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A COMPOSITE STUDY EXAMINING FIVE HEAVY SNOWFALL PATTERNS FOR SOUTH-CENTRAL MONTANA

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A COMPOSITE STUDY EXAMINING FIVE HEAVY SNOWFALL PATTERNS FOR SOUTH-CENTRAL MONTANA

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Abstract

This study identifies heavy snow patterns for south-central Montana. A snow amount of 6 inches or greater for each event was considered heavy snow for this study. Data for the years 1948-1994 was compiled using the NCEP Version III Grid Point Data Set. Patterns were examined during the time of heaviest snow, and composites made of 5 distinct flow patterns. The five flow patterns composited were: Southwest Flow, Amplified Southwest Flow, West Flow, Northwest Flow, and Closed Low. Composites were obtained by using the GEMCD program. Fields chosen for the composites were: 500 mb heights, Mean Sea-Level Pressure (MSLP), and 250 mb winds. Data for 250 mb winds was only available since 1965. To isolate the heavier snowfalls, separate composites were performed for single day totals of 5-9 inches. Single day snows of 10+ inches were rare, so they were examined individually.

I. INTRODUCTION

Heavy snows affect large segments of the population in southern Montana. The general public, as well as special interest groups such as ranchers, emergency managers, and transportation officials, can benefit greatly from an accurate snowfall forecast. Prior to this study, no documentation was available to aid the forecaster with identifying heavy snow patterns for southern Montana. This study attempted to diagnose surface and upper-level patterns most commonly linked to heavy snowfall. For this study, heavy snow was defined as 6 inches of snow falling in an event. An event was defined as six inches or more snowfall on a single day, or at least 2 inches of snowfall on consecutive days totaling 6 inches or more. Data for a 47-year period, 1948-1994, was used to determine heavy snowfall events. The 500 mb heights during the period of heaviest snow were used as a "snapshot" of each event's upper-level flow. Based upon these snapshots, the events were then divided into five distinct upper-level flow patterns. Composites of Mean Sea-Level Pressure (MSLP), 500 mb heights, and 250 mb winds were performed for each of the five upper-level flow patterns. These composites were the focus of this study.

II. PROCEDURE

To determine heavy snowfall events, daily climate data for Billings, Montana was examined for the period 1948-1994. These data were obtained from the World Weatherdisc. Composites were generated using the GEMCD program, developed by Dan St. Jean (NWSFO Boise), which used data from the National Center for Environmental Prediction (NCEP) Grid Point Data Set: Version III CD-ROM. Surface and 500 mb data were available for the period: June 1948 through December 1994. The 250 mb wind data were available from 1965 through 1994.

Before compositing, 500 mb heights for each case were extracted from the NCEP CD. The 500 mb heights were then regrouped into similar flow patterns. Five distinct patterns were identified: Southwest Flow, Amplified Southwest Flow, West Flow, Northwest Flow, and Closed Lows. For each pattern, MSLP, 500 mb heights, and 250 mb winds were composited. Standard deviations were computed to get a measure of the spread of each field for a given flow pattern. To see if events within each flow pattern had a tendency to be "quick-hitters" or long-lived, statistics on the length of events were calculated. Separate composites were made for "Big" events, which were categorized as 5-9 inches on a single day. "Super" events, 10 inches or more on a single day, were rare, so they were not composited.

III. ANALYSIS AND OBSERVATIONS

A. Southwest Flow

1. All Southwest Flow Events (18 Cases)

The Southwest Flow cases were characterized by a split-flow regime over western North America (Fig. 1a). The southern stream trough axis was located near the West Coast, which resulted in broad southwest flow over southern Montana. The northern stream flowed south in western Canada and merged with the southern stream in southern Saskatchewan. The ridge in the northern stream over western Canada provided a source of arctic air for the northern Plains, as evidenced by the 1024+ mb surface high in northwest Canada (Fig. 1b). The location of the arctic high provided northeast winds at the surface over south-central Montana. The Rocky Mountains in Montana have a northwest-southeast orientation through the western half of the state (Fig. 2). Thus, northeast winds provide good upslope for southern Montana. Moist, southwest flow aloft originating off the West Coast resulted in a good overrunning situation (i.e. isentropic lift) over the area. At 250 mb (Fig. 1c), the core of the jet stream (~85 knots) extended from northern Utah into the Dakotas. This configuration would place the left-front quadrant of approaching jet-streaks over southern Montana, enhancing vertical motion. The upslope flow over south-central Montana was further enhanced by surface waves moving through central Wyoming, which can be inferred from the Region of lower pressure extending from near Salt Lake City to the Nebraska panhandle (Fig. 1b).

Standard deviations at 500 mb (Fig. 3a) are largest in Canada and the West Coast of the U.S., and smallest from eastern Montana southeast into Colorado. The large spread in Canada reflects the varying strength and position of the northern stream ridge, while the differences in the western U.S. stem from the position and amplitude of the southern stream trough. Deviations in MSLP, (Fig. 3b) greatest in Canada, are related to the strength of the arctic high.

At 250 mb (Fig. 3c), the greatest variations, located from the eastern Pacific into the Dakotas, are due to the location and strength of the jet.

2. *"Big" Southwest Flow Events (10 Cases)*

The composite plots of "Big" Southwest flow cases (Fig. 4a-c), showed some important, though subtle, differences from the composite plots of all Southwest Flow cases. At 500 mb, the northern stream was farther south, which resulted in a slightly stronger arctic high (~2 mb). The southern stream at 500 mb had a tighter gradient, and not surprisingly, a stronger jet at 250 mb. The configuration of the 250 mb jet (Fig. 4c) put southern Montana in an area of divergence aloft, which helped enhance vertical motions.

Standard deviations from the "Big" Southwest Flow cases were similar to the composite of all Southwest Flow cases, in terms of both magnitude and location of minimum and maximum values.

3. *"Super" Southwest Flow Events (1 Case)*

The one "Super" Southwest flow case was vastly different than the composites of the "Big" cases and the composite of all Southwest Flow cases. In this case, all three fields (Fig. 5a-c) were much stronger than the composites in Sections 1 and 2. At 500 mb (Fig. 5a), there was a very tight gradient in the southern stream, with a 145 knot west-southwest jet (Fig. 5c) at 250 mb. This jet supported a 996 mb surface low which propagated from southwest Montana across northern Wyoming. The arctic high in northwest Canada was not very intense, but the pressure gradient of 20 mb from northeastern to southwestern Montana was more than twice as strong as either of the composites in Sections 1 and 2, which resulted in enhanced upslope flow.

B. Amplified Southwest Flow

1. *All Amplified Southwest Flow Events (23 Cases)*

The Amplified Southwest Flow cases (Fig. 6a-c) had a sharp trough at 500 mb extending from central Canada to the western Great Basin. This trough was sharper and farther east than the Southwest Flow cases. Also, the distinct split-flow in the previous flow pattern was not as apparent in the Amplified Southwest Flow cases, although there was a hint of a southern stream in the western Great Basin (Fig. 6a). The configuration of the 250 mb jet (Fig. 6c) put southern Montana in an area of divergence aloft. At the surface (Fig. 6b), the arctic high was centered in central Alberta, with the lowest pressures in eastern Utah and western Colorado. So while the upper-air patterns for the Southwest Flow and Amplified Southwest Flow events were quite different, the surface patterns in the two flow regimes were similar.

Standard deviations at 500 and 250 mb (Figs. 7a&c) were largest near the trough axis, which were related to the position and amplitude of the trough. The largest deviations of MSLP (Fig. 7b) were in Canada, associated with the strength and location of the arctic high.

2. *"Big" Amplified Southwest Flow Events (14 Cases)*

The "Big" Amplified Southwest Flow composites (not shown) looked nearly identical to the composites done with all cases. The similarity was due in large part to the large number of cases (14), that were included in both sets of composites. Moisture availability was likely higher in the "Big" cases, but there was no means of quantifying moisture in this study. The standard deviations were also similar, with maxima and minima in the same locations. However, the magnitudes were somewhat smaller with the "Big" cases.

3. *"Super" Amplified Southwest Flow Events (2 Cases)*

The first "Super" case (Fig. 8a-b) had a split-flow pattern at 500 mb. In the southern stream, a sharp 500 mb trough axis was located in central Nevada, with southwest flow from the eastern Great Basin into the Plains. The northern stream had a ridge in the Gulf of Alaska, with northerly flow over Alberta. The ridge over the northeast Pacific Ocean supported a 1040+ mb surface high in northwest Canada. A low-pressure center was located in central Utah. There were no 250 mb winds available for this case, but based upon the flow at 500 mb, there was likely a jet from Utah into the Dakotas.

Case 2 (Fig. 9a-c) had a split-flow at 500 mb also, but it was weaker than Case 1. The trough axis in the southern stream was located from western Wyoming into western Colorado. Southwest flow extended from Colorado into the eastern Dakotas. The placement of the northern stream ridge and trough were the same as Case 1. At 250 mb (Fig. 9c), there was a 130+ knot jet from Nebraska into eastern North Dakota. At the surface, an arctic high was located in northwest Canada, with a low-pressure center in the Nebraska panhandle. Implied surface winds in this case were northwest in southern Montana, but strong dynamics compensated for the lack of upslope flow.

A stronger jet was associated with both "Super" cases, which meant stronger dynamical forcing. This would account for the heavier snowfall in the "Super" cases.

C. West Flow

1. All West Flow Events (13 Cases)

West Flow cases (Fig. 10a-c) had a split-flow at 500 mb (Fig. 10a). The southern branch was nearly zonal, and confined mostly to the U.S. The northern branch had a ridge in the northeast Pacific, with northwest flow across Alberta and Saskatchewan. The flow in the northern branch became more zonal in central Canada where the two streams combined. At the surface (Fig. 10b), an arctic high was centered in northwest Canada, with an area of low pressure centered over southern Idaho. The jet (Fig. 10c) at 250 mb extended from northeast Oregon into western North Dakota, and was 85-90 knots. The surface pattern and the location of the jet indicated frontal waves likely helped enhance vertical motion over southern Montana.

Standard deviations (Fig. 11a-c) at 500 mb (Fig. 11a) were largest in Canada, associated with the strength of the northern stream. MSLP standard deviations (Fig. 11b) were fairly uniform, but were largest in Canada and the northern Plains, due to the intensity of the arctic high. The 250 mb standard deviations were on the order of 20 knots, with largest values in the upper Midwest, related to the strength of the confluence of the northern and southern streams.

2. *"Big" West Flow Events (7 Cases)*

Composites of "Big" West Flow events (not shown) were not significantly different from the composites of all West Flow events. Over half of West Flow events were "Big", which contributed to the similarity of the two composites. The jet was about 10 knots stronger in the "Big" cases, but moisture availability was likely the determining factor in these scenarios. .

Standard deviations (not shown) were similar to those in Section 1, in terms of the magnitude and location of minimum and maximum values.

3. *"Super" West Flow Events (None)*

There were no West Flow events which had more than 10 inches of snow in a single day.

