SOME CLIMATOLOGICAL AND SYNOPTIC ASPECTS OF SEVERE WEATHER DEVELOPMENT IN THE NORTHWESTERN UNITED STATES

Eric C. Evenson and Robert H. Johns*

National Weather Service
National Severe Storms Forecast Center
Kansas City, Missouri

Abstract

This study examines severe convective storms (those producing either 3/4 inch in diameter or greater hail, wind gusts equal to or greater than 50 knots, or tornadoes) occurring in that portion of the northwestern United States extending from Washington and Oregon through Idaho into the western portions of Montana and Wyoming. The climatology of severe weather events in this region reveals that the frequency of occurrence is greatest near the Continental Divide with the frequency progressively decreasing towards the Washington and Oregon coasts. Compared with other portions of the United States (e.g., the Great Plains), the frequency is relatively low. However, the data reveal that within the region, significant severe weather episodes (SSWEs) that are particularly destructive, and/or affect relatively large areas occur about twice a year. To aid forecasters in the anticipation of SSWEs in the northwestern United States, composite charts displaying common patterns and parameter values have been prepared.

1. Introduction

Severe convective storms[1] are not as common over the northwestern United States as in other parts of the country (e.g., the Great Plains region). However, severe convective storms do occur in this region, and in certain situations can be quite widespread and destructive. Determining days when severe thunderstorms are a significant threat in this region is a challenge for operational meteorologists. Thus, a better understanding of the synoptic and thermodynamic conditions that are associated with significant episodes of severe weather in the northwestern United States is needed to aid meteorologists in forecasting such events.

This study examines the climatology of severe weather events occurring in the northwestern United States. Further, significant severe weather events are identified, and the associated meteorological conditions are examined to determine common synoptic patterns and parameter values.

2. Methodology

For this study, the northwestern United States is defined as the following area: Washington, Oregon, Idaho, and the western portions of Montana and Wyoming (Fig. 1). The eastern boundary across Montana and Wyoming is roughly 50 to 100 miles east of the Continental Divide, and was selected to allow for those severe weather episodes that commence west of the Divide but produce some reports immediately to the east. In general, the eastern boundary was placed near the divide to delineate between different convective environments. For example, the eastern portions of Montana and Wyoming are typically affected by higher concentrations of low-level moisture, and the upslope flow lifting mechanism (Doswell 1980) is usually more clearly defined.

To aid in developing a severe weather climatology for the study region, both *Storm Data* and the SVRPLOT data analysis program (Hart 1993) were utilized to collect and analyze severe weather events for the period from 1955 through 1993. Further, events from this data set were systematically examined to identify significant severe weather episodes (SSWEs).

For this study, a SSWE is defined as any of the following:

1) A severe weather episode where 10 or more severe weather events occur in the study area during a 24-hour period beginning at 1200 UTC.
2) A severe weather episode with 5 or more severe weather events in the study area during a 24-hour period beginning at 1200 UTC, including at least one tornado of F3 or greater intensity.
3) A severe weather episode in which the *Storm Data* description suggests a widespread severe weather event had occurred in the study area even though the specific severe weather report criteria in either 1) or 2) are not met (e.g., a generalized entry indicating that numerous trees were blown down and/or large hail had occurred over a large portion of a state or over portions of several states).

Johns and Doswell (1992) have noted that composite analyses are useful in identifying basic meteorological patterns and parameters related to the development of severe local storms. Two types of composite charts have been constructed for use in this study. The parameter field composite chart displays the composite pattern of a single parameter field (e.g., 700-mb temperatures) for a number of cases. A more complex composite analysis is the ''severe weather mean composite chart''. By using symbols, this chart displays the mean position of multiple meteorological features at various levels of the atmosphere from a number of cases. This synthesis allows one to obtain a three-dimensional picture of the conditions associated with severe weather development.

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*Current affiliation: National Weather Service, Storm Prediction Center, Norman, Oklahoma.

[1] Severe convective storms are defined as those that produce hail 3/4 of an inch in diameter or greater, wind gusts of 50 knots or greater or convectively induced wind damage, and/or tornadoes.

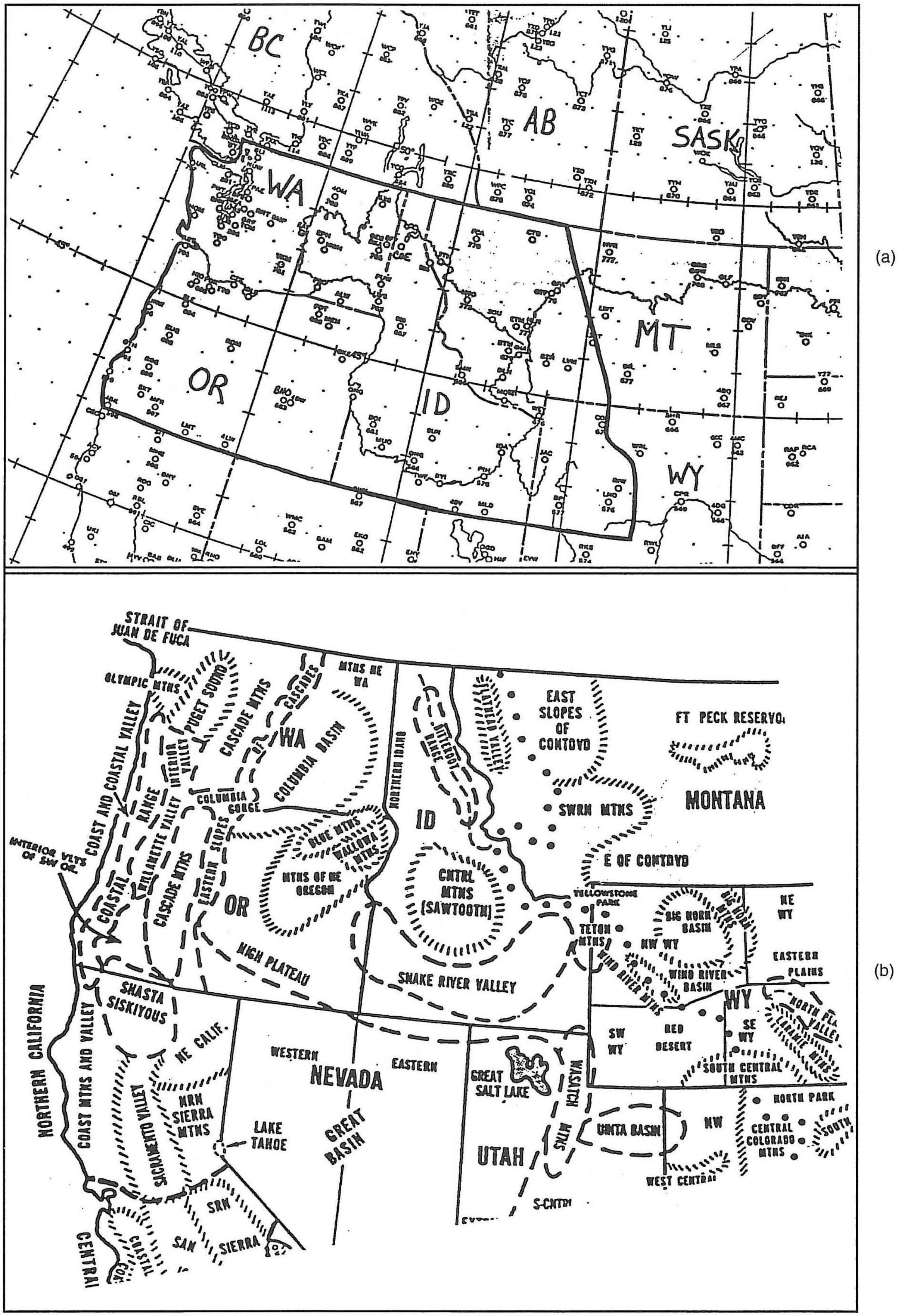

Fig. 1. (a) area within solid black lines denotes study area and is defined in this paper as the northwestern United States while (b) shows important topographical features within the study area.

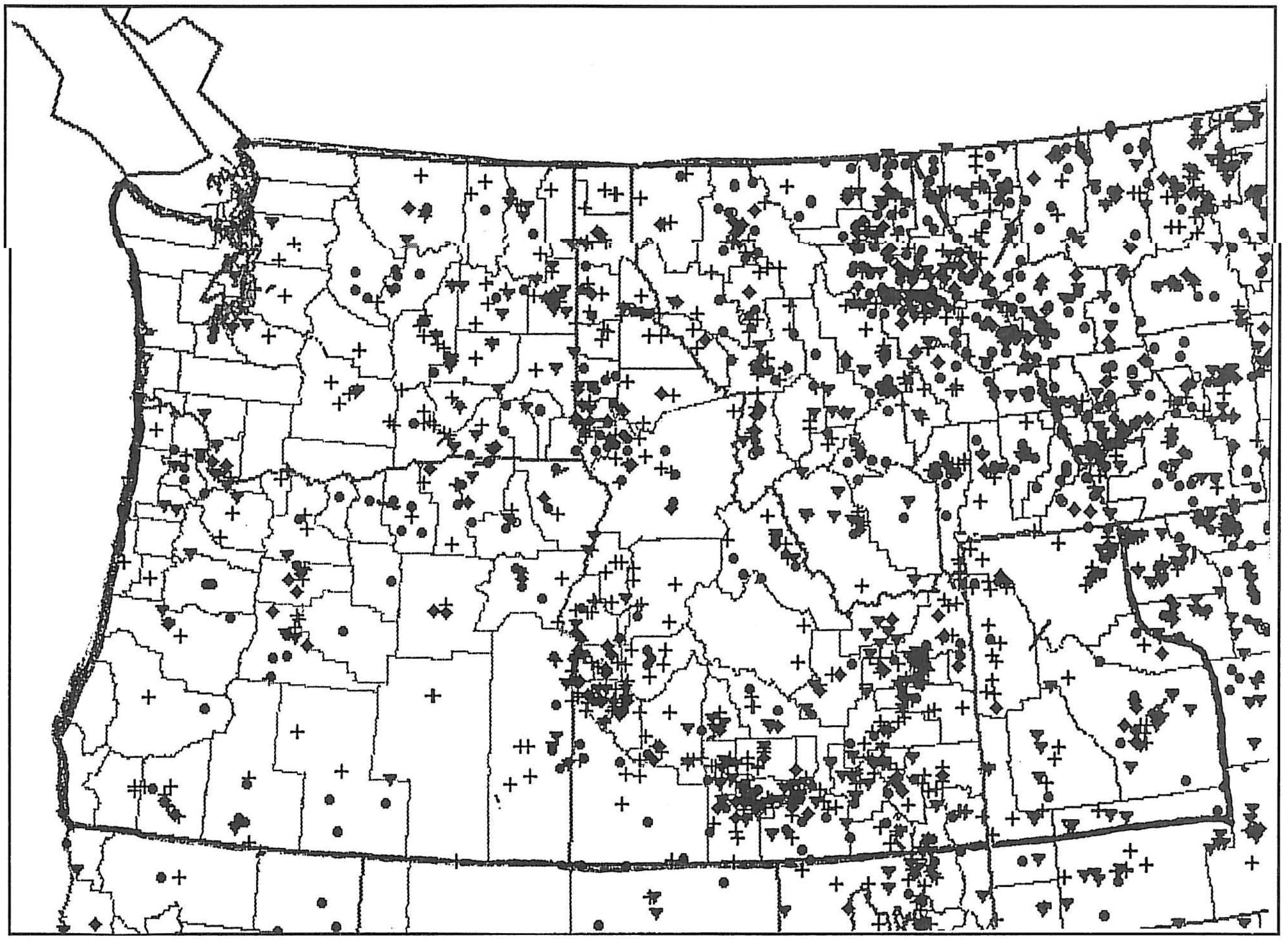

Fig. 2. Plot of all severe weather reports during each March through September period from 1955 through 1993. Triangles represent tornadoes while straight lines indicate tornado tracks. Dark circles indicate hail reports while the cross symbol represents wind gusts or damage. Diamond shapes indicate hail and wind damage reported at the same location.

