, the nature of the vorticity and temperature advection for each of the 17 cases is shown. These quantities were determined observationally. Taking into consideration the differences in the sample sizes of the SW and NW flow cases, it was important to note that there was a greater percentage of SW flow cases with cyclonic vorticity advection at both 700 and 500 mb than for NW flow. In addition, 60 percent of the NW flow cases had 700 mb warm advection, whereas only one of the SW flow cases (14 percent) had warm advection at 700 mb. Recalling Figure 25, the surface composite for NW flow indicated upslope flow was at the surface over eastern Wyoming. Thus, observationally, the forcing for upward vertical motion for SW flow was apparently in the middle- and upper-troposphere, whereas in NW flow the forcing for rising motion was confined mainly to the lower troposphere. Furthermore, as shown in Table 3, there was twice as much directional vertical wind shear for NW

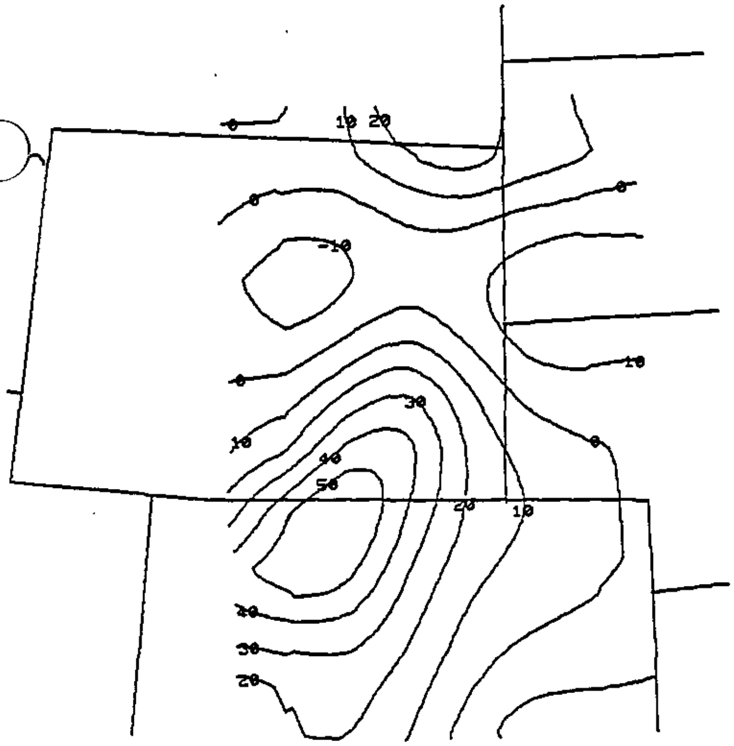

Figure 41. Wind convergence (10^{-6} sec^{-1}) for July 16, 1979, 2100 GMT (Bothwell, 1985).

Figure 42. Moisture convergence (g kg^{-1} hr^{-1} x 10) for July 16, 1979, 2100 GMT (Bothwell, 1985).

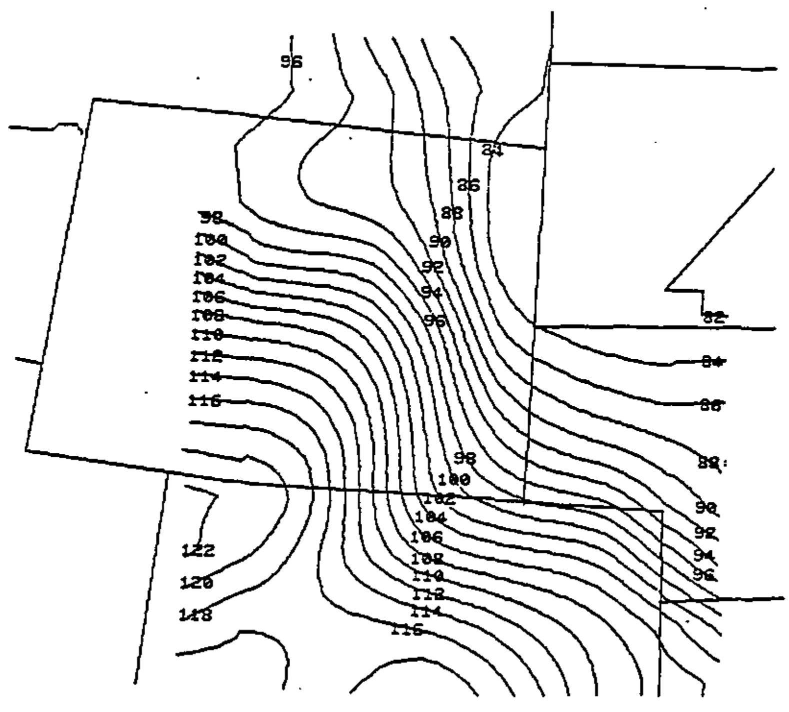

Figure 43. Potential temperature (°F) for July 16, 1979, 2100 GMT (Bothwell, 1985).