D. Northwest Flow

1. *All Northwest Flow Events (19 Cases)*

Northwest Flow cases (Fig. 12a-c) were characterized by a Hudson Bay Low at 500 mb (Fig. 12a), with northwest flow over western Canada and the U.S.. A large surface high (1032+ mb) was located in northwest Canada (Fig. 12b). Ridging extended into northeast Montana, which resulted in upslope flow in southern Montana. The jet at 250 mb (Fig. 12c) extended from British Columbia into the central Plains, with a core of 100 knots over central Montana. The southerly ageostrophic flow associated with the exit Region of the jet produced isentropic lift over the arctic boundary which rested along the Rocky Mountains.

Standard deviations (Fig. 13a-c) at 500 mb (Fig. 13a) were smallest along the Rocky Mountains. Largest values were located in central Canada, associated with the strength and location of the Hudson Bay Low, and off the Pacific Northwest coast, due to the amplitude of the ridge. Surface standard deviations

(Fig. 13b) were largest on the cold side of the arctic boundary, attributable to the strength and eastward extent of the arctic high. At 250 mb (Fig. 13c), deviations were greatest over British Columbia and the southern Rockies, and can be related to the strength and orientation of the jet.

2. *"Big" Northwest Flow Events (6 Cases)*

The "Big" cases showed noticeable differences from the previous events. At 500 mb (Fig. 14a), the Hudson Bay Low was located farther east. The flow into the west coast of North America was more westerly, which would allow greater moisture influx. At the surface (Fig. 14b), pressures were weaker over Montana (~4 mb), with a hint of a surface wave in central Wyoming. The shallower layer of arctic air over southern Montana would result in higher moisture capacity at low- and mid-levels. The low-pressure wave rippling along the arctic front would concentrate the available moisture and enhance snowfall rates. At 250 mb (Fig. 14c), the jet was slightly weaker with more of a westerly orientation.

Standard deviations (not shown) were similar to those in Section 1, in terms of location and magnitude.

3. *"Super" Northwest Flow Events (4 Cases)*

The four "Super" cases were different enough from each other to prohibit compositing, but did share common elements: a source of cold air and a jet near Montana. Case 1 (Fig. 15a-b) had a strong Hudson Bay Low at 500 mb (Fig. 15a) with northwest flow over Montana, and west flow associated with the southern branch of the jet over Oregon and California. At the surface (Fig. 15b), an area of high pressure was located over northern British Columbia, with a wave of low pressure in western Nebraska. Ridging in northern Montana produced upslope flow in southern Montana. Case 2 (Fig. 16a-b) had a polar vortex over Hudson Bay at 500 mb (Fig. 16a) with northwest flow over Montana and no southern stream. At the surface (Fig. 16b), a large arctic high was over northern Alberta, with the arctic boundary lying against the Rockies. Pressure gradients across Montana were weak, but there was upslope flow in southern Montana. Case 3 (Fig. 17a-c) had low heights and northwest flow over Montana at 500 mb (Fig. 17a). Surface features (Fig. 17b) were similar to Case 1, with a wave of low pressure near the Montana/Wyoming/South Dakota border. Again, ridging into northeast Montana provided upslope flow. Aloft, a 120+ kt jet at 250 mb (Fig. 17c) was entering western Montana, with the favorable left-front quadrant of the jet over southern Montana. The 500 mb flow in Case 4 (Fig. 18a) was similar to Case 3, but the gradient across Montana was stronger. This case had downslope flow (southwest winds) at the surface (Fig. 18b), but a 115 knot jet moving into southern Montana at 250 mb (Fig. 18c), likely minimized these effects.

The surface patterns in each of the "Super" cases were distinctly different, but each case did have a polar vortex in the vicinity of Hudson Bay, which supplied the cold air to southern

Montana. Also, a strong jet at 250 mb was near southern Montana in each case (implied from the 500 mb flow in Cases 1 and 2), which helped produce the necessary lift needed for heavy snow. Upslope flow at the surface was present in three of four cases, which probably served to enhance snowfall, but was not a requirement for generating the snow.

E. Closed Lows

1. All Closed Low Events (21 Cases)

The composite of all Closed Low events (Fig. 19a-c) had a closed circulation at 500 mb (Fig. 19a) near the Idaho/Utah/Wyoming border with southeast flow over southern Montana. The dominant surface feature was a low-pressure area over southeast Colorado (Fig. 19b), with high pressure located in central Canada. Upslope surface flow was not a factor in these cases, which were dynamically driven for the most part. The 250 mb winds (Fig. 19c) were strongest across New Mexico and Arizona, with the nose of the jet entering southeast Colorado, supporting the low-pressure area there. Over southern Montana, the flow was diffluent, and likely divergent as well, enhancing vertical motion.

Standard deviations at 500 mb (Fig. 20a) were uniform over the western U.S. and Canada. Strength of the closed circulation accounted for most of the variability. Deviations at the surface (Fig. 20b) were less than 10 mb across the West. This fairly small variability was the result of the consistent strength and position of the Canadian high and Colorado low. At 250 mb (Fig. 20c), values were largest in the western and southern U.S., associated with the strength of the jet, and smallest in the deformation zone over central Montana.

2. "Big" Closed Low Events (13 Cases)

Due to the large number of "Big" cases (13, or 62 percent of the total number of cases), the composites and standard deviations of the "Big" cases (not shown) were almost identical to those in Section 1.

3. "Super" Closed Low Events (2 Cases)

Case 1 of the "Super" Closed Lows (Fig. 21a-b) was the biggest snowfall on record in Billings, where 42 inches of snow fell in two days! At 500 mb (Fig. 21a), the center of the closed circulation was located over southeast Wyoming, with diffluent east flow over southern Montana. A surface low-pressure center was over western Nebraska, with an inverted trough extending into southwest Saskatchewan (Fig. 21b). An arctic high was centered over northwest Canada. The flow around the 500 mb low-pressure center allowed for Gulf of Mexico moisture to be advected over the arctic air, which is an extremely rare occurrence for southern Montana. Case 2 (Fig. 22a-c) was a more typical event, with the 500 mb low (Fig. 22a) over southwest Montana. Weak high pressure (~1022 mb) was centered over southern Alberta (Fig. 22b), with the low-pressure center in southeast Colorado, and an inverted trough extending into eastern Montana. The jet at 250 mb (Fig. 22c) was diving south from the Pacific Northwest into southern Utah, which is farther north and west than the composite in Section 1. A deformation zone was located over southern Montana, enhancing vertical motion.

The 500 mb closed circulations in both "Super" cases were farther north than the composite in Section 1. The northward displacement places the deformation zone over southern Montana, and allows for large amounts of moisture to overrun the arctic air. Though less frequent than in northwest flow, closed lows have a higher snowfall potential than the other four cases due to possible entrainment of Gulf of Mexico moisture, and slow movement of the system. Case 1 shows the result of both these parameters acting together.

F. Snowfall Distribution Statistics

1. Amount and Duration of Events

The total number of events for each flow pattern was distributed fairly evenly (Table 1). Each pattern other than West Flow represented about 20 percent of the total. The percentage of "Big" events was over 50 percent for four of five flow patterns. The exception was Northwest Flow, but that was compensated by a higher percentage of "Super" events. The most significant numbers were the percentage of "Super" events for Northwest and West Flow. No 10-inch one-day snowfalls were observed in West Flow patterns, whereas over 20 percent of Northwest Flow cases were "Super" events. A possible explanation for the absence of "Super" events in West Flow was that moisture had to travel over several mountain ranges before reaching southern Montana while moisture in Northwest Flow only had to pass over the Canadian Rockies. Also, the powerful jet in Northwest Flow cases meant stronger dynamical forcing, which would lead to greater snowfall rates.

Each flow pattern averaged over 7 inches of snow per event (Table 2), with Northwest Flow and Closed Lows each having average snowfalls over 10 inches. The average length of each event was smallest for Amplified Southwest Flow, and largest for Closed Low. The average snowfall showed a direct relationship with the average length of each event. Taking the ratio of the average snowfall and average length for each event yielded similar values. This showed that the average snow total was determined more by the length of the event, rather than snowfall intensity. Breaking down the length of each event, Closed Low events were the longest lasting, with almost 30 percent of the events more than two days long. Amplified Southwest Flow events were the shortest, with over 65 percent of the cases lasting only one day.

2. Snowfall Event Distribution By Month

The seasonal distribution for all events (Fig. 23), showed a peak in early Spring, with nearly 20 events in March. A minimum in the number of events occurred in February. The "Big" and "Super" events were spread out evenly between October and April.

Southwest Flow (Fig. 24a) events peaked in January, with secondary peaks in March and April. No events were recorded in February throughout the 47-year data set, which is climatologically the driest month in Billings. "Big" events were evenly distributed from October through March, with the only "Super" event occurring in January.

Amplified Southwest Flow (Fig. 24b) events peaked in fall and spring, with only four events during the winter months. The majority of the "Big" and "Super" snows were also in the fall and spring.

West Flow (Fig. 24c) cases were most common in November, December, and March, with none occurring in January. "Big" cases were distributed in a similar manner. The lack of cases in January could be due to a southward displacement of the jet stream.

The vast majority of Northwest Flow (Fig. 24d) cases (17 of 19) occurred during the winter months, with no spring events. This can be explained by the seasonal strength of the polar vortex, which is at its maximum strength during the winter. The distribution of the "Big" and "Super" cases followed a similar pattern.

Closed Low cases (Fig. 24e) showed an opposite signature when compared to Northwest Flow. The peak was in the spring, with a few cases in October. No Closed Low events were recorded from late fall through winter. This correlated well with the climatological occurrence of closed lows. The two "Super" cases occurred in mid to late spring, which could be due to the higher moisture availability during this time.

IV. SUMMARY AND CONCLUSIONS

Heavy snow events in south-central Montana were broken down into five different flow patterns. The identified patterns were: Southwest, Amplified Southwest, West, Northwest and Closed Lows.

In all patterns except Closed Low, upslope flow, jet energy, and overrunning moisture were key ingredients to the heavy snowfall. In the Closed Low events, a slow-moving deformation zone coupled with abundant moisture were the key factors.

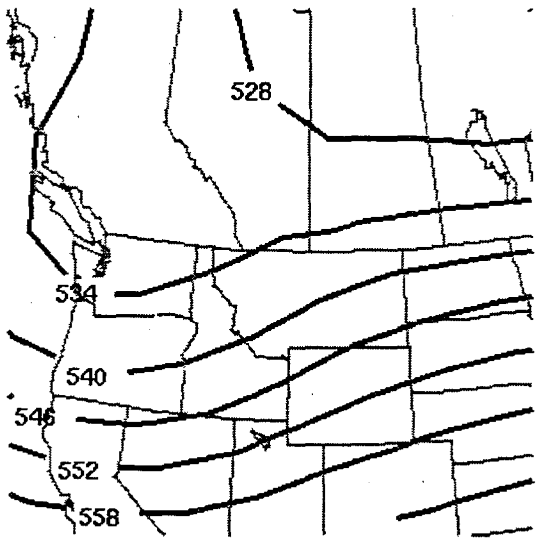
Southwest Flow, Amplified Southwest Flow, and West Flow events were fairly evenly distributed from September through May, whereas Northwest Flow and Closed Low cases were mainly winter and spring events, respectively.

Closed Low and Northwest Flow patterns were the biggest snow producers, which was directly related to the length of those events.

Hopefully, these composites will help alert forecasters to potential developing heavy snow patterns, and lead to longer lead times for watches and warnings.