3. Climatology

a. All severe weather events

During the March-September[2] periods from 1955 through 1993, over two thousand (2,133) severe weather events were reported in the study area (Fig. 2). During this 39-year period, there were 817 reports of severe weather in Idaho and 766 in western Montana. The number of reported events is considerably less in Oregon (216 reports), western Wyoming (184 reports), and Washington (150 reports). The low number of reports in Wyoming can partly be attributed to the fact that this is the smallest subdivision of the study area. Examination of the distribution of reports in Fig. 2 indicates that, in general, the frequency of severe weather decreases as one progresses westward from the Continental Divide to the Washington and Oregon coasts.

Local variations in report frequency on Fig. 2 suggests that the highest concentrations of reports are closely correlated with the highest density of population (McNulty 1981). For example, in Idaho the primary concentration is across the southern portion of the state in the Snake River valley (Fig. 1b). Other concentrated areas include the Lewiston and Coeur d'Alene areas of northern Idaho. Note there is a distinct minimum in frequency over central Idaho (Fig. 2), where population is limited due to the existence of the Sawtooth mountains (Fig. 1b). Mountainous terrain exists in other areas of the study region and these areas also show a relative minimum of severe weather reports.

Three fourths of the total number of reports in the data set occur during the summer months of June (27%), July (29%) and August (19%). A state by state breakdown of the type and number of severe weather reports in the northwestern United States for the March-September period from 1955 through 1993 is illustrated in Fig. 3. The most common type of event is convective wind gusts (or damage) making up over half (53%) of the total number of reports. Large hail comprises 34% of all reports with tornadoes accounting for 13%. The frequency of large hail appears to decrease rapidly as one goes west from the Continental Divide region to the Pacific Ocean. Over one-half (57%) of all hail reports occurred over Montana and Wyoming with 28% over Idaho and only 15% over Washington

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[2] This time period was chosen since 98 percent of all severe weather reported in the region occurred during these months. Only 52 reports (2 percent) of severe weather occurred during the fall and winter months from October through February.

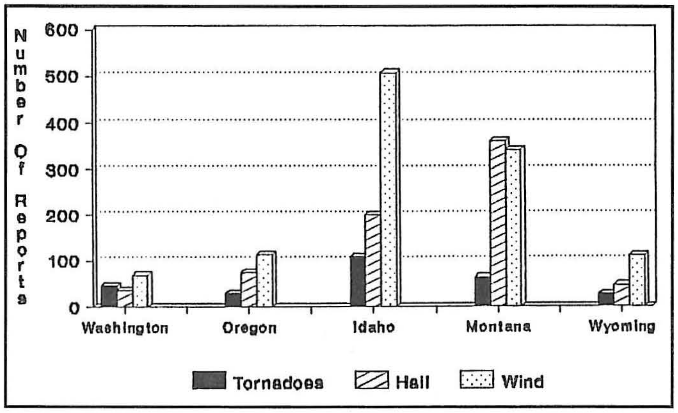

Fig. 3. Type and number of severe weather reports in the northwestern United States for the March–September periods from 1955 through 1993.

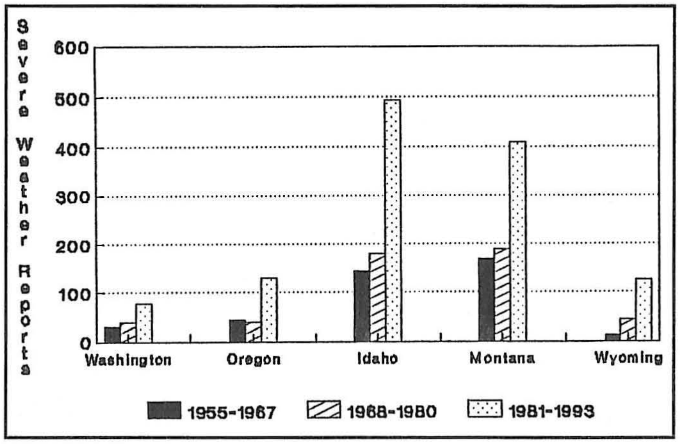

Fig. 4. Severe weather reports in three 13-year intervals for the March–September periods from 1955 though 1993.

and Oregon. This frequency distribution is likely associated with greater amounts of moisture and instability that usually exist further east toward the Continental Divide during the warm season.

A comparison of the number of severe weather reports in three 13-year intervals (1955–1967, 1968–1980 and 1981–1993) for the March-September period is shown in Fig. 4. Note that over 50% of all reports in each state were reported in the latest 13-year period, 1981–1993. Wyoming showed the greatest increase with 68 percent of all severe weather events reported in the latest period.

b. Significant Severe Weather Episodes (SSWEs)

Using the criteria defined in Section 2, 27 SSWEs were identified during the 39 year period (Table 1). Of this total, 22 cases met criterion 1) while three episodes met criterion 3). Only two episodes, which were associated with the Vancouver, Washington F3 tornado on 5 April 1972 (Hales 1994) and the Teton Wilderness F4 tornado in Wyoming on 21 July 1987 (Fujita 1989) met criterion 2).

The data set suggests that SSWEs are confined to the spring and summer months (April-September; see Fig. 5). Further, one-third of the SSWEs (9) were reported during the month of

Table 1. Significant Severe Weather Episodes

No.	Date	States	Reports T/W/A	D/I	Significant Events
1	9/4/60	OR/ID/MT	—	0/0	Widespread wind damage
2	6/27/70	ID/MT/WY	0/16/1	0/0	80-100 mph winds in Montana
3	4/5/72	WA/OR	5/0/0	6/301	Two F3 tornadoes in Washington
4	6/22/73	ID/MT	—	0/0	Widespread wind damage
5	6/23/75	ID/MT	1/-/-	0/1	One F2 tornado and wind damage
6	7/14/75	WA/ID	0/3/11	0/0	2-3″ diameter hail near Reubens, ID
7	6/28/82	ID/MT	1/4/6	0/0	30 million dollars damage in Helena, MT due to 3″ diameter hail
8	8/9/82	WA/OR	1/9/2	0/0	Winds estimated to 100 mph in NE OR
9	8/11/82	ID/MT	0/8/8	0/0	
10	7/6/83	ID/MT/WY	0/14/1	1/2	80-100 mph winds reported in ID, MT, and WY
11	7/9/83	ID	0/7/7	0/0	
12	8/24/84	ID/MT	1/8/6	0/0	
13	4/30/87	ID/MT/WY	0/16/2	0/0	80-100 mph winds in western MT
14	6/15/87	ID/MT/WY	1/27/2	0/6	$10 million worth of damage in Nampa, ID
15	7/21/87	OR/ID/WY	2/5/2	0/0	F4 tornado in the Teton Wilderness
16	6/28/88	MT	0/0/13	0/0	Baseball size hail in western MT
17	5/10/89	ID/MT/WY	0/11/1	0/0	
18	9/17/89	ID/MT	1/13/0	0/4	Extensive wind damage in SE ID
19	8/20/90	WA/OR/ID/MT	0/5/7	0/0	
20	8/6/91	WA/OR	0/9/7	0/5	80-100 mph winds in NE OR with 2″ diameter hail
21	9/10/91	ID/WY	1/3/6	0/0	
22	4/17/92	ID	0/24/1	0/0	
23	6/12/92	ID/MT	1/9/2	0/0	
24	6/28/92	WA/OR/ID	0/10/3	0/0	
25	7/22/92	OR/ID/MT	2/6/3	0/0	
26	5/3/93	OR/ID	1/10/0	0/4	Extensive wind damage in SE ID
27	6/21/93	OR/ID/MT	3/11/0	0/1	97 mph winds at Choteau, MT

Note: Reports column denotes number of tornadoes(T)/wind(W)/ hail(A) events while D/I column denotes number of deaths/ injuries.

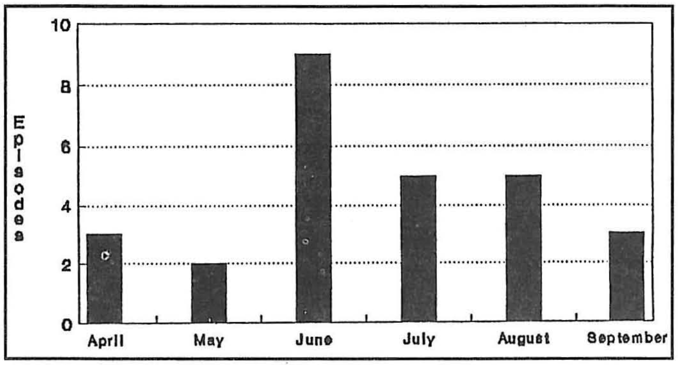

Fig. 5. Monthly distribution of SSWEs during the period from 1955 through 1993.

June. The distribution of SSWEs for the three 13-year periods discussed earlier shows that one SSWE was reported between 1955–1967, five SSWEs from 1968–1980 and 21 SSWEs from 1981–1993. Therefore, about eighty percent (78%) of the SSWEs were reported in the last 13-year period! The higher number of severe weather reports and resultant SSWEs during the latest 13-year period are likely the result of several factors including increased population, a heightened meteorological awareness from the public, and improved National Weather Service (NWS) verification and storm reporting procedures (Hales 1987). Given this evolution in improved reporting, it appears the data supports a frequency of SSWEs in the study area of close to two per year. With the improved detection capabilities of the WSR-88D radars currently being installed throughout the region, it is likely to be found that the actual frequency distribution is greater than two per year.

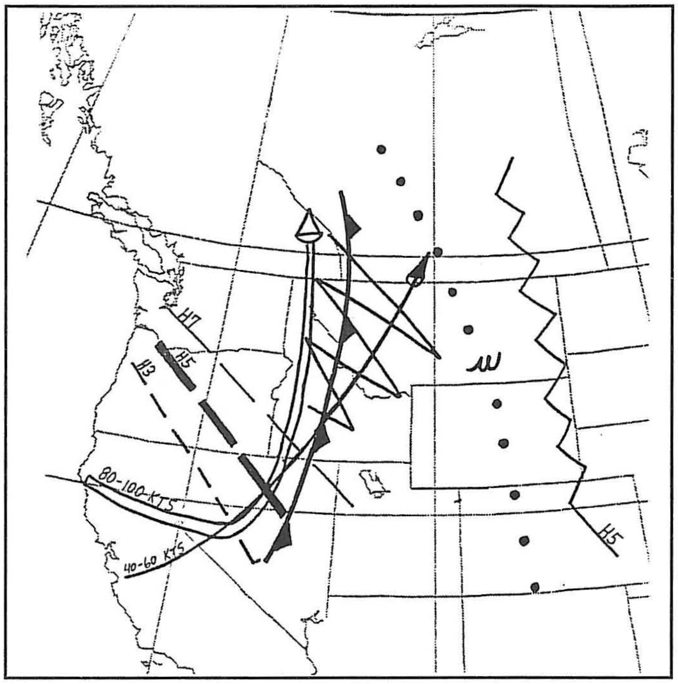

Fig. 6. Mean composite chart at 0000 UTC on the day of occurrence for Pattern A SSWEs affecting Idaho, Montana, and Wyoming. Dotted line denotes 850-mb thermal ridge. Frontal boundary is position of 700-mb front. Long dashed lines labeled H7, H5, and H3 indicate trough axis positions at 700, 500, and 300 mb. Thin line with arrow indicates the jet axis at 500 mb while thick line with arrow represents the jet axis at 300 mb. Broad zigzag line shows an area of 500 and 300-mb diffluence while 500 and 300-mb ridge axes are denoted by long, north-south oriented narrow zigzag line.