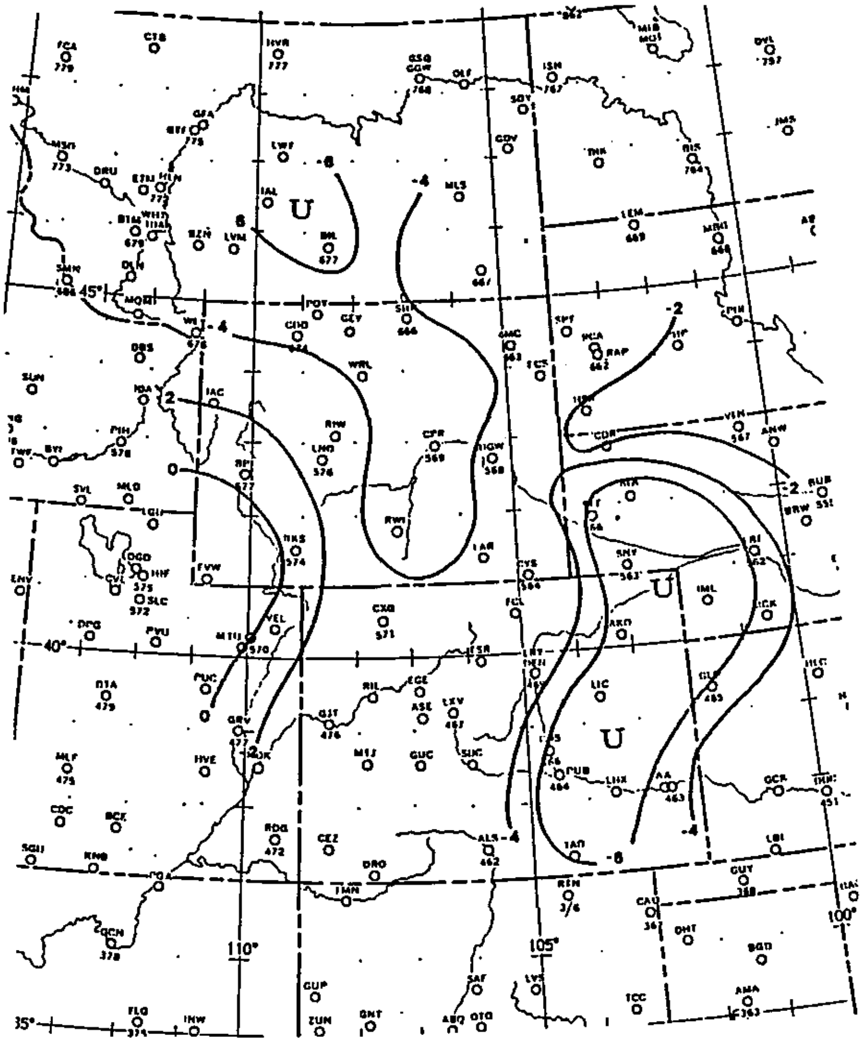

Figure 44. Surface based lifted indices for July 16, 1979 (Berry, 1981).

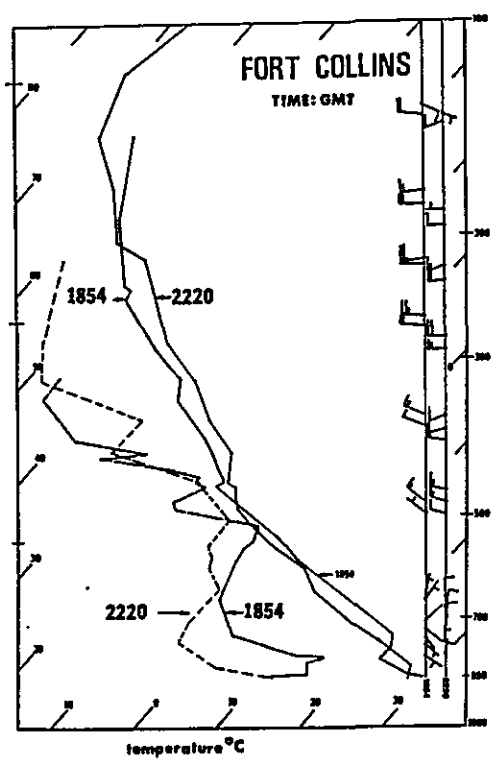

Figure 45. Skew-T, Log-P diagram for two soundings taken in Fort Collins, Colorado, July 16, 1979, by the Colorado State University Department of Atmospheric Science. The soundings were taken at 1854 GMT (1254 MDT) and 2220 GMT (1620 MDT). Full wind barb is 10 m/s.

flow situations than for SW. Hence, the NW flow scenario of the summer of 1979 seemed to suggest that a synoptic scale environment, favorable for the development of tornadoes, was created; and this NW flow synoptic-scale regime was apparently a direct result of the circulation of the westerlies around the Northern Hemisphere for the summer of 1979.

3. Conclusion

The composite charts for the surface and selected constant pressure surfaces have demonstrated that an environment favorable for the development of tornadoes over Wyoming can result from either SW or NW flow. Moreover, the formation of this environment is linked to the circulation of the Northern Hemispheric-scale westerlies. In essence, the principle of the "forecast funnel" technique of focusing first on the large-scale and then stepping down to the synoptic- and mesoscale has been highlighted in this study (Snellman, 1982). The positioning of the middle- and upper-tropospheric ridge over the western and central Rockies during July and August of 1979 was believed to be a major contributing factor to producing the anomalous number of tornadoes over eastern Wyoming.

Far too often forecasters are concerned (and rightly so) with the mesoscale and synoptic-scale events, which can be overwhelming on critical days. But the link to the large-scale, as is evident in this analysis, can be critical to setting the stage in Wyoming for extended severe weather events.

Extensions of this study are planned which will (1) quantify the advections of vorticity and temperature discussed in this paper, and (2), quantify the forcing from the Northern Hemispheric-scale dynamics to developing a severe weather environment over Wyoming. The authors believe this may be particularly significant in this state due to the orographic uniqueness and climatological propensity toward creating a severe weather environment.

4. Acknowledgements

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