ACKNOWLEDGMENTS

The authors would like to thank Keith Meier (BIL) and Dave Bernhardt (GTF) for their reviews and helpful suggestions regarding this manuscript. Thanks also goes out to Dan St. Jean (BOI) for providing the GEMCD program, which allowed us to easily access and display the data for this study. Finally, we would like to thank Sally Springer (BIL) for her help in producing the tables.



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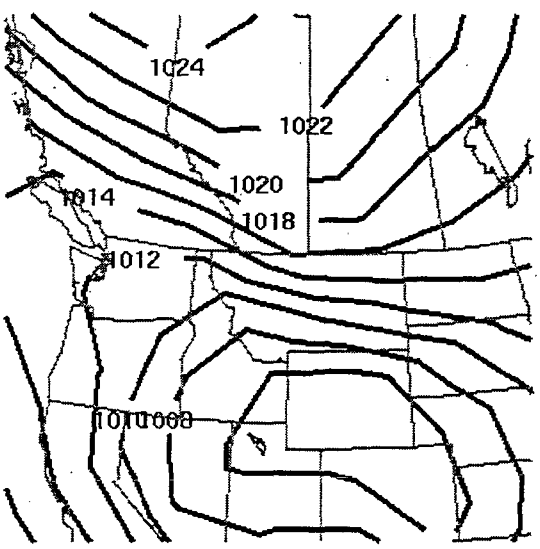

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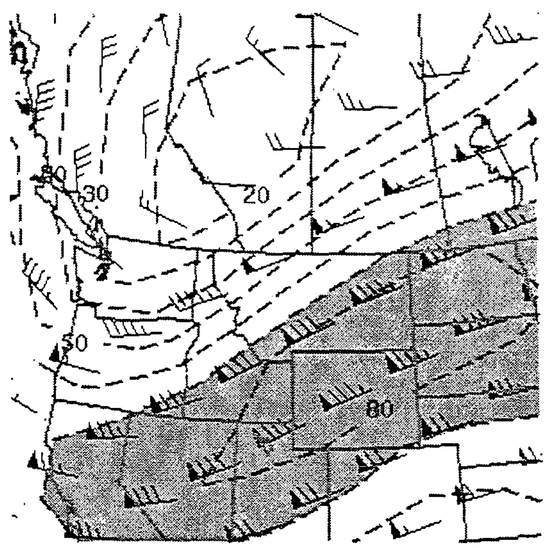


C) 250MB Wind (knots)

Figure 1 – Southwest Flow Cases

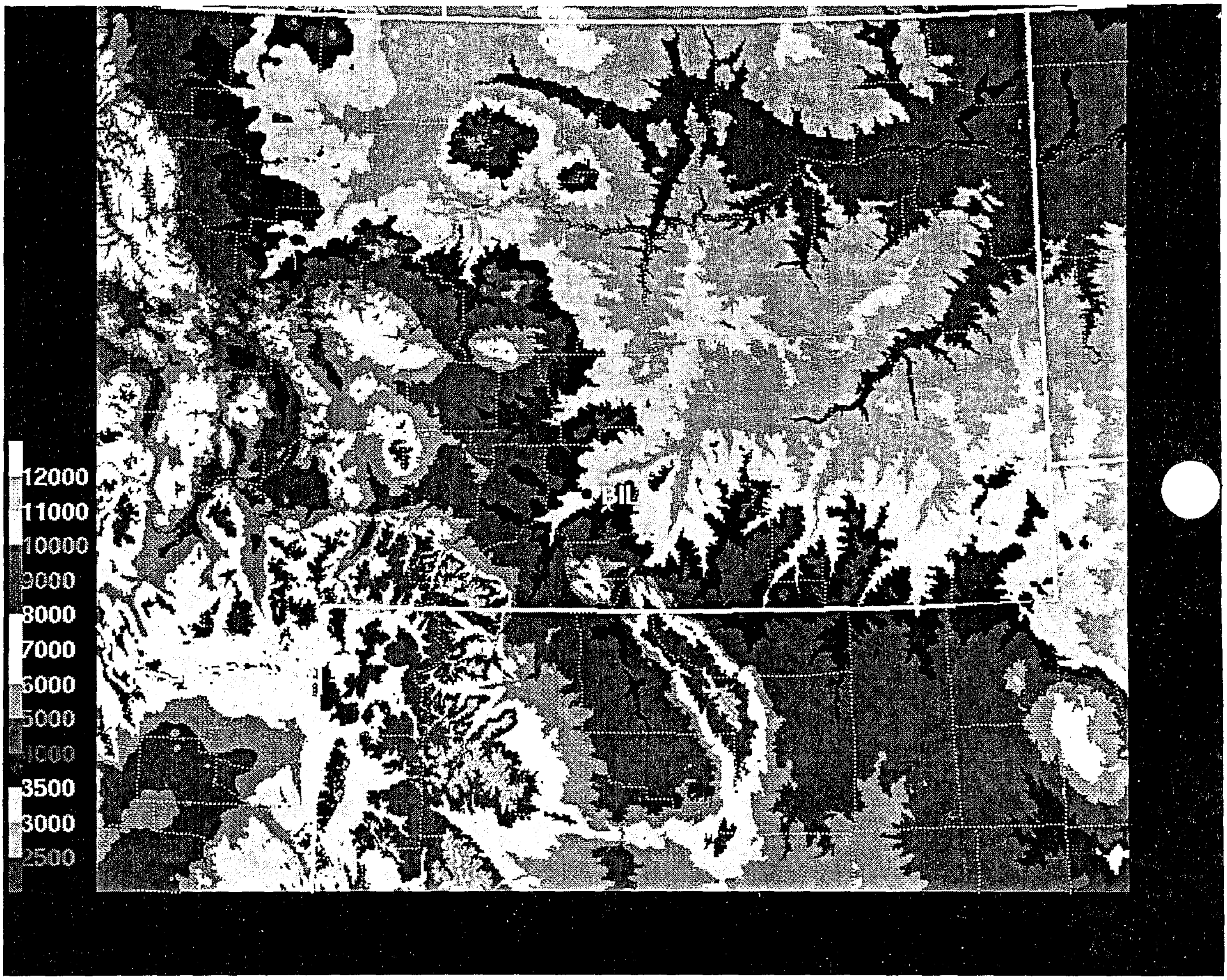
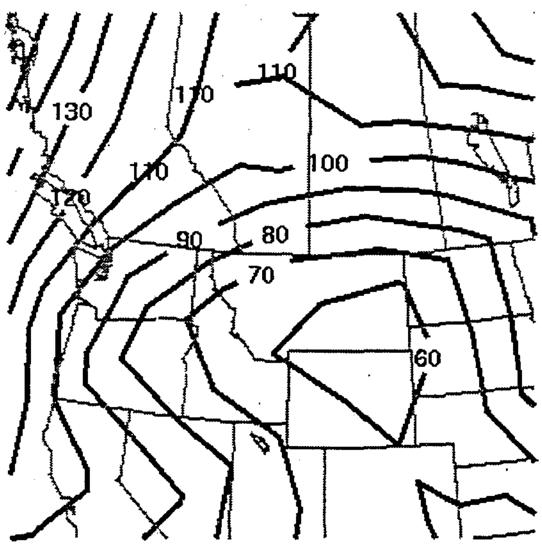


Figure 2 - Topography of Montana and northern Wyoming
Contour Interval = 500 feet



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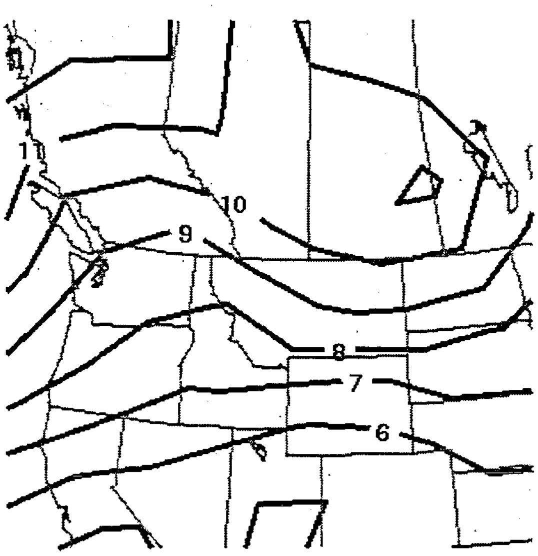

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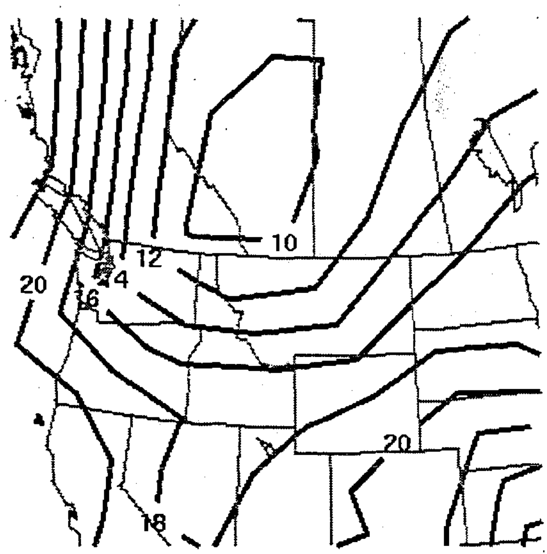
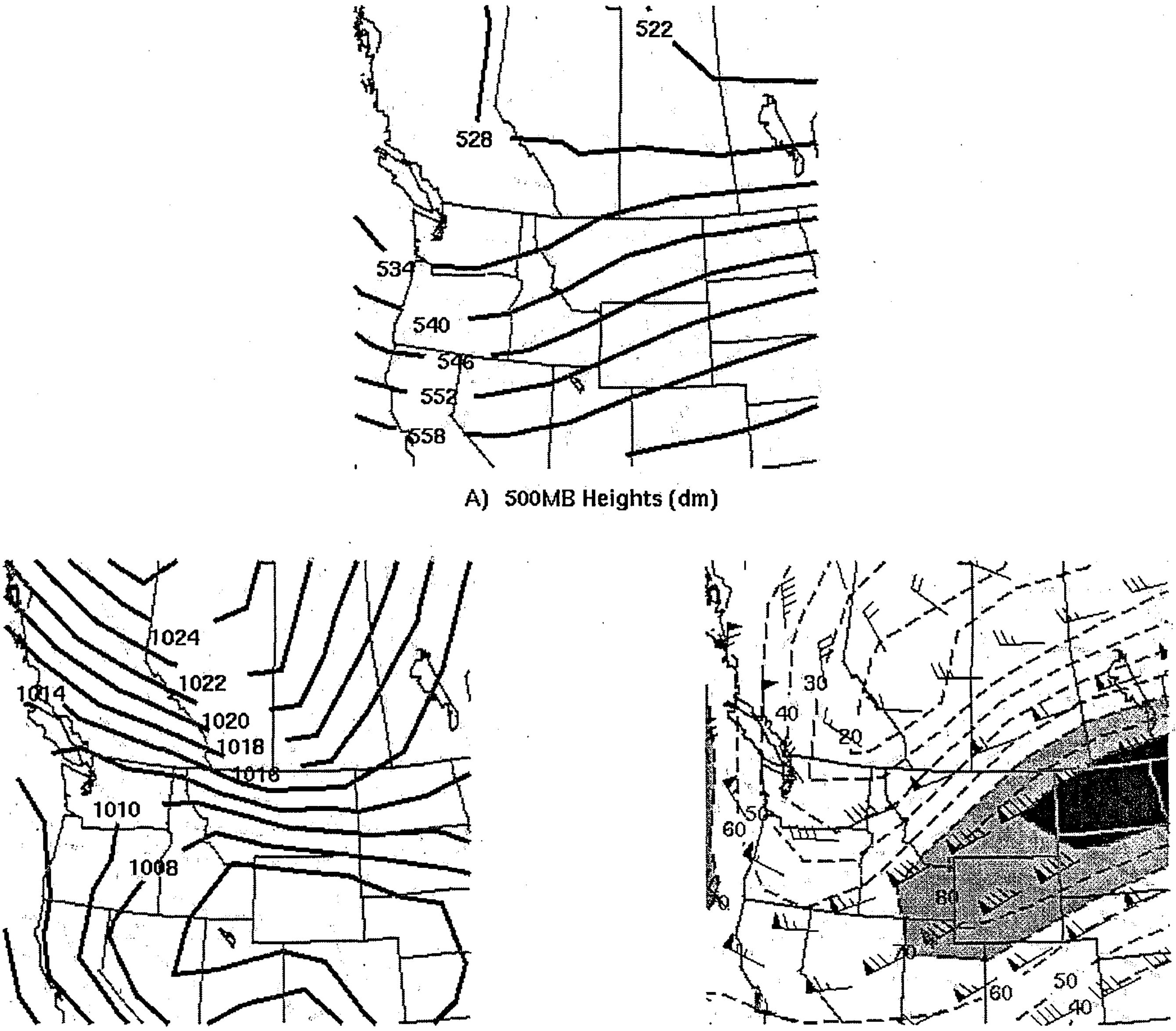