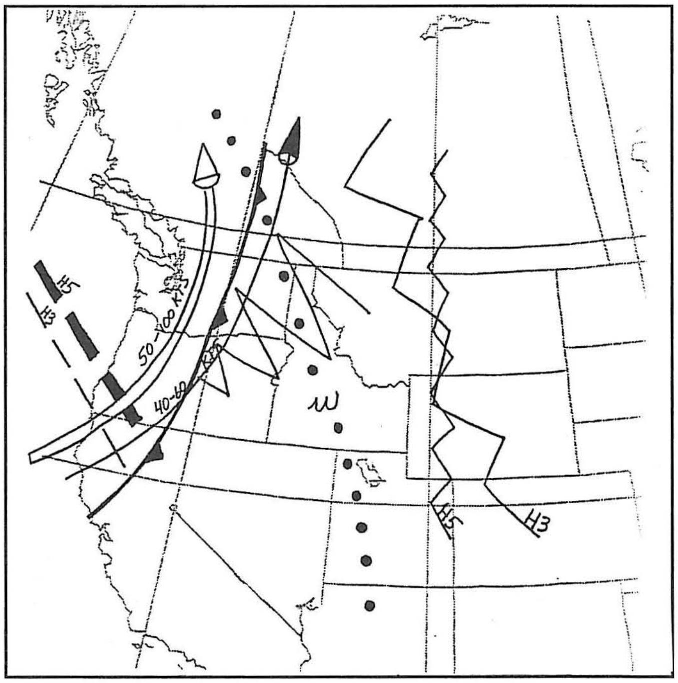

Fig. 7. As in Fig. 6, except for Pattern A SSWEs affecting Oregon and Washington.

4. Synoptic and Thermodynamic Conditions Associated with SSWEs

Meteorological features associated with each of the individual SSWEs in the data set were examined to determine common patterns. This examination suggests two common synoptic patterns based on mid and upper-level trough orientation:

1) Pattern A—the "negative tilt" pattern, and
2) Pattern B—the "trough axis" pattern.

To better assess the relative locations of meteorological features associated with these patterns to the area of severe weather occurrence, the study region was divided into two subregions: 1) Idaho, western Montana and western Wyoming (ID/MT/WY), and 2) Oregon and Washington (OR/WA). Pattern A is the most common synoptic pattern associated with SSWEs occurring in the northwestern United States (21 cases) and it has been observed in both subregions (Figs. 6 and 7). Pattern B is less frequent (5 cases) and it has been observed in the ID/MT/WY subregion only (Fig. 8). Meteorological features associated with one SSWE, the tornado episode of 5 April 1972, which occurred in the OR/WA subregion, fits neither Pattern A nor Pattern B. Further, it is the only case in the OR/WA subregion that affected areas west of the Cascade Mountain range. This case is discussed further in Section 4b.

In the interior northwestern United States (i.e., east of the Cascade Mountains) during the warmer months of the year moisture values are usually low and inverted-V soundings are typically present (Beebe 1955; Barnes and Newton 1986). How-

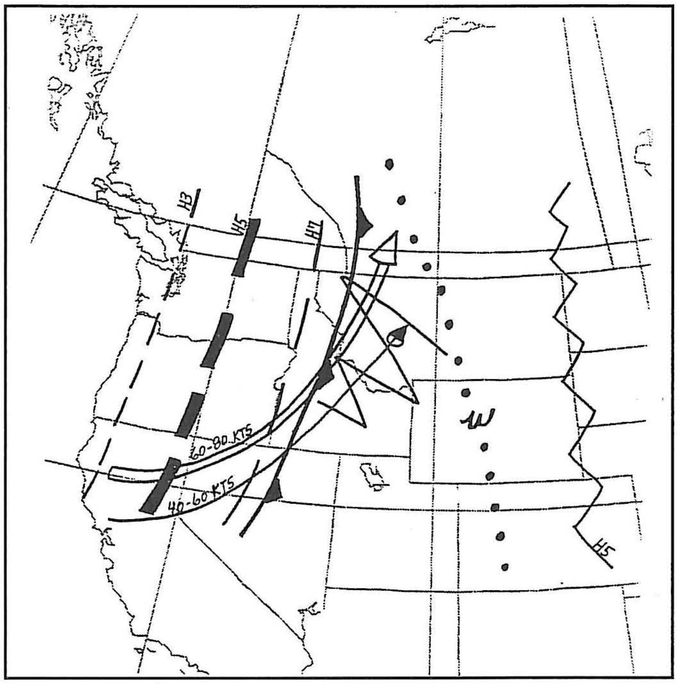

Fig. 8. As in Fig. 6, except for Pattern B SSWEs affecting Idaho, Montana, and Wyoming.

ever, the air mass associated with SSWEs in this region is often modified with generally higher moisture values in the lower portions of the troposphere. Surface dew points are typically 45°F or greater in the area of occurrence before the event.

In many of the SSWE cases, moisture values increase downward from the mid levels with time (e.g., Fig. 9). This moisture increase appears to result from both advection and mixing. Northward transport of moisture into the region typically occurs in the southerly to southwesterly flow ahead of the upper trough and is typically concentrated in the vicinity of the frontal band at 700 mb. At times, particularly later in the warm season, this moisture transport appears to be a northward extension of the southwest monsoon (Hales 1974). The northward transport is greatly facilitated by the strongly backed (southerly) flow ahead of a negatively-tilted, upper-air, low pressure trough (Pattern A). This helps to explain why Pattern A is the most common upper-air pattern associated with severe thunderstorm development in the northwestern United States.

Because of the high mountain ranges in the western United States, the northward transport of moisture into the region is most effective at mid levels. Once mid-level moisture has advected into the region, a significant contribution to low-level moisture appears to result from mid-level moisture mixing downward into the relatively deep mixed layer typical of the region. One of the authors (Evenson) and forecasters in the region (personal communication) have also noted that precipitation from high-based convection (cloud bases generally between 600 and 500 mb) commonly occurs in the area during the 24-hour period preceding an SSWE event. This precipitation is usually light (less than one-quarter in. at the surface), but can serve to redistribute moisture into the lower portions of the troposphere, enhancing potential instability.

a. Idaho, western Montana, and western Wyoming

Examination of meteorological features associated with the 22 SSWEs affecting this subregion reveals that 17 cases are associated with Pattern A, the ''negative tilt'' pattern. The remaining 5 cases are associated with Pattern B, the ''trough axis'' pattern.

1) Pattern A (negative tilt pattern) in ID/MT/WY subregion

For the ID/MT/WY subregion cases, this pattern typically features a long-wave trough position in the eastern Pacific Ocean (not shown) with a mid-level ridge axis extending from central Saskatchewan southward into eastern Wyoming (Fig. 6). A negatively-tilted, short-wave trough[3] extending from 700 mb up through 300 mb is lifting northeastward into the subregion from the west central United States. Significant 300-mb, 12-hour height falls, as large as 80 to 100 meters, are associated with the short-wave trough. South to southwesterly flow aloft prevails across the subregion ahead of the trough with pronounced diffluence indicated at both the 500 and 300-mb levels. A 500-mb jet axis of 40 to 60 kt winds typically extends along a band from west central Nevada into west central Montana while a jet axis of 60 kt or greater winds at 300 mb extends from western Nevada north northeastward into northern Idaho. In nearly half of the cases the 300-mb wind maxima were between 80 and 100 kt.

The precursor 500-mb thermal field (at 1200 UTC) displays a warm axis across central Montana with a cold axis somewhere off the west coast (Fig. 10). Colder temperatures (less than −15°C) are confined to an area from the central portions of Washington and Oregon westward. During the 12-hour period between 1200 and 0000 UTC temperatures cool slightly (1 to 2°C) over central and southern Idaho as a weak thermal trough axis moves northeastward into the area. However, during the same 12-hour period, temperatures warm slightly, on average, over western Montana and western Wyoming. This suggests that destabilization owing to cooling aloft is typically not a major factor with these cases.

Probably the most significant contributions to destabilization are: 1) the increase in moisture values in the lower half of the troposphere from moisture transport, mixing and precipitation moistening, and 2) diurnal heating. Surface dew points are typically in the 50 to 60°F range ahead of the cold front with 45°F being the lower limit. A relatively warm north northwest to south southeast oriented 850-mb thermal ridge (temperatures in the 18–20°C range) is present ahead of the cold front (Fig. 11) and strong diurnal heating typically adds to destabilization in the warm sector. Surface-based CAPE values are typically between 1000 and 2000 J Kg^{-1} in the subregion at 0000 UTC, and in some instances values reach 2500 J Kg^{-1}. Surface-based lifted index values (SBLIs) are relatively stable in the precursor soundings (at 1200 UTC), ranging from +2 to −2. However, by 0000 UTC instability has increased significantly. SBLI values by that time typically range from −3 to −6, with a few values reaching −8.

All of the 17 Pattern A cases in this subregion are associated with a cold front, with severe thunderstorm development typically occurring in the vicinity or ahead of the front. However, surface reflections of fronts in the western United States are

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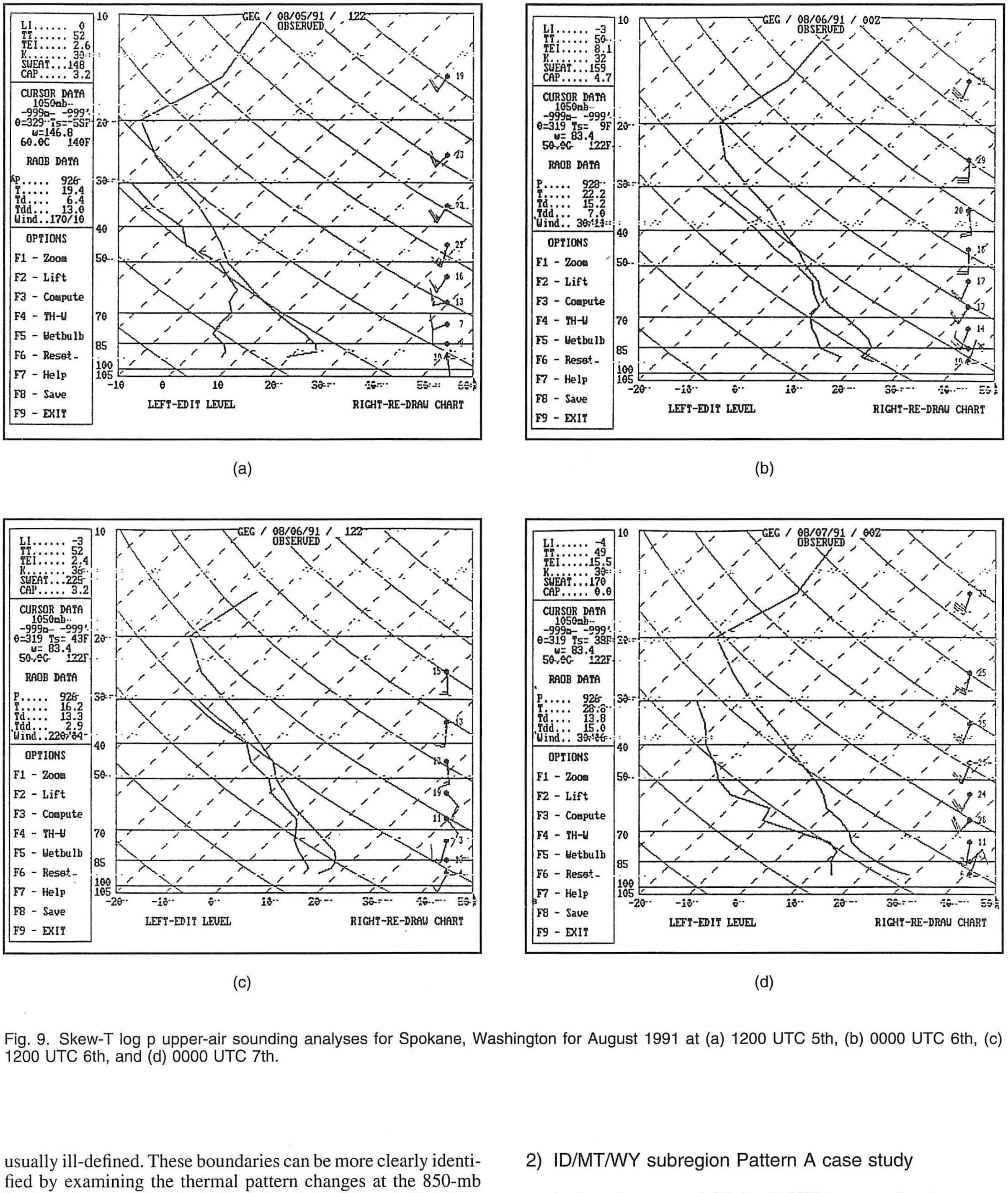
[3] A negatively tilted trough is one whose axis in not meridionally oriented, but leans toward the west with increasing latitude (Bluestein 1992).



LI...... 0
TT...... 52
TEI..... 2.6
K....... 30
SWEAT...148
CAP..... 3.2

CURSOR DATA
1050mb
-999m -999'
θ=329 Ts=-55F
w=146.8
60.0C 140F

RAOB DATA
P..... 926
T..... 19.4
Td.... 6.4
Tdd... 13.0
Wind..170/10

(a)

LI...... -3
TT...... 50
TEI..... 8.1
K....... 32
SWEAT...159
CAP..... 4.7

CURSOR DATA
1050mb
-999m -999'
θ=319 Ts= 9F
w= 83.4
50.0C 122F

RAOB DATA
P..... 928
T..... 22.2
Td.... 15.2
Tdd... 7.0
Wind.. 30/13

(b)

LI...... -3
TT...... 52
TEI..... 2.4
K....... 36
SWEAT...225
CAP..... 3.2

CURSOR DATA
1050mb
-999m -999'
θ=319 Ts= 43F
w= 83.4
50.0C 122F

RAOB DATA
P..... 926
T..... 16.2
Td.... 13.3
Tdd... 2.9
Wind..220/04

(c)

LI...... -4
TT...... 49
TEI.....15.5
K....... 30
SWEAT...170
CAP..... 0.0

CURSOR DATA
1050mb
-999m -999'
θ=319 Ts= 38F
w= 83.4
50.0C 122F

RAOB DATA
P..... 926
T..... 28.8
Td.... 13.8
Tdd... 15.0
Wind.. 30/26

(d)

Fig. 9. Skew-T log p upper-air sounding analyses for Spokane, Washington for August 1991 at (a) 1200 UTC 5th, (b) 0000 UTC 6th, (c) 1200 UTC 6th, and (d) 0000 UTC 7th.

usually ill-defined. These boundaries can be more clearly identified by examining the thermal pattern changes at the 850-mb level, and especially the 700-mb level (Williams 1972). The composite 850 and 700-mb temperature fields associated with Pattern A cases in the ID/MT/WY subregion (Figs. 11 and 12) suggest that a cold front usually extends from northwestern Montana across central Idaho into northeastern Nevada at 0000 UTC (Fig. 6).

2) ID/MT/WY subregion Pattern A case study

On the afternoon of 30 April 1987, severe thunderstorms producing primarily damaging winds struck western and northern Idaho and northwestern Montana (Fig. 13). Winds estimated between 80 and 100 mph in northwestern Montana caused extensive damage. Damaging winds were also reported across southern Idaho as well and into portions of western Wyoming.

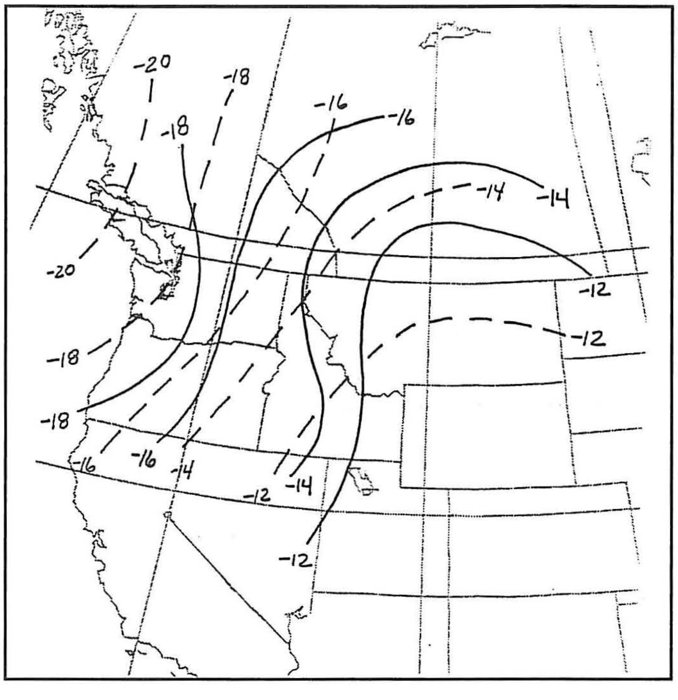


Fig. 10. Average 500-mb temperatures (°C) at 1200 UTC (dashed) and 0000 UTC (solid) during Pattern A SSWEs in Idaho, Montana, and Wyoming.

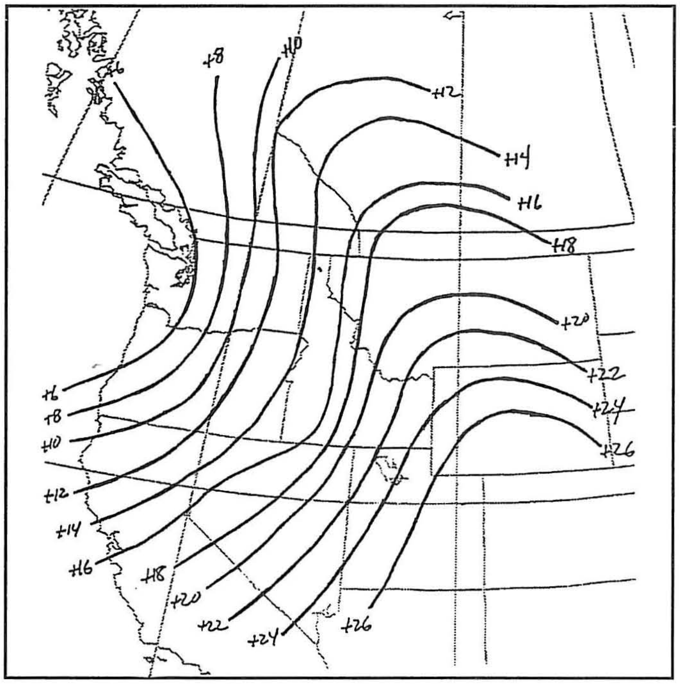


Fig. 11. Average 850-mb temperatures (°C) at 0000 UTC during Pattern A SSWEs in Idaho, Montana, and Wyoming.

The severe weather composite chart for the 30 April 1987 case (Fig. 14) appears to fit Pattern A relatively well. The locations of most features associated with this case are close to those in the mean severe weather composite chart for Pattern A in the ID/MT/WY subregion (Fig. 6). There are a few variations, however. For example, in the 0000 UTC 1 May 1987 case the 500 and 300-mb jet axes downstream from the short-wave trough, are farther west than the mean and there is an easterly component to the flow (Fig. 15). Further, the short-wave trough is moving more northward than northeastward, in part because of the strong ridge over south central Canada. Despite these variations in jet structure and trough movement, large 12-hour (1200 to 0000 UTC) 300-mb height falls are associated with the short-wave trough (from 90 meters at Boise, Idaho to 140 meters at Salem, Oregon). Further, an area of pronounced diffluence at the mid and upper-levels is nearly coincident with the primary area of severe weather occurrence, a signal common to Pattern A cases.

Also typical of Pattern A, the 500-mb temperature changes over the subregion between 1200 and 0000 UTC in the 30 April 1987 case are relatively small. Temperatures remained constant or warmed slightly in Montana and Wyoming, with modest cooling taking place in southwestern Idaho (-2°C at Boise). Diurnal heating contributed to destabilization, particularly over the western portions of Montana and Wyoming where afternoon temperatures reached the upper 70s and lower 80s (°F).

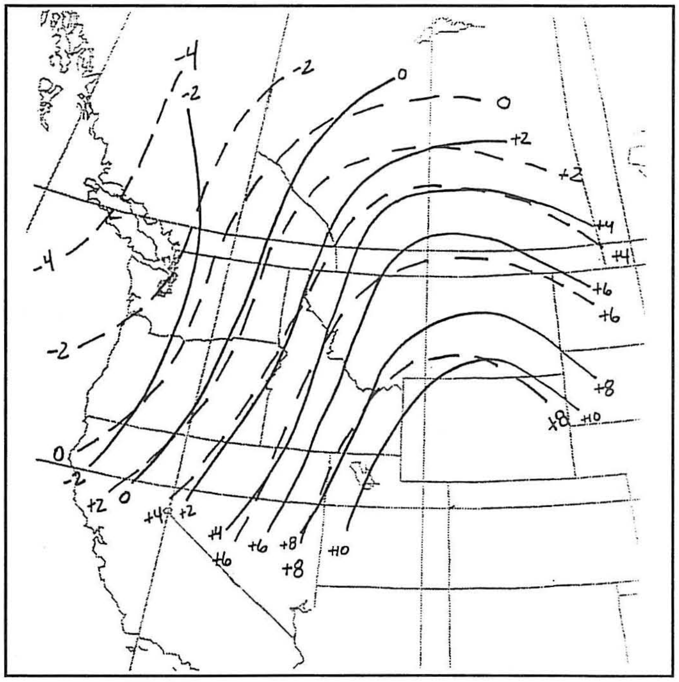


Fig. 12. Average 700-mb temperatures (°C) at 1200 UTC (dashed) and 0000 UTC (solid) during Pattern A SSWEs in Idaho, Montana, and Wyoming.