C) 250MB Winds (knots)

Figure 3 – Southwest Flow Standard Deviation

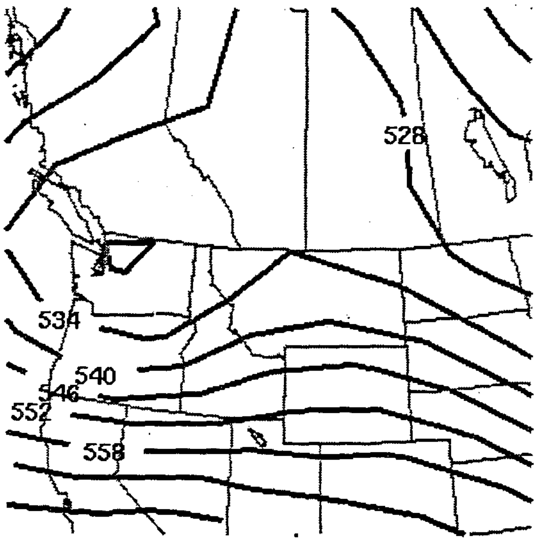


A) 500MB Heights (dm)

B) MSLP (mb)

C) 250MB Winds (knots)

Figure 4 - "Big" Southwest Flow Cases



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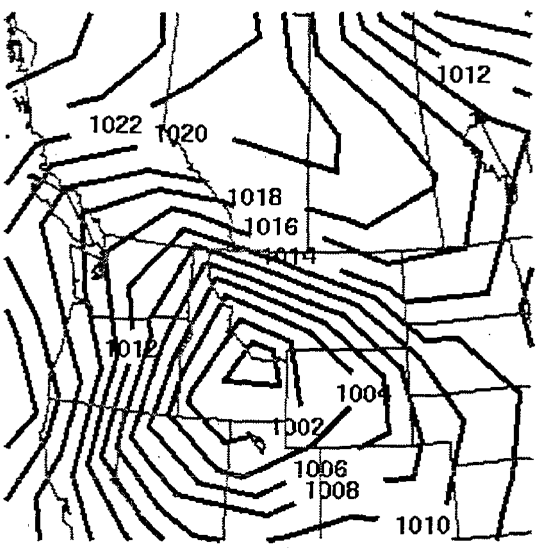

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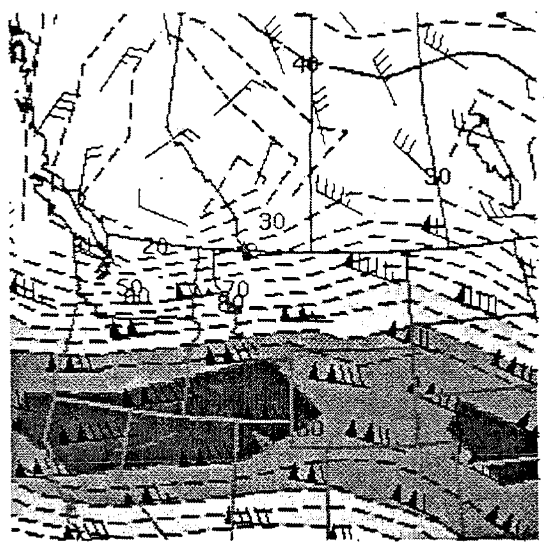
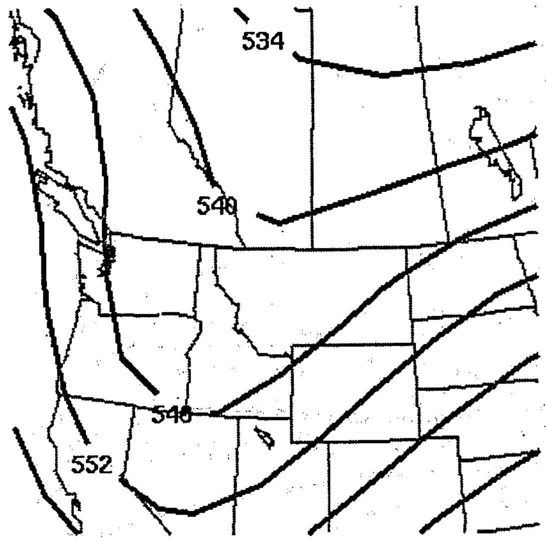


C) 250MB Winds (knots)

Figure 5 – "Super" Southwest Flow Case



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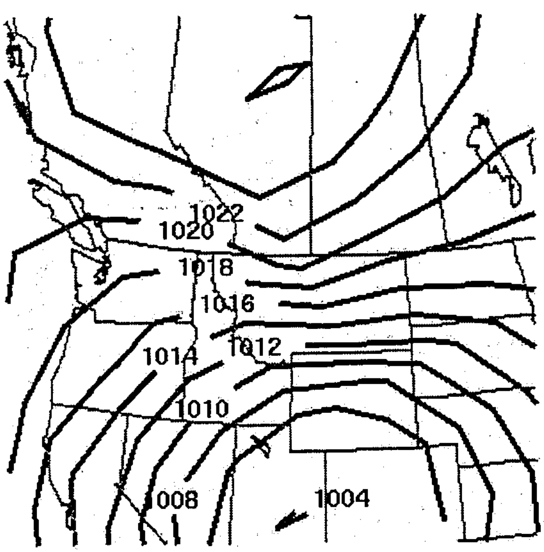

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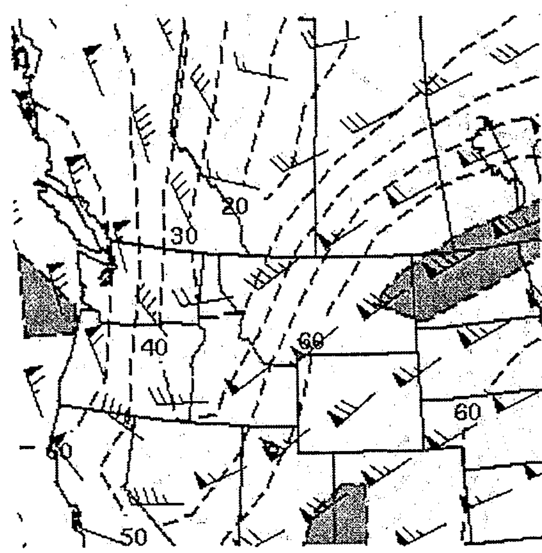
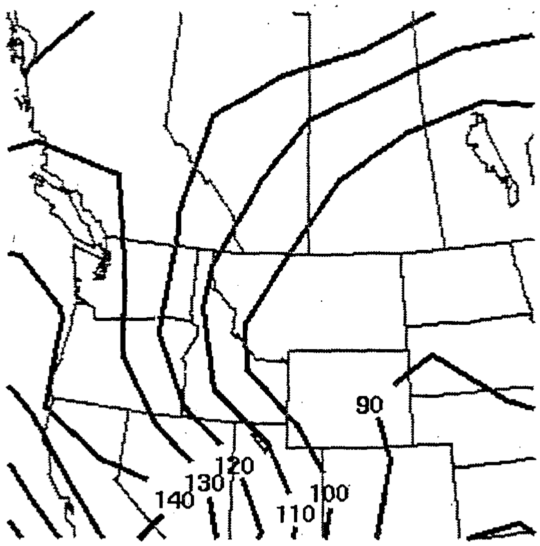


C) 250MB Wind (knots)

Figure 6 – Amplified Southwest Flow Cases



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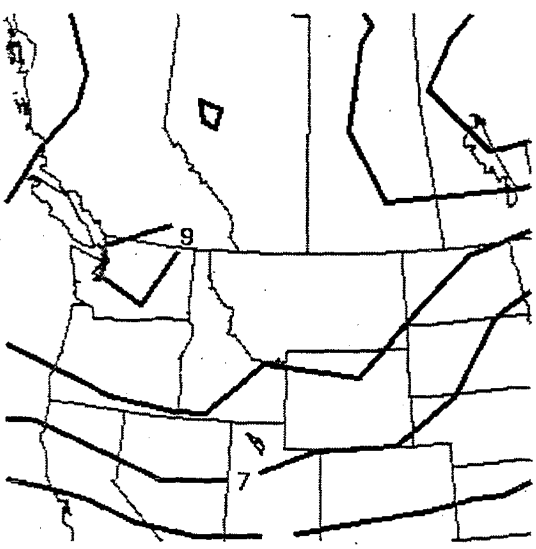

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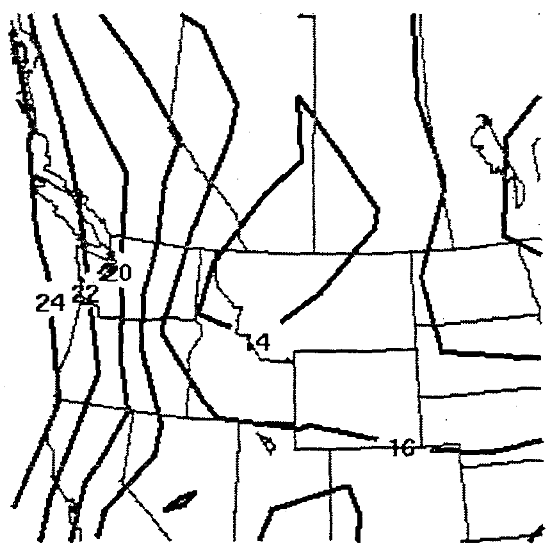
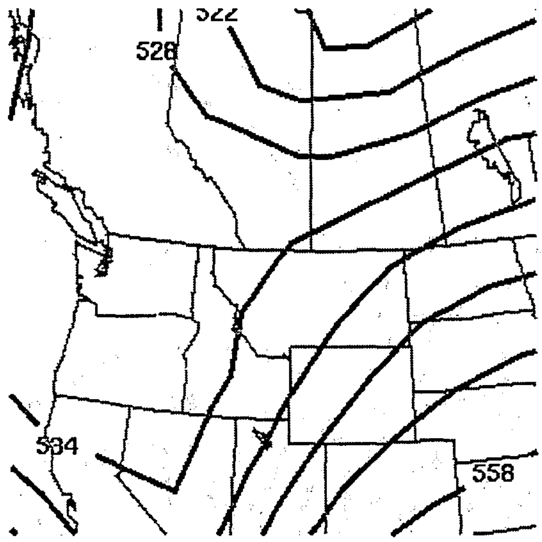