3) Pattern B (trough axis pattern) in the ID/MT/WY subregion

Pattern B or the "trough axis" pattern differs from Pattern A in that a positively-tilted long-wave trough (at 700, 500 and 300 mb) is propagating eastward across the northwestern states. Since there are only five Pattern B cases in the data set, the composite charts of associated features (Figs. 8, 16, 17, and 18) should be used with caution. Generally, many of the features and their locations are similar to those in Pattern A. These include the 850-mb thermal axis, the 700-mb and 500-mb thermal patterns, the 500-mb wind speeds, the location of the cold front (at 700 mb) and the upper-air ridge axis over the northern

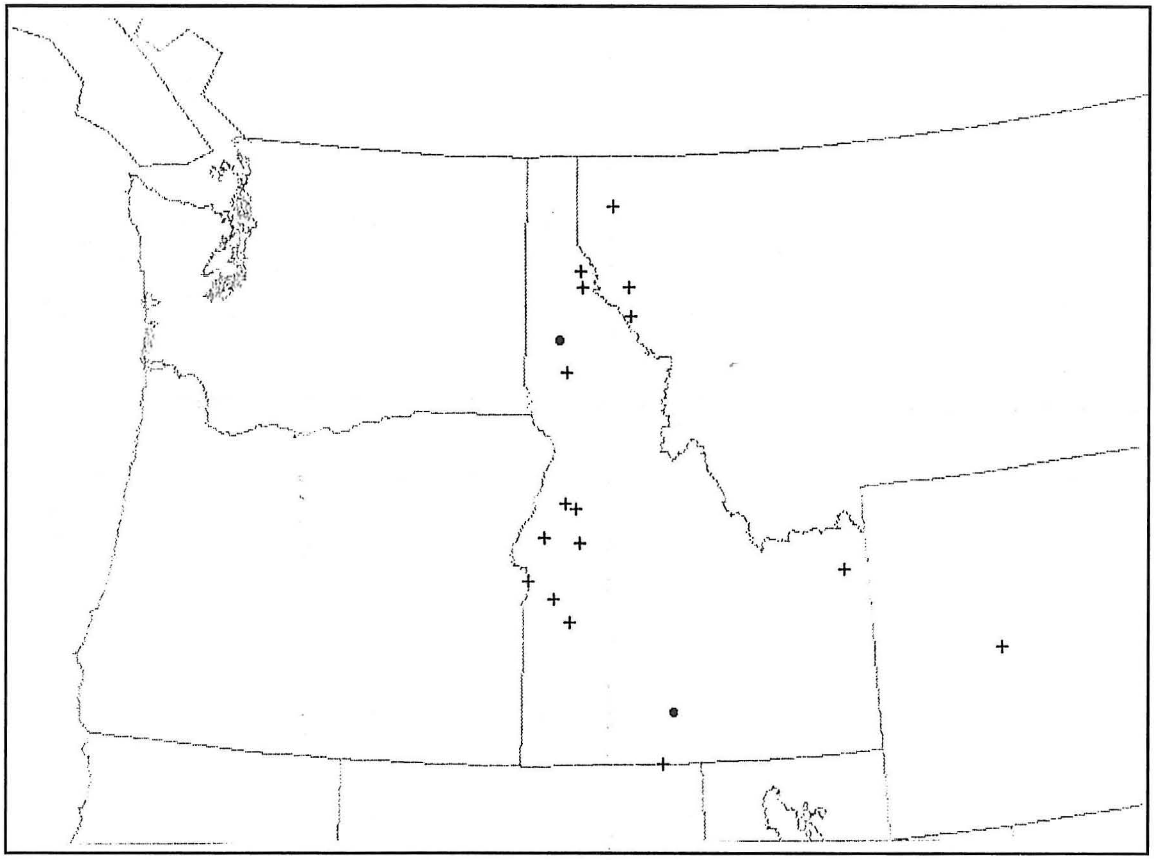


Fig. 13. Plot of all severe weather reports for the 24-hour period beginning at 1200 UTC 30 April 1987. Dark circles indicate hail reports while the cross symbol represents wind gusts or damage.

Plains. Further, cooling aloft over the subregion between 1200 and 0000 UTC is minimal. The severe weather composite chart suggests that there is typically some upper-level diffluence over the subregion, but it appears to be less pronounced than it is with Pattern A. Also, there may be a closed low associated with the mid and upper-level trough in Pattern B cases.

Within the subregion, Pattern B cases are typically associated with weaker instability than Pattern A cases. CAPE and SBLI values at 0000 UTC in Pattern B cases range from 700 to 1500 J Kg^{-1} and -2 to -5, respectively. The weaker instability associated with this pattern results largely from lower values of moisture than is the case with Pattern A cases. Surface dew points ahead of the cold front range from the mid 40s to the lower 50s (°F).

4) ID/MT/WY subregion Pattern B case study

Several clusters of severe thunderstorms producing damaging winds and isolated large hail affected portions of western Montana, southeastern Idaho and western Wyoming on 10 May 1989 (Fig. 19). The storms became severe during the late morning hours, continued through the afternoon and diminished during the evening. Wind gusts reaching 70 and 80 mph were reported in portions of western Montana and southeast Idaho, damaging buildings and felling trees and power poles. Winds blew the roof off a commercial building and hail accumulated to 5 inches in depth in the south central Idaho town of Jerome.

The mid and upper-level flow pattern in this case is basically Pattern B with a positively-tilted long-wave trough moving

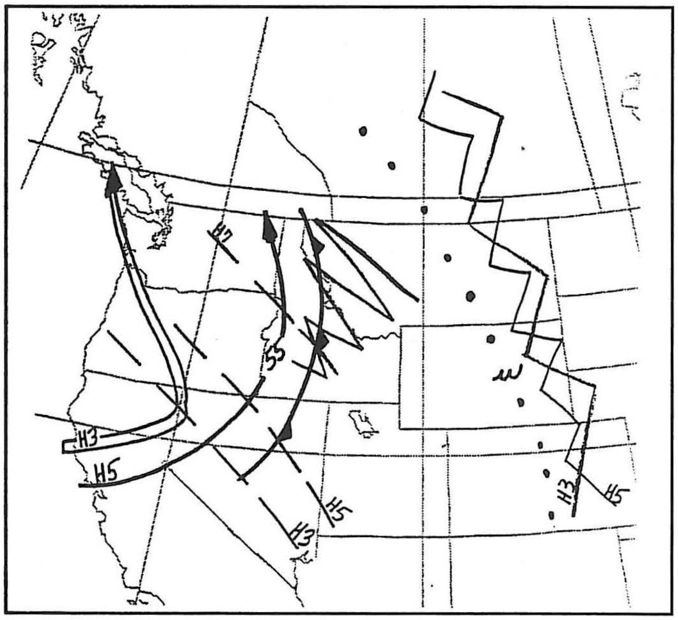
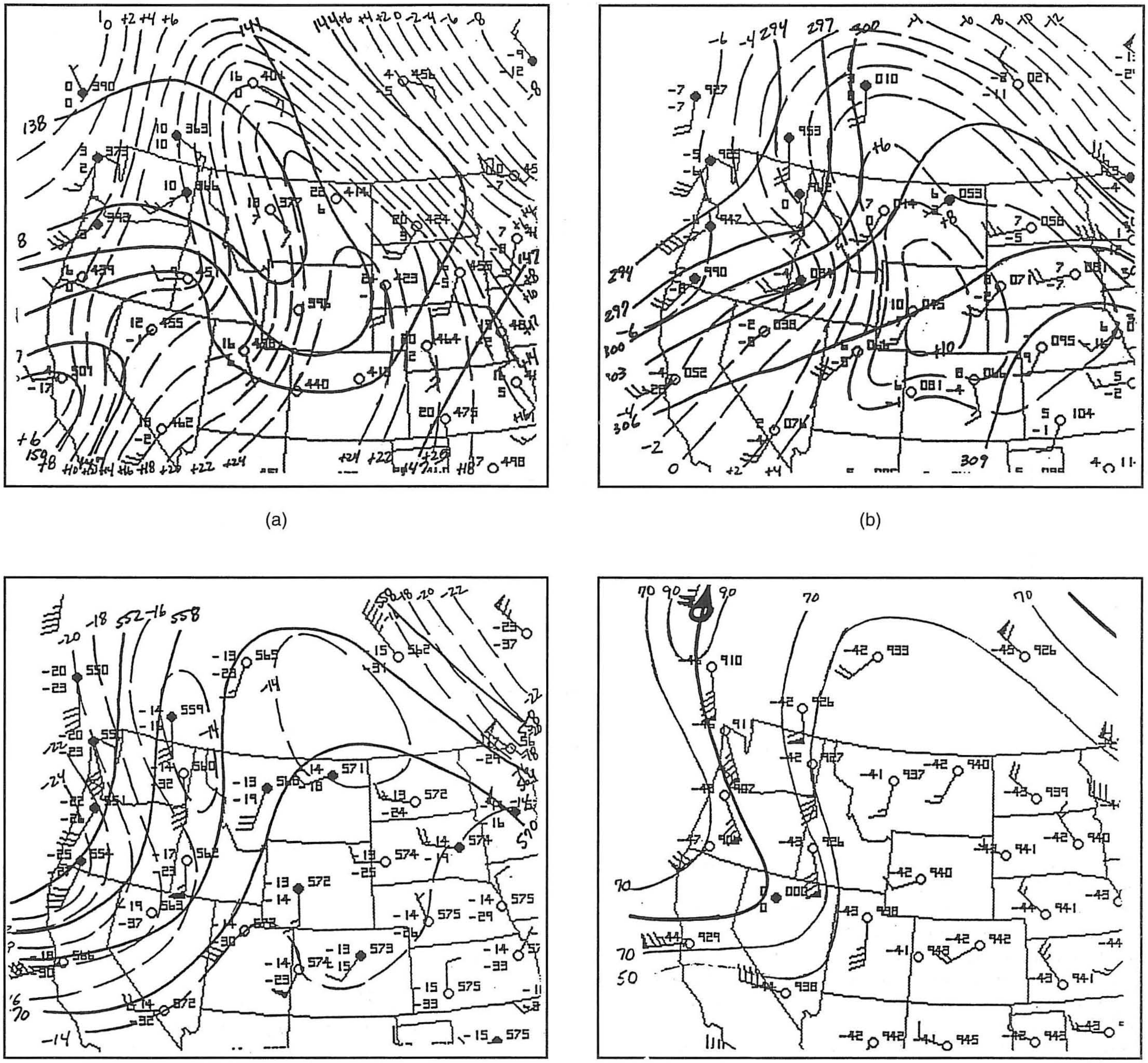


Fig. 14. Composite chart for 0000 UTC 1 May 1987. Symbols same as used in Fig. 6.



(a) (b)

(c) (d)

Fig. 15. Upper-air analyses at (a) 850-mb, (b) 700-mb, (c) 500-mb, and (d) 300-mb levels for 0000 UTC 1 May 1987.

eastward over the western United States (Figs. 20 and 21). However, it does vary from the Pattern B severe weather composite in that there are two distinct short-wave troughs that have come into phase. Consequently, there are two branches to the mid and upper-level jets, and the severe thunderstorm development appears to occur near and to the left of the southern branch 300-mb jet. Any diffluence in the subregion appears to be weak. Further, mid and upper-level wind speeds in the subregion appear to be weaker than the mean.

The low-level (850-mb) thermal ridge remained nearly stationary during the day and extended from southern Saskatchewan southward across eastern Montana into central Wyoming at 0000 UTC (Fig. 21a). A north-south trough axis at 700 mb, initially along the Oregon/Washington coast at 1200 UTC, shifted eastward into the intermountain region during the day and a strong thermal gradient representing the 700-mb front extended from northwestern Montana into southwestern Idaho at 0000 UTC (Fig. 21b). The thermal gradient and 12-hour

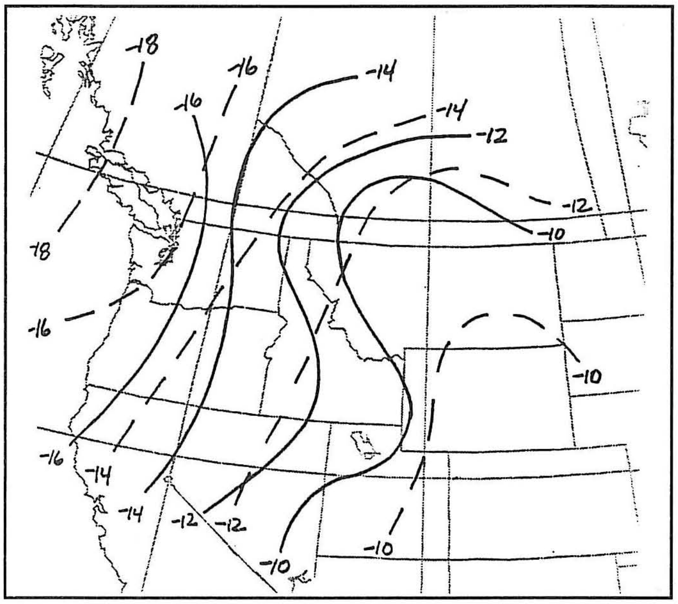


Fig. 16. Average 500-mb temperatures (°C) at 1200 UTC (dashed) and 0000 UTC (solid) during Pattern B SSWEs in Idaho, Montana, and Wyoming.

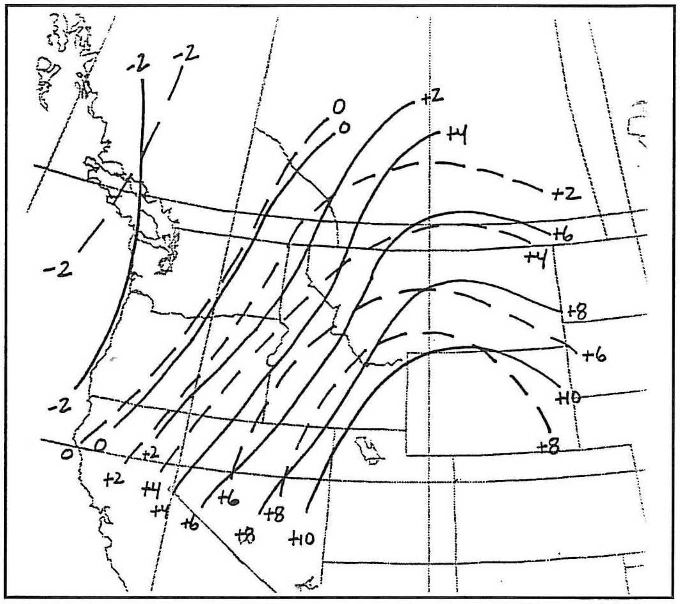


Fig. 17. Average 700-mb temperatures (°C) at 1200 UTC (dashed) and 0000 UTC (solid) during Pattern B SSWEs in Idaho, Montana, and Wyoming.

changes at 500 mb, however, were generally quite weak (Fig. 21c). The only significant cooling occurred at Great Falls, Montana where the 500-mb temperature fell 3°C in the 12-hour period ending at 0000 UTC.

b. Oregon and Washington

Examination of the meteorological features associated with the 5 SSWEs affecting this subregion reveals that 4 cases display Pattern A characteristics. The remaining case (5 April 1972) has some characteristics that fit neither Pattern A nor Pattern B. Because of this, it is discussed separately later in this section and is not included in the composite.

1) Pattern A (negative tilt pattern) in OR/WA subregion

Generally, the Pattern A severe weather composite chart for the OR/WA subregion resembles that of the ID/MT/WY subregion, but with the features shifted westward (Fig. 7). The mid and upper-level short-wave troughs are typically offshore at 1200 UTC and move northeastward into the Oregon/northern California region by 0000 UTC. Because of the sparsity of data offshore, satellite imagery is critical in assessing the orientation and timing of the short-wave trough in these instances.

As the short-wave trough moves into the subregion, temperature changes in the mid levels are typically not large. In the 12-hour period ending at 0000 UTC some cooling may occur over the western portions of both Washington and Oregon while minor warming is likely over eastern Washington (Figs. 22 and 23). Changes are typically less than 2°C at the 500-mb level. The cooling is greater at 700 mb, averaging more than 2°C along coastal sections of Washington and Oregon.

At the 850-mb level, a thermal ridge extends from Utah across Idaho and into southeast British Columbia. Temperature values at Boise, Idaho (BOI) are greater than 25°C and at Spokane, Washington (GEG) greater than 18°C. Maximum afternoon surface temperatures are typically in the 80s and lower 90s (°F). Surface-based lifted index values of −4 or less and CAPE values of 1000 and 2000 J Kg^{-1} are common in the area of severe weather occurrence.

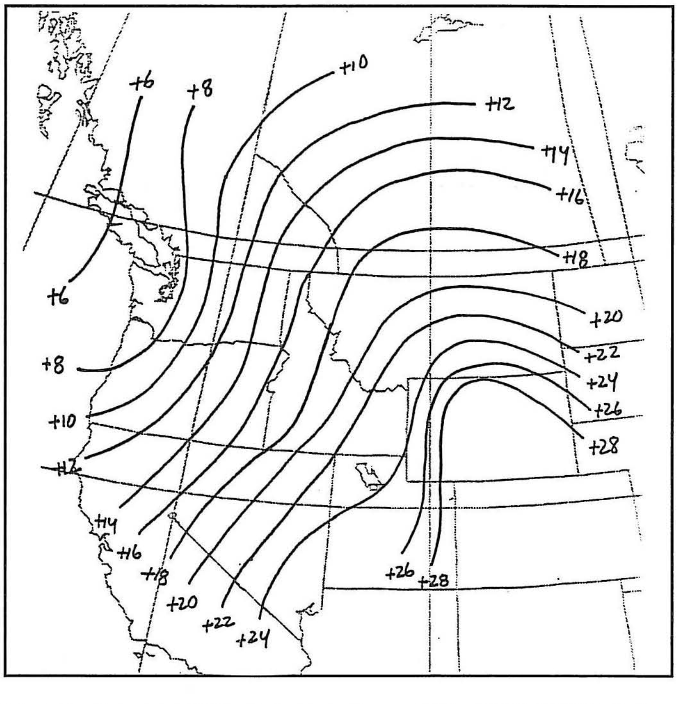


Fig. 18. Average 850-mb temperatures (°C) at 0000 UTC during Pattern B SSWEs in Idaho, Montana, and Wyoming.

2) OR/WA subregion Pattern A case study

Severe thunderstorms producing damaging winds and large hail developed in north central Oregon just east of the Cascade Mountains early on the afternoon of 6 August 1991 (Fig. 24). This activity developed northward into central Washington by late afternoon and spread northeastward over eastern Washington and portions of northeast Oregon during the late afternoon

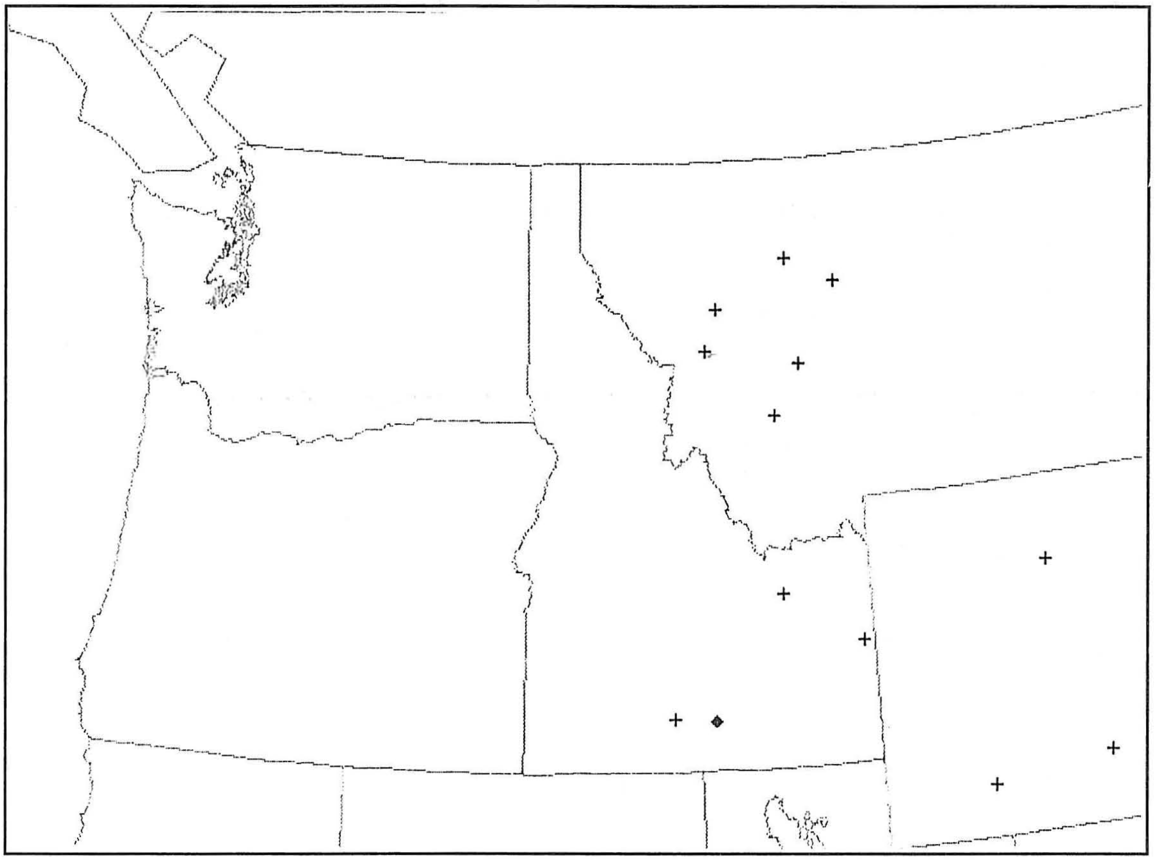


Fig. 19. Plot of all severe weather reports for the 24-hour period beginning at 1200 UTC 10 May 1989. Dark circles indicate hail reports while the cross symbol represents wind gusts or damage. Diamond shapes indicate hail and wind damage reported at the same location.