C) 250MB Winds (knots)

Figure 7 – Amplified Southwest Flow Standard Deviation



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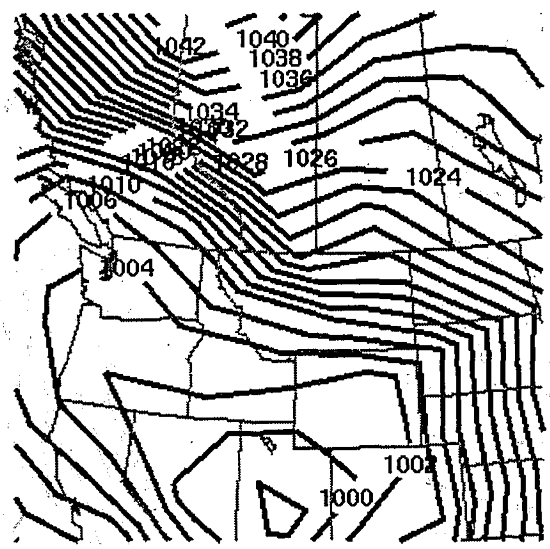
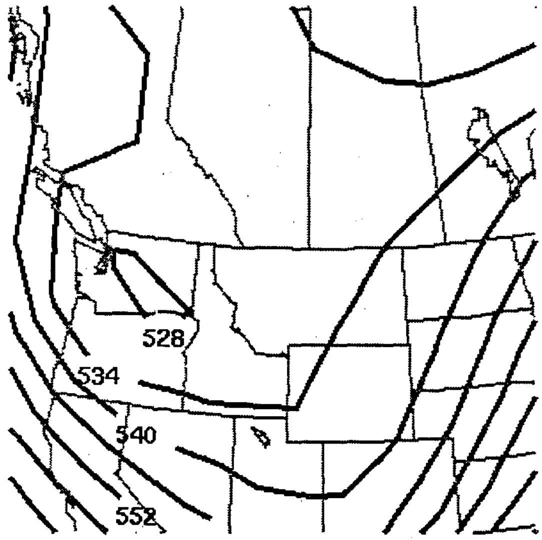


B) MSLP (mb)
Figure 8 – "Super" Amplified Southwest Flow (Case 1)



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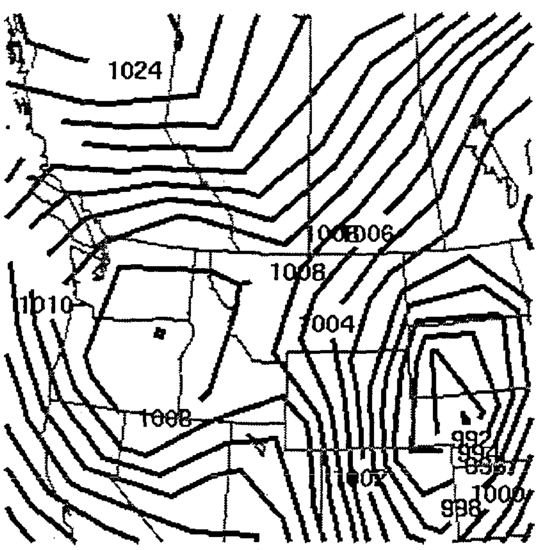

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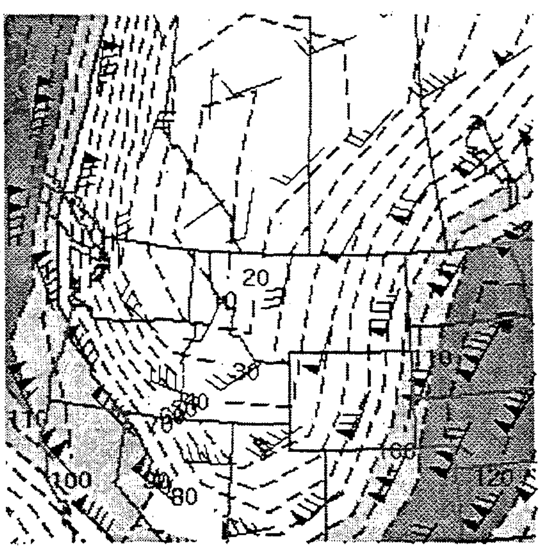
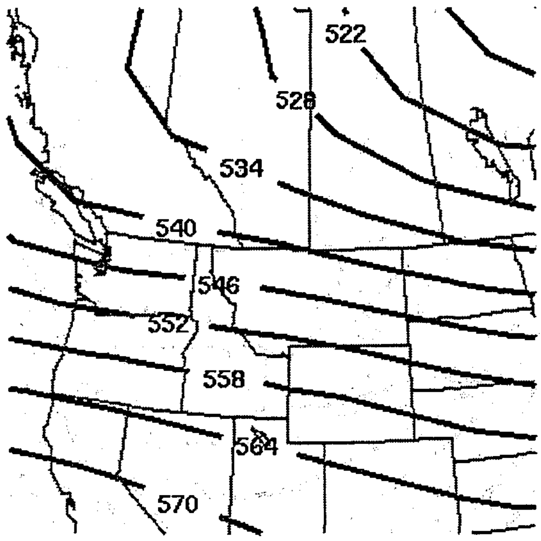


C) 250MB Winds (knots)

Figure 9 – "Super" Amplified Southwest Flow (Case 2)



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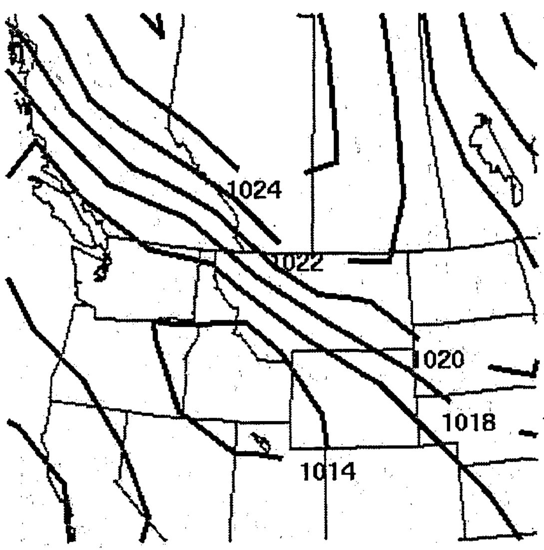

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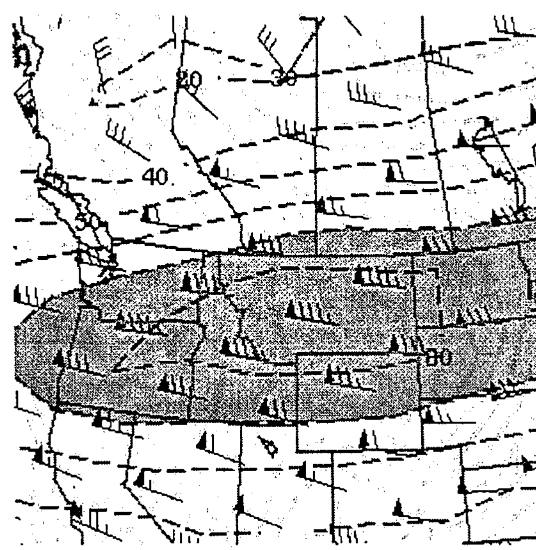
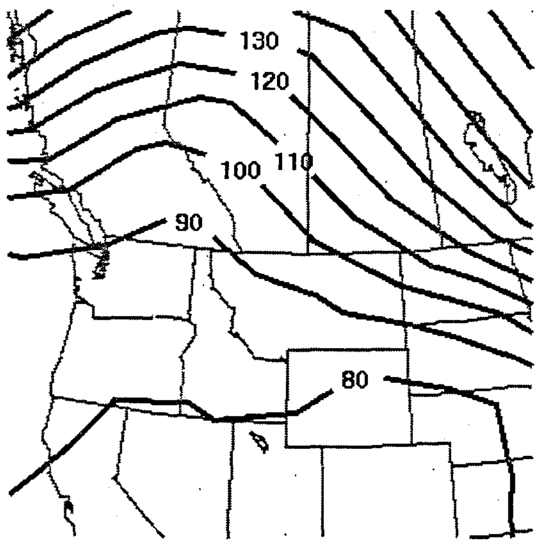


C) 250MB Wind (knots)

Figure 10 – West Flow Cases



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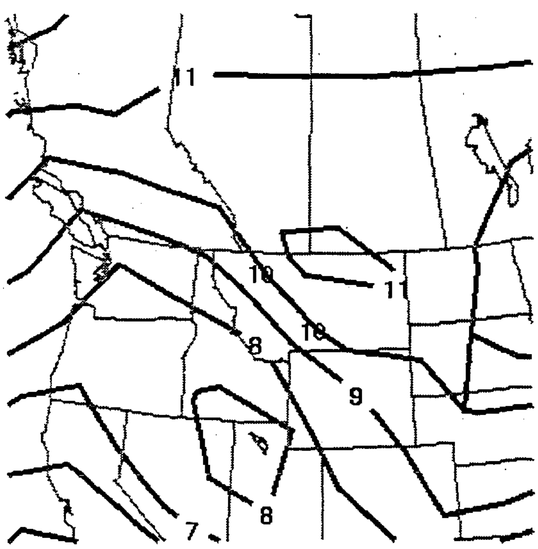