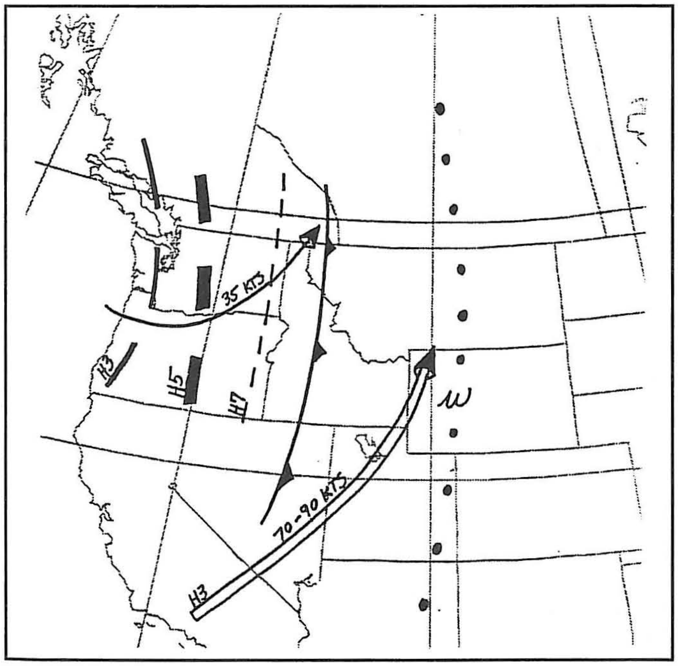
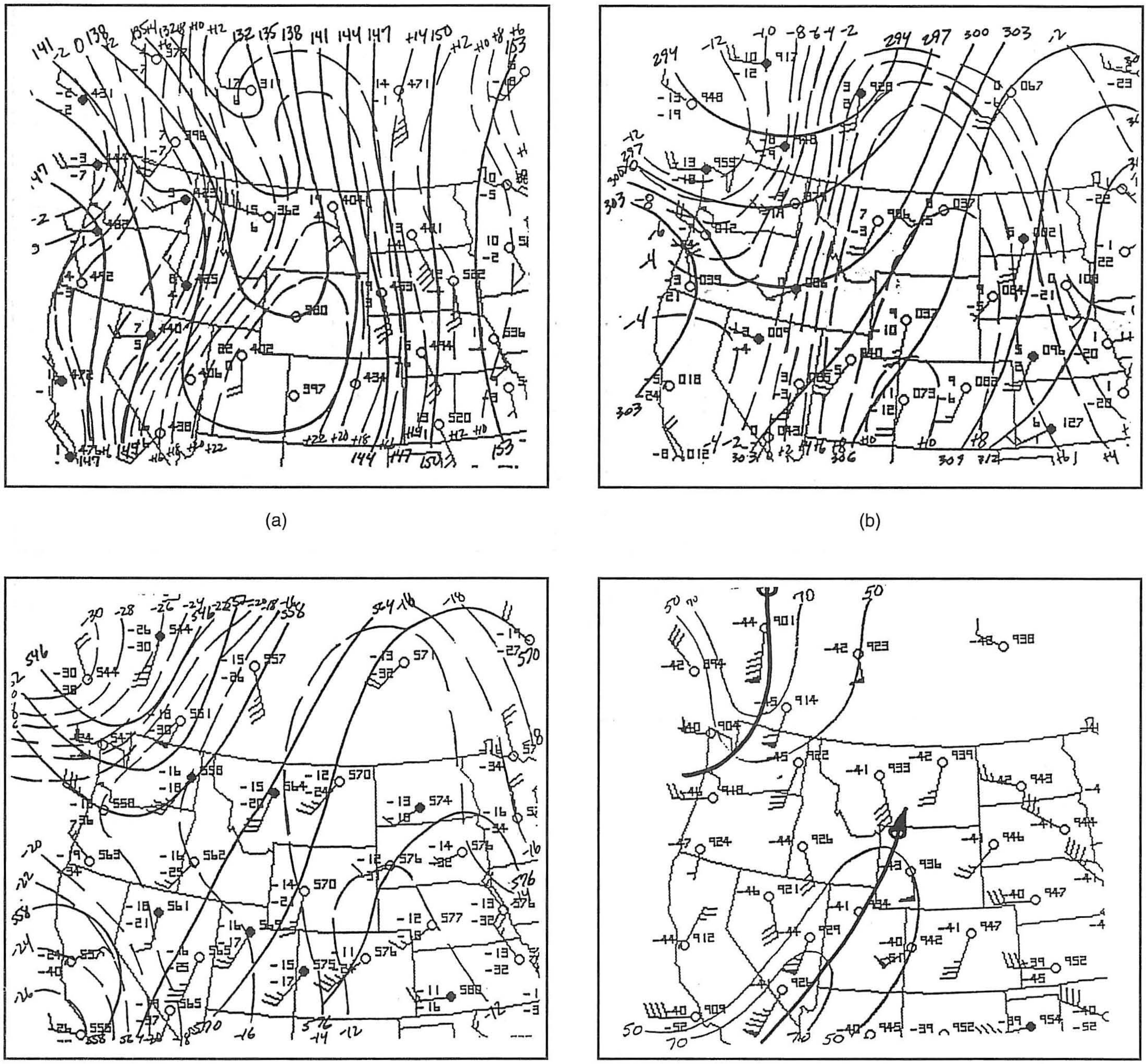


Fig. 20. Composite chart for 0000 UTC 11 May 1989. Symbols used are same as in Fig. 6.

and evening hours. Convective gusts as high as 70 to 90 mph and golfball-size hail were reported at several locations. A gust to 100 mph was recorded at the Umatilla Army Depot in northeast Oregon. Five people were injured when a tent collapsed at the Umatilla County Fair in Hermiston, Oregon and a trailer was picked up and turned upside down by thunderstorm winds in Omak, Washington.

The composite chart for the 6 August 1991 case (Fig. 25) resembles the OR/WA Pattern A mean composite chart (Fig. 7). The primary differences are that in the 6 August case, the short-wave trough is a bit farther west and the upper ridge is farther east than on the mean composite.

Other characteristics of the 6 August 1991 case include, relatively dry warm axes at 850 and 700 mb that extended northward across Idaho and northwestern Montana at 0000 UTC 7 August (Figs. 26a and b). A moist axis can be noted along the 700-mb thermal gradient from central Washington southward into northwestern California. A moist axis is also noted at 850 mb, but the axis appears to lag behind (west) the 850-mb cold front. Surface temperatures during the afternoon reached the mid 80s to lower 90s (°F) over much of Washington and Oregon east of the Cascades. Surface dew points were greater than 50°F from east central Oregon northward. Some early morning precipitation may have contributed to higher low-level moisture values in portions of the region. Surface-based lifted index values reached −4 or less and surface based



(a)

(b)

(c)

(d)

Fig. 21. Upper-air analyses at (a) 850-mb, (b) 700-mb, (c) 500-mb, and (d) 300-mb levels for 0000 UTC 11 May 1989.

CAPE values averaged around 1000 to 1500 J Kg^{-1} at 0000 UTC. These values are somewhat lower than was found with the other case studies, but were still sufficient for SSWE development.

At the 500 and 300-mb levels (Figs. 26c and d), relatively strong southerly winds prevailed. An area of diffluence is noted over the eastern portions of Washington and Oregon. Cooling aloft was minimal and confined to areas west of the Cascade mountains.

3) The unusual OR/WA subregion case of 5 April 1972

About midday on 5 April 1972, severe weather developed in northwest Oregon and extreme southwestern Washington west of the Cascades and spread northeastward during the afternoon hours into eastern Washington before ending. Five tornadoes were reported, including two of F3 intensity and two of F2 intensity. One of the F3 intensity tornadoes killed 6 people and injured 300 others in Vancouver, Washington.

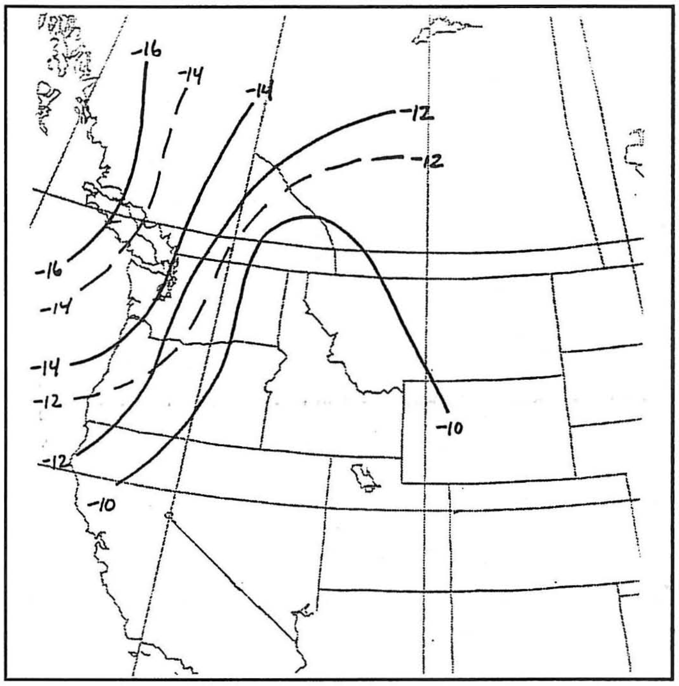


Fig. 22. Average 500-mb temperatures (°C) at 1200 UTC (dashed) and 0000 UTC (solid) during Pattern A SSWEs in Washington and Oregon.

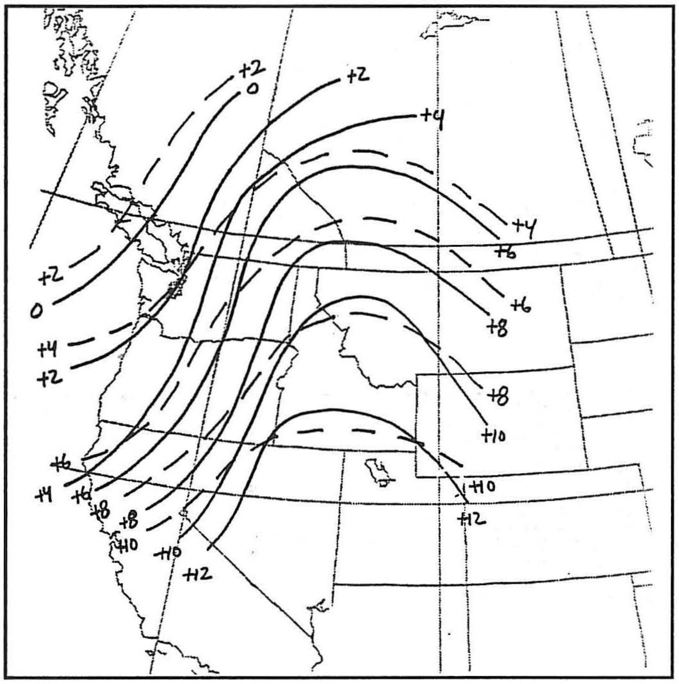


Fig. 23. Average 700-mb temperatures (°C) at 1200 UTC (dashed) and 0000 UTC (solid) during Pattern A SSWEs in Washington and Oregon.

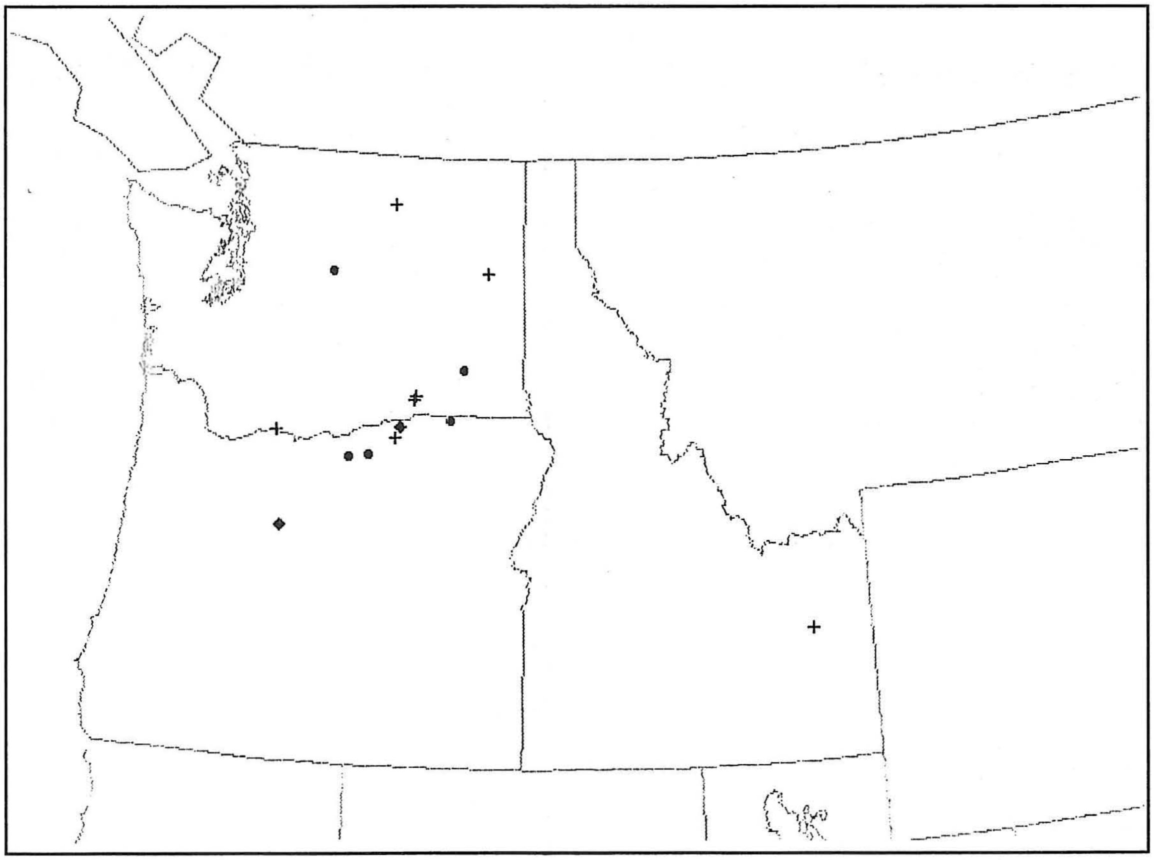


Fig. 24. Plot of all severe weather reports over Washington and Oregon for the 24-hour period beginning at 1200 UTC 6 August 1991. Dark circles indicate hail reports while the cross symbol represents wind gusts or damage. Diamond shapes indicate hail and wind damage reported at the same location.

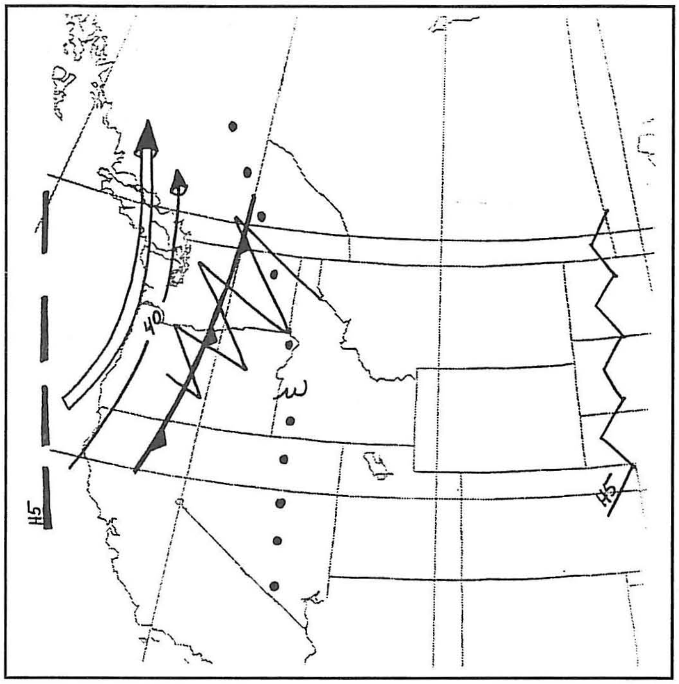


Fig. 25. Composite chart for 0000 UTC 7 August 1991. Symbols used are same as in Fig. 6.

Although this case was associated with southwesterly flow aloft and a negatively-tilted short-wave trough (Pattern A characteristics), other features differ significantly from those typically found in Pattern A cases. The episode commenced on the west side of the Cascades and was associated with a surface trough, well behind the cold front. Further, temperatures aloft were quite cold compared with the other cases with 500-mb temperatures generally less than $-20°C$. These conditions closely resemble those that Hales (1985) found to be associated with cool season tornado development in coastal portions of southern California. For additional details concerning the meteorology and evolution of this case the reader is referred to Hales (1994).

5. Summary and Conclusions

The results of this study have shown that severe weather occurrence in the northwestern United States is generally restricted to spring and summer (98% of events reported during March through September) and is most common during the summer months of June through August (75% of all reports). Generally the frequency of occurrence decreases as one goes west from the Continental Divide to the Pacific Coast.

The most common type of event reported is damaging convective winds and many of these events are likely associated with isolated microbursts and downbursts that are common in the western United States during the warm season. On occasion, however, when the wind fields are relatively strong and instability and forcing are sufficient, organized deep convection develops over the northwestern United States and more widespread severe weather results. In recent years, these more widespread and significant severe weather episodes (SSWEs) have been reported about twice a year.

To assist forecasters in anticipating SSWE development, mean composite charts of those pertinent meteorological features and parameter values associated with SSWEs occurring within that portion of the region east of the Cascades were prepared. Although the number of cases (26) available to construct these charts was limited, several common features appear to stand out. All of the cases are associated with a long-wave trough to the west of the area of occurrence and south to southwesterly flow at mid and upper-levels prevails over the area of occurrence. Also, all cases are associated with a short-wave trough moving into the region.

In most cases the short-wave trough is negatively tilted (80% of the cases) which appears to facilitate moisture transport into the region. This is probably a primary reason why those cases (20%) that are associated with positively-tilted short-wave troughs are restricted to the eastern portions of the region where moisture is more readily available.

Other conditions common to the composite cases are the relatively strong winds associated with the mid and upper-level jets entering the region (40 to 60 kt at 500 mb and 50 to 100 kt at 300 mb), and the lack of any strong cooling above the region at mid levels (500 mb). Severe weather development is typically associated with a diffluent zone aloft and usually takes place along to well ahead of the boundary-layer cold front. Because of mountainous terrain, the boundary-layer cold front is usually most easily identified by examining the 700-mb thermal field. The front is typically located near or just east of the leading edge of the stronger thermal gradient at 700 mb.

Instability typically reaches moderate values in Pattern A (negatively-tilted trough) cases with surface-based lifted index values of -3 to -6 and CAPE values of 1000 to 2000 J Kg^{-1}. However, in a few cases lifted index values may reach -8 and CAPE values may reach 2500 J Kg^{-1}. In Pattern B cases instability is typically weak to moderate with surface-based lifted index values of -2 to -5 and CAPE values of 700 to 1500 J Kg^{-1}. This degree of instability is achieved in part through diurnal heating and moisture transport. Moisture is most efficiently transported into the region by the mid-level flow and likely mixes downward through precipitation, evaporation, and other means.

This study demonstrates that there are some common meteorological characteristics associated with most significant severe weather episodes occurring in the northwestern United States. Further, recent trends in severe weather reporting for the area suggests that such episodes occur on average about twice a year or more. With continued trends in increased awareness in the region and with vastly increased capabilities for detection with the installation of the WSR-88D radar network, it may be found that SSWEs in the region are even more common than current statistics would indicate. For this reason, it is important for forecasters to have effective tools to aid in forecasting these larger scale events. It is hoped that this study will lead to improved forecast techniques concerning SSWE development in the northwestern United States.

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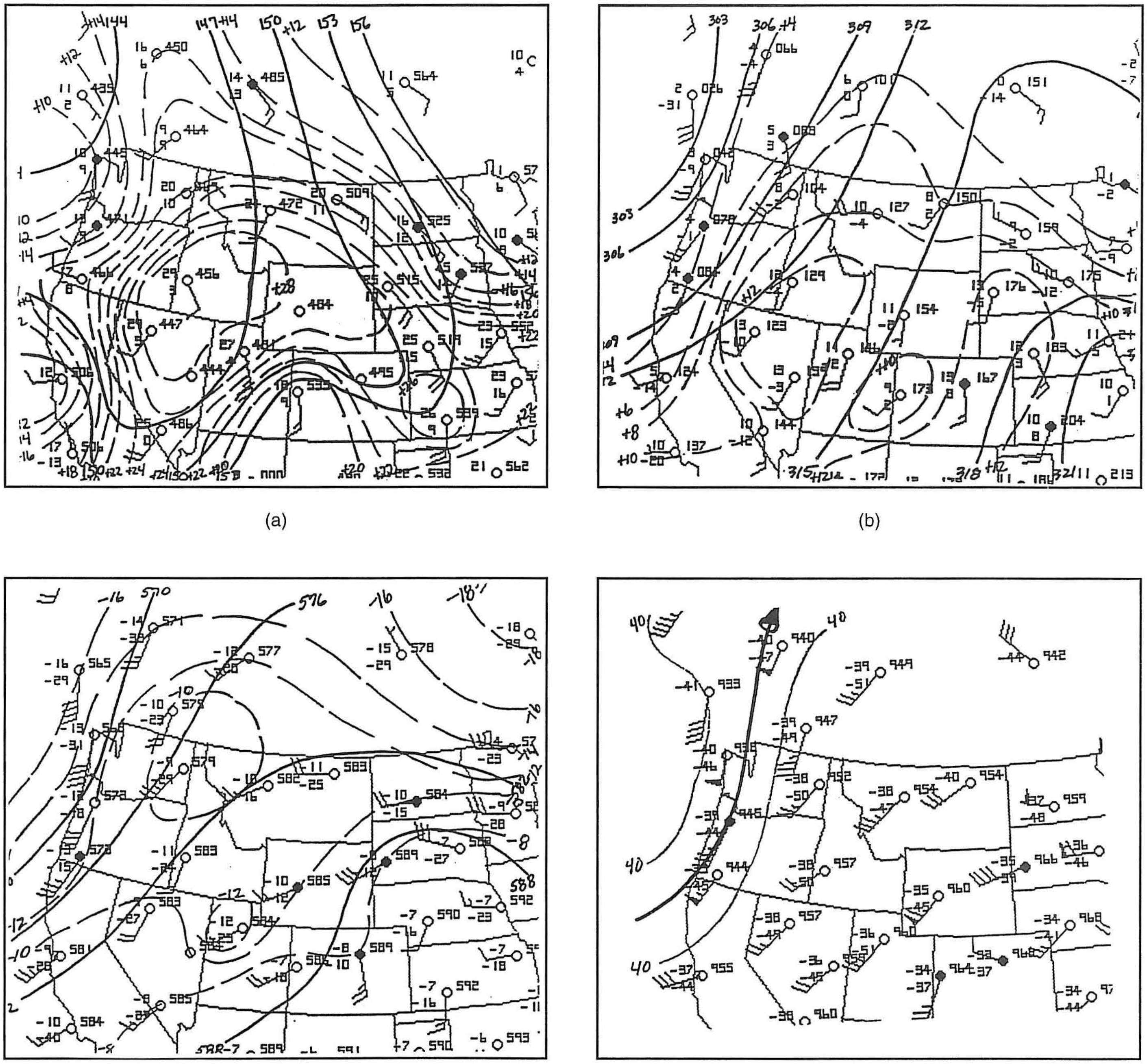
Authors

Eric C. Evenson is currently a mesoscale meteorologist in the Severe Local Storms Unit (SELS) at the National Severe



(a)

(b)

(c)

(d)

Fig. 26. Upper-air analyses at (a) 850-mb, (b) 700-mb, (c) 500-mb, and (d) 300-mb levels for 0000 UTC 7 August 1991.

Storms Forecast Center (NSSFC) in Kansas City, Missouri. Eric has also worked as a SELS assistant forecaster as well as in the Public Service Unit. Prior to coming to Kansas City, he worked as a general forecaster at the National Weather Service Forecast Office (NWSFO) in Great Falls, Montana and began his career as a meteorologist intern at the NWSFO in Portland, Maine. He attended the University of Wisconsin at Milwaukee where he earned a B. S. degree in Meteorology in 1989. He has written papers related to severe weather over portions of the northern Rockies and upper Midwest and on heavy snow affecting portions of New England.

Robert H. Johns received his B. S. degree in Meteorology at the University of Oklahoma in 1965. He began his employment with NOAA/NWS as a Student Trainee at Indianapolis in 1962. Since then, he has served in the NOAA Corps as an officer on the research ship Oceanographer based in Seattle, and held NWS positions at Fort Wayne, Chicago, Suitland, Maryland (NMC) and Kansas City (NSSFC). He was a lead forecaster in the SELS Unit of NSSFC from 1979 until 1994 when he accepted a position as Science and Operations Officer at the NWS Storm Prediction Center in Norman, Oklahoma. Mr. Johns is interested in forecasting, applied research and forecaster training. Besides working as an operational forecaster for most of his career, he has published a number of applied research papers and developed and conducted numerous forecaster training workshops.

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