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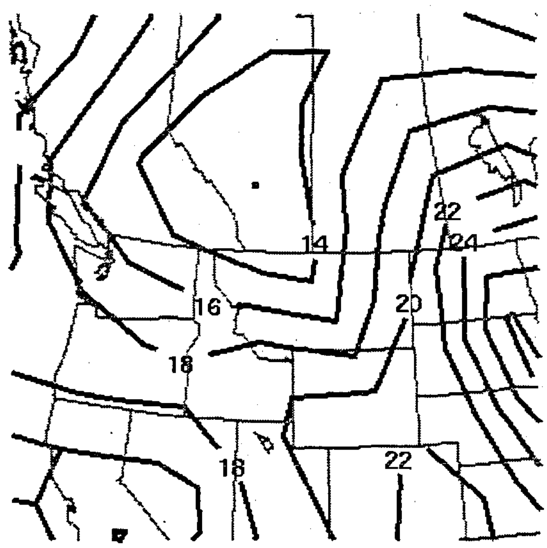
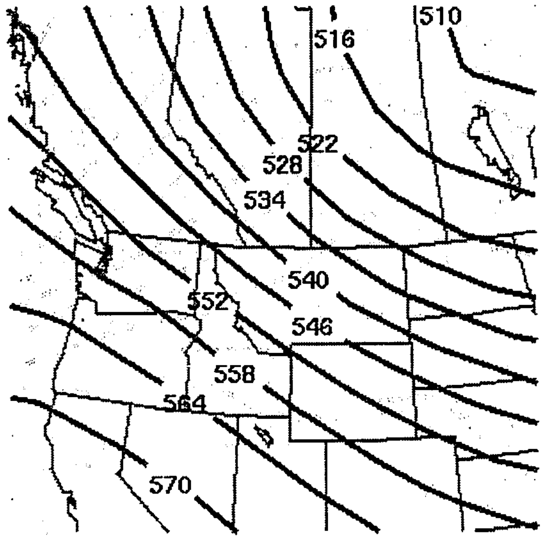


C) 250MB Winds (knots)

Figure 11 – West Flow Standard Deviation



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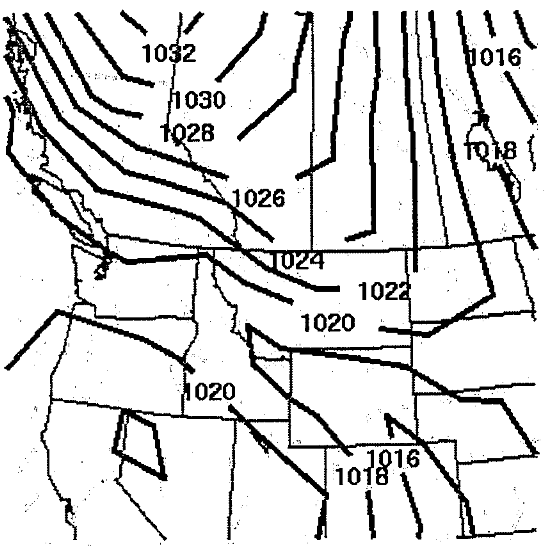

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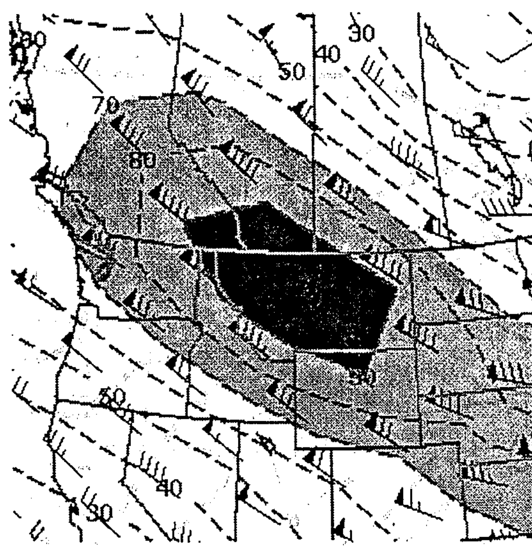
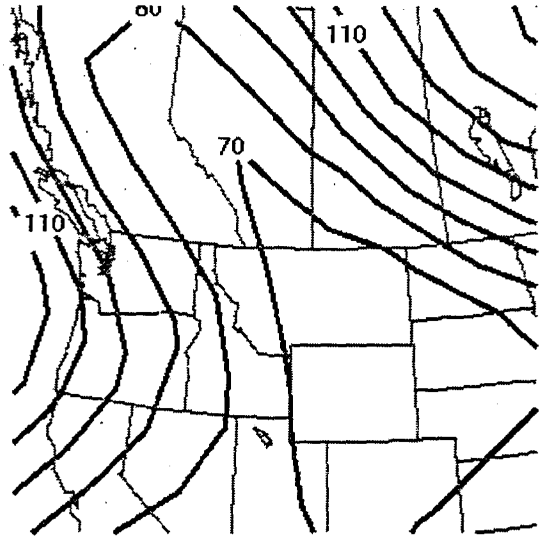


C) 250MB Winds (knots)

Figure 12 – Northwest Flow Cases



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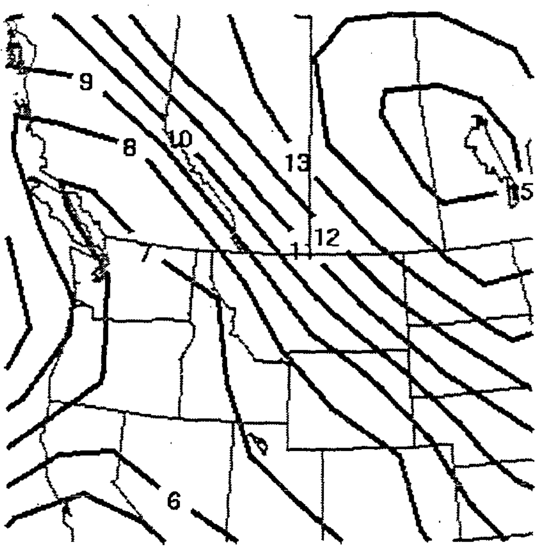

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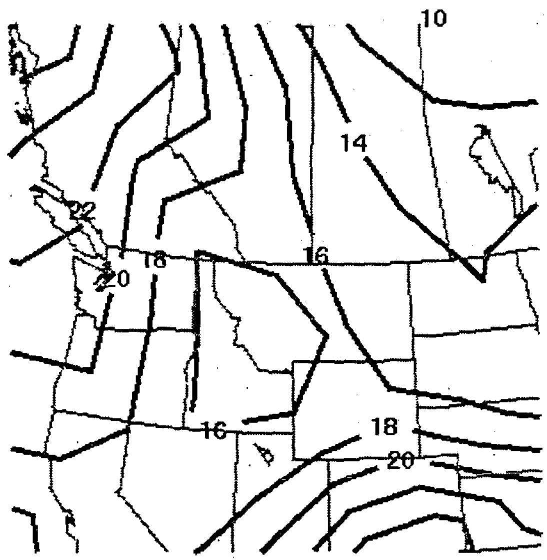
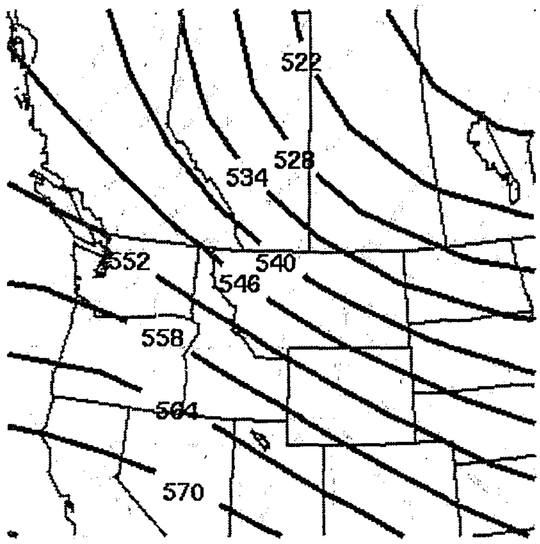


C) 250MB Winds (knots)

Figure 13 – Northwest Flow Standard Deviation



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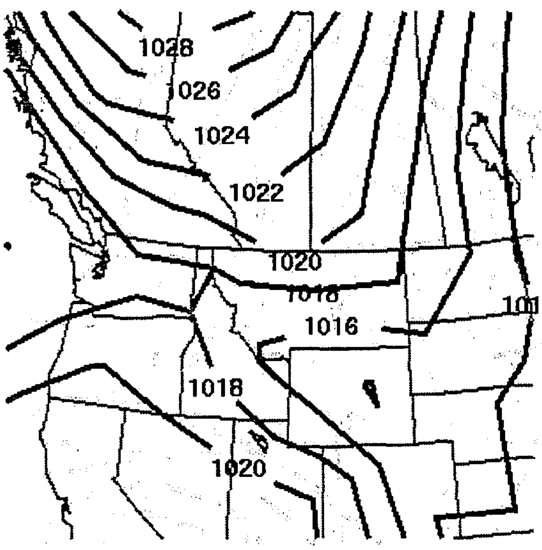

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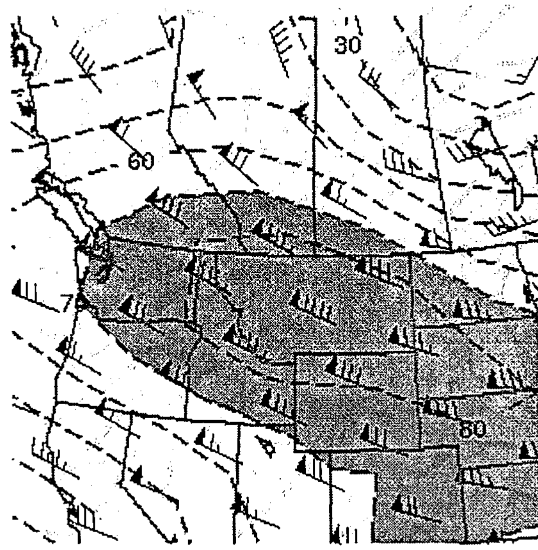
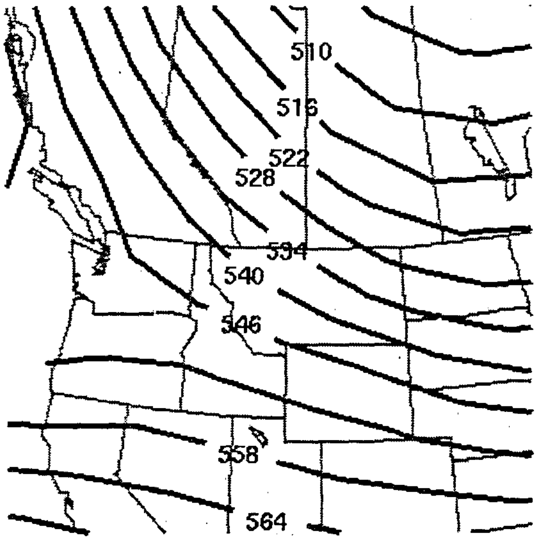
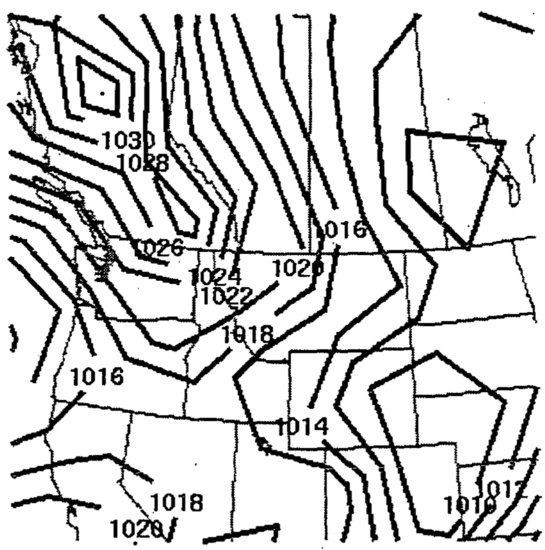


C) 250MB Winds (knots)

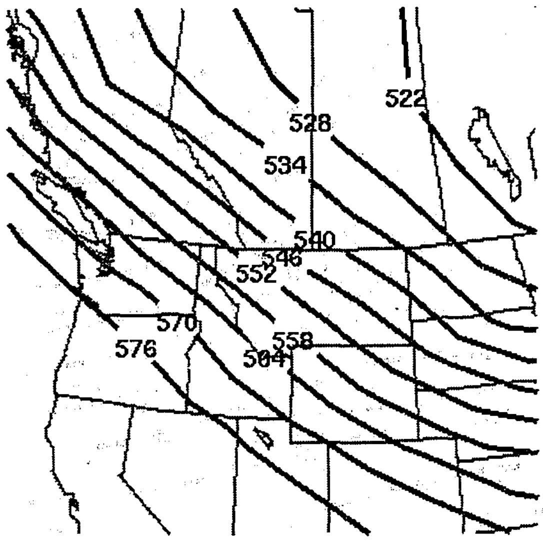
Figure 14 – "Big" Northwest Flow Cases



A) 500MB Heights (dm)



B) MSLP (mb)
Figure 15 - "Super" Northwest Flow (Case 1)



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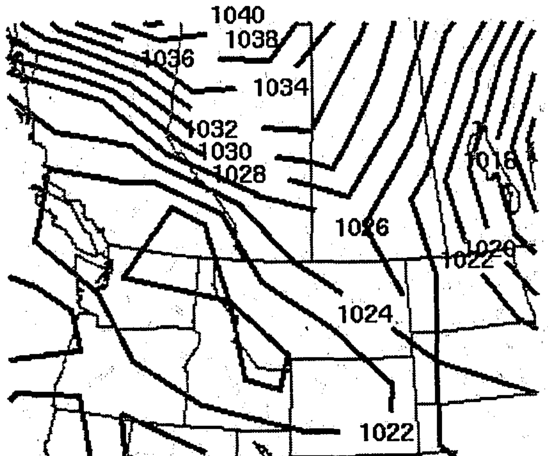
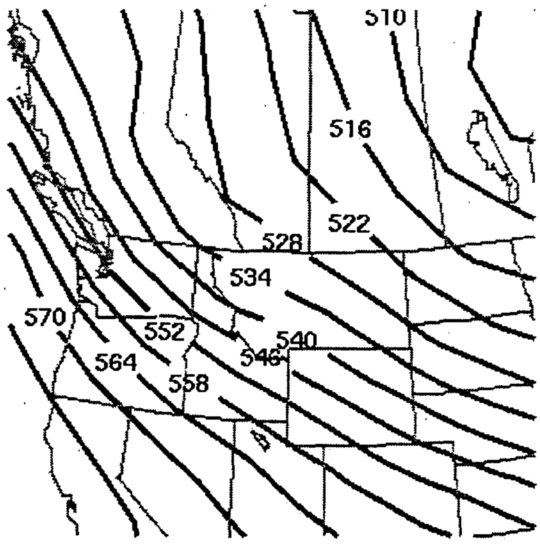


B) MSLP (mb)
Figure 16 – "Super" Northwest Flow (Case 2)



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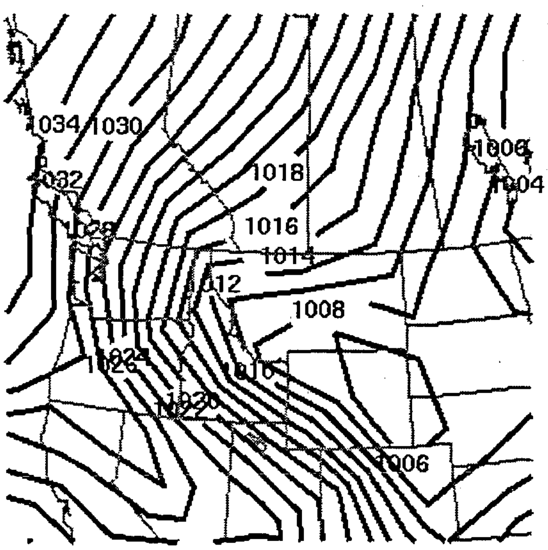

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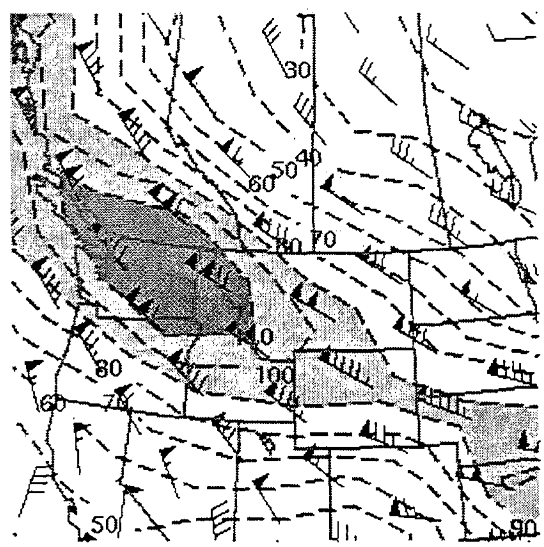
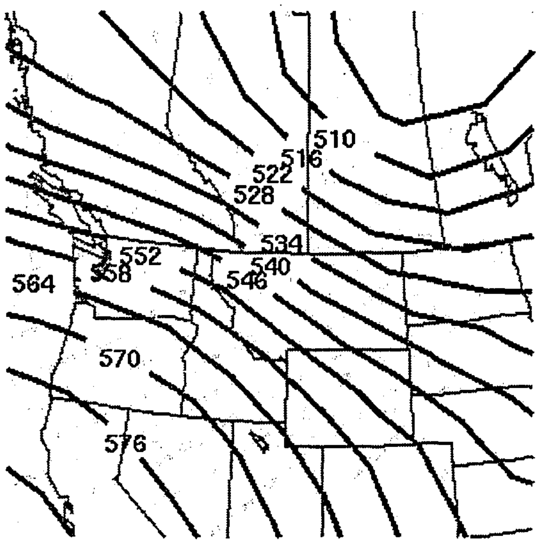


C) 250MB Winds (knots)

Figure 17 – "Super" Northwest Flow (Case 3)



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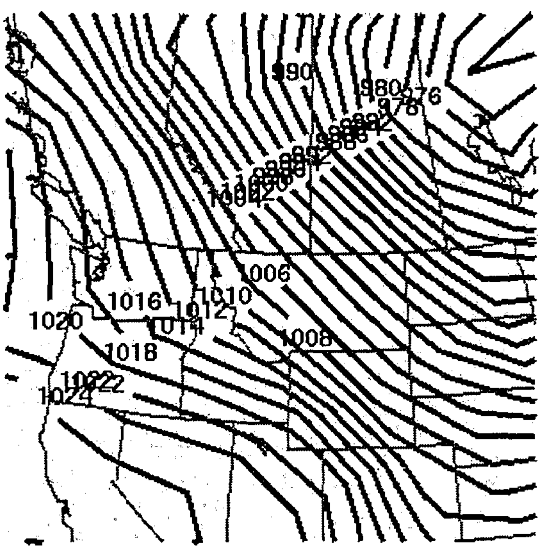

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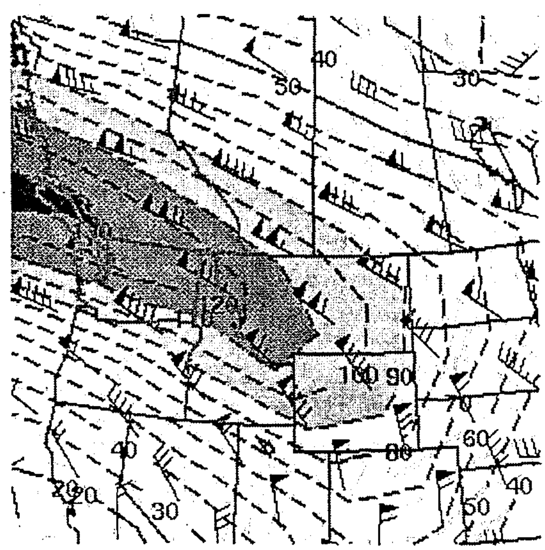
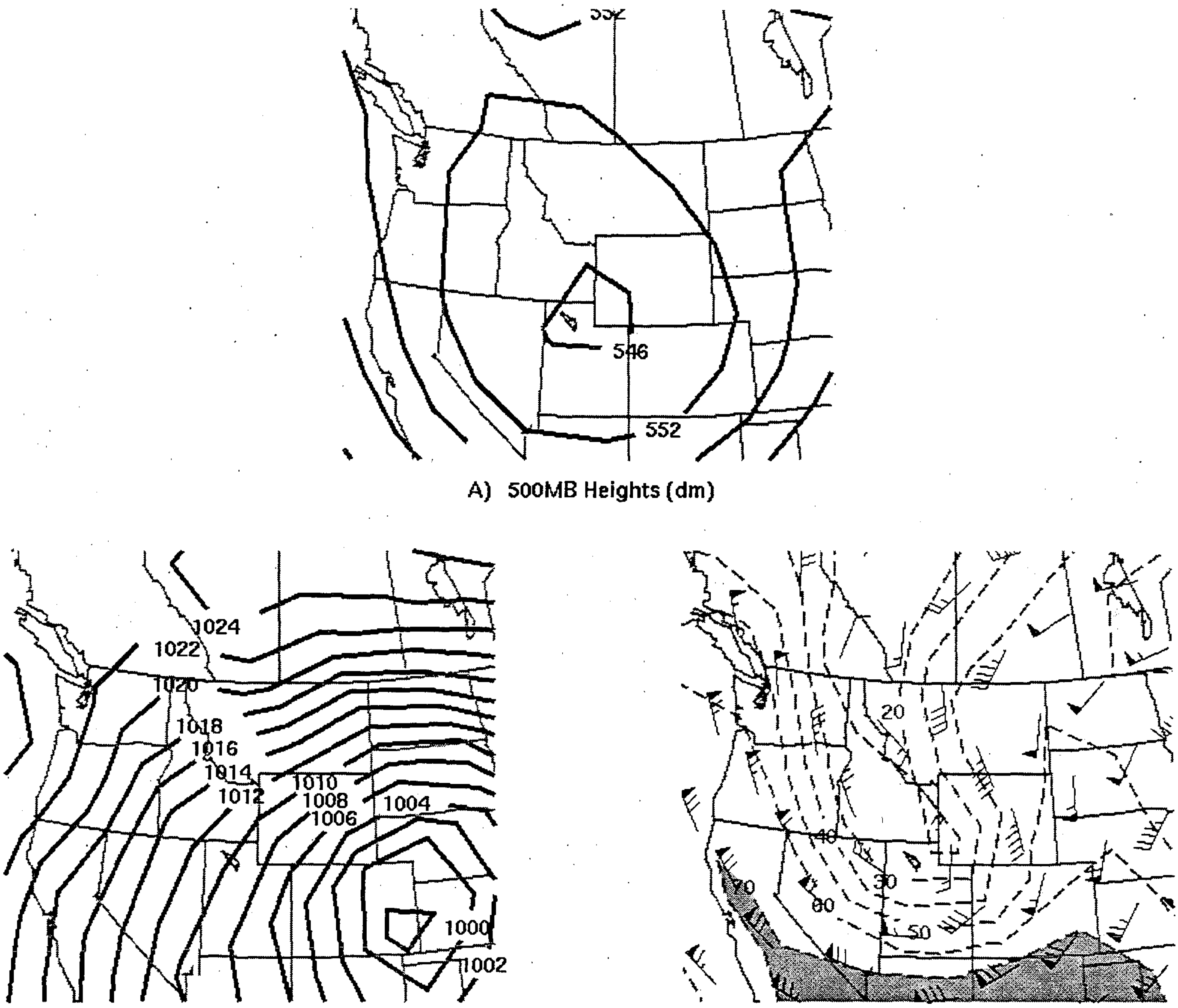


C) 250MB Winds (knots)

Figure 18 – "Super" Northwest Flow (Case 4)

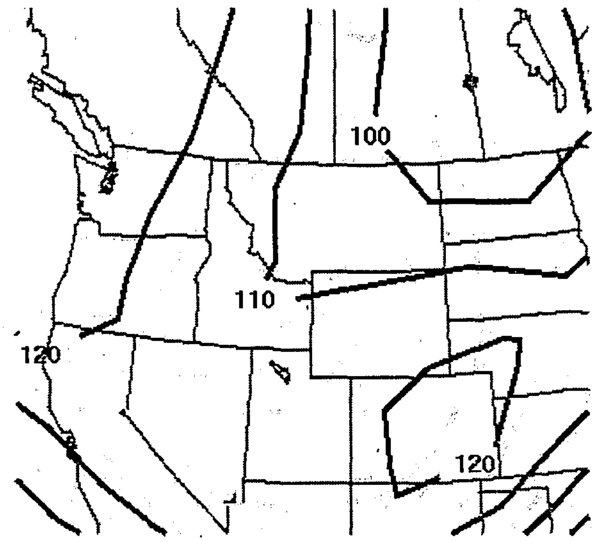


A) 500MB Heights (dm)

B) MSLP (mb)

C) 250MB Winds (knots)

Figure 19 – Closed Low Cases



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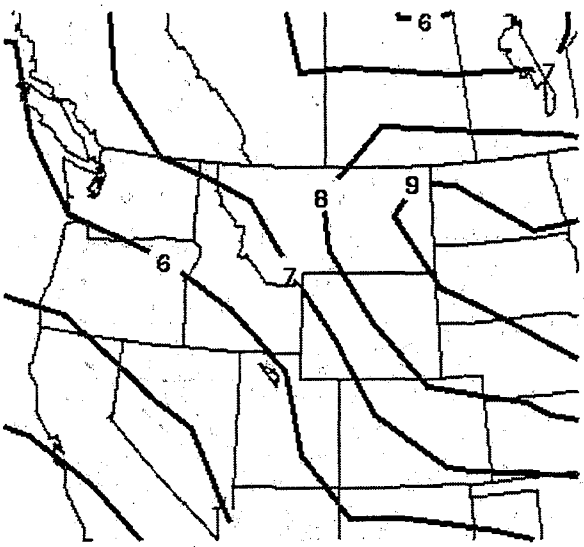

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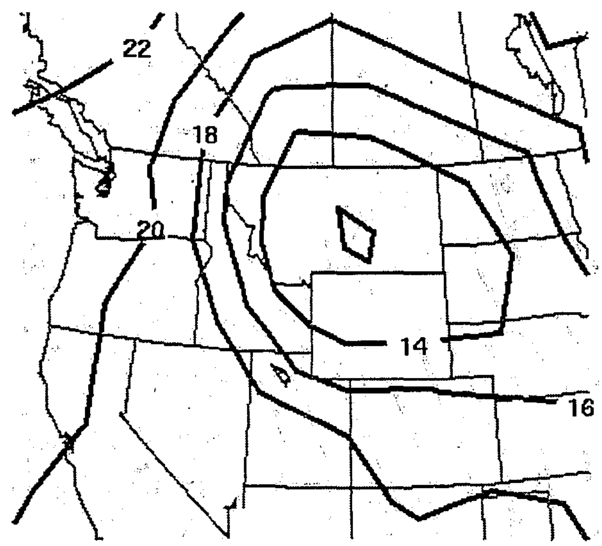
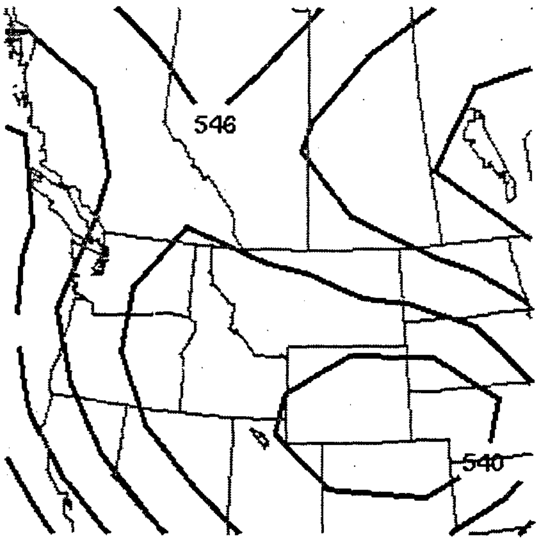
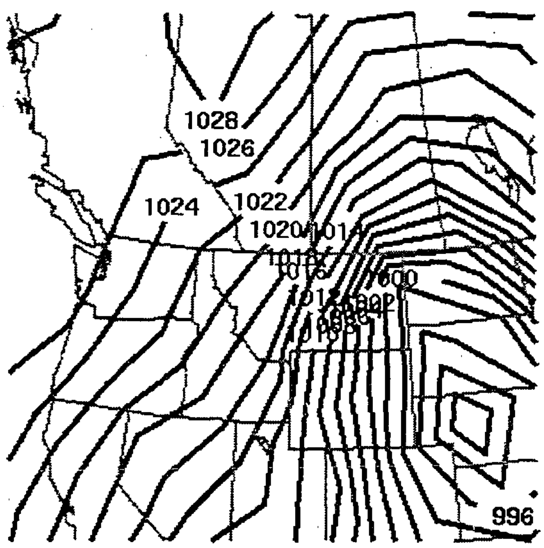


C) 250MB Winds (knots)

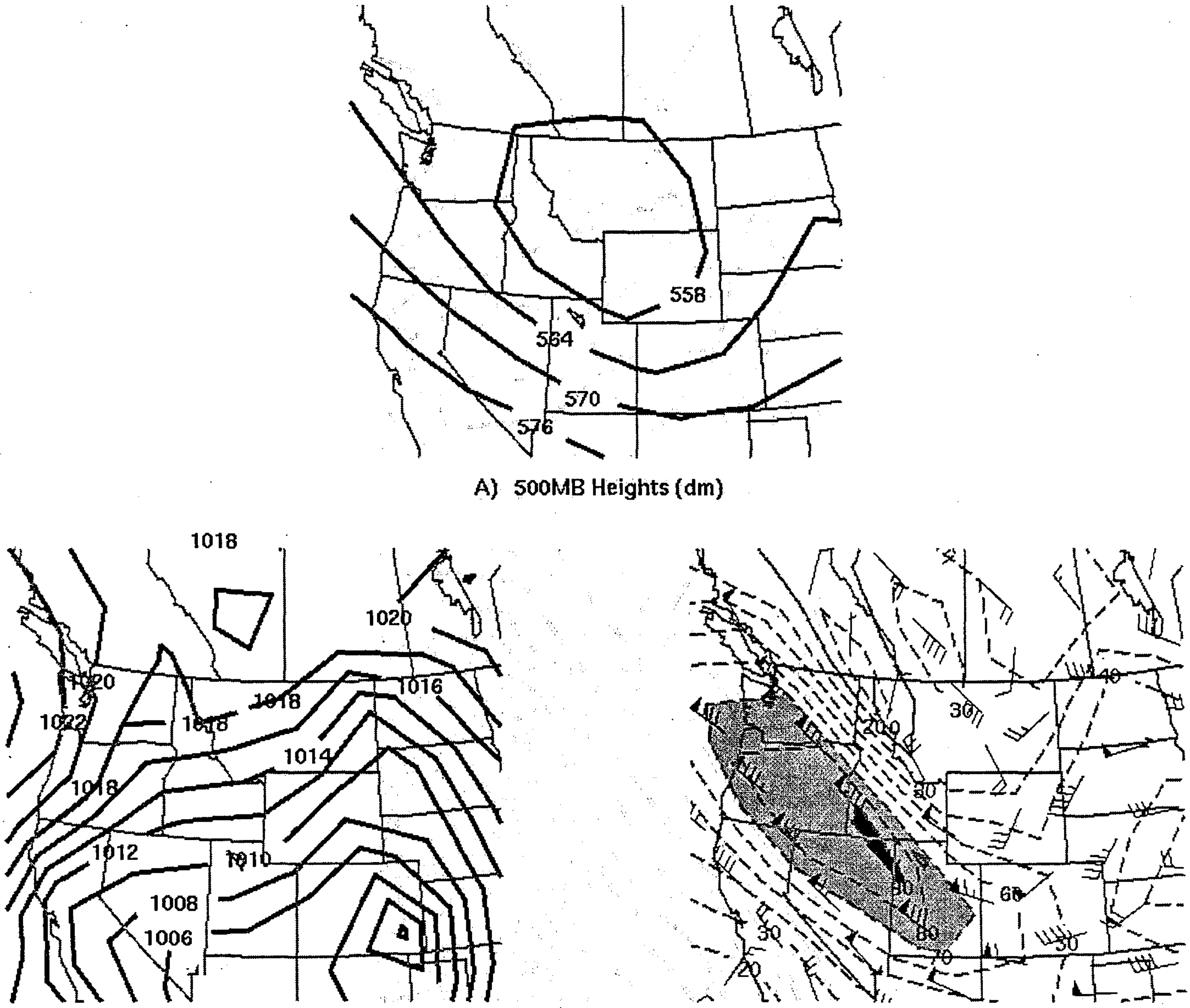
Figure 20 – Closed Low Standard Deviation



A) 500MB Heights (dm)



B) MSLP (mb)
Figure 21 - "Super" Closed Low (Case 1)



A) 500MB Heights (dm)

B) MSLP (mb)

C) 250MB Winds (knots)

Figure 22 – "Super" Closed Low (Case 2)

Snowfall Distribution -- Table 1					
Flow Pattern	**Number of Events**	**"Big" Events**	**% "Big" Events**	**"Super" Events**	**% "Super" Events**
Southwest	18	10	55.6	1	5.6
Amplified SW	23	14	60.9	2	8.7
West	13	7	53.8	0	0
Northwest	19	6	31.6	4	21.1
Closed Low	21	13	61.9	2	9.5

Snowfall Distribution -- Table 2					
Flow Pattern	**Average Snowfall (inches)**	**Avg. Length of Event (days)**	**Percentage of 1-Day Events**	**Percentage of 2-Day Events**	**Percentage of Events >2 Days**
Southwest	8.5	1.8	44.4	38.9	16.7
Amplified SW	7.4	1.4	65.2	30.4	4.4
West	7.9	1.8	30.8	61.5	7.7
Northwest	10.7	2.0	15.8	73.7	10.5
Closed Low	12.7	2.2	14.3	57.1	28.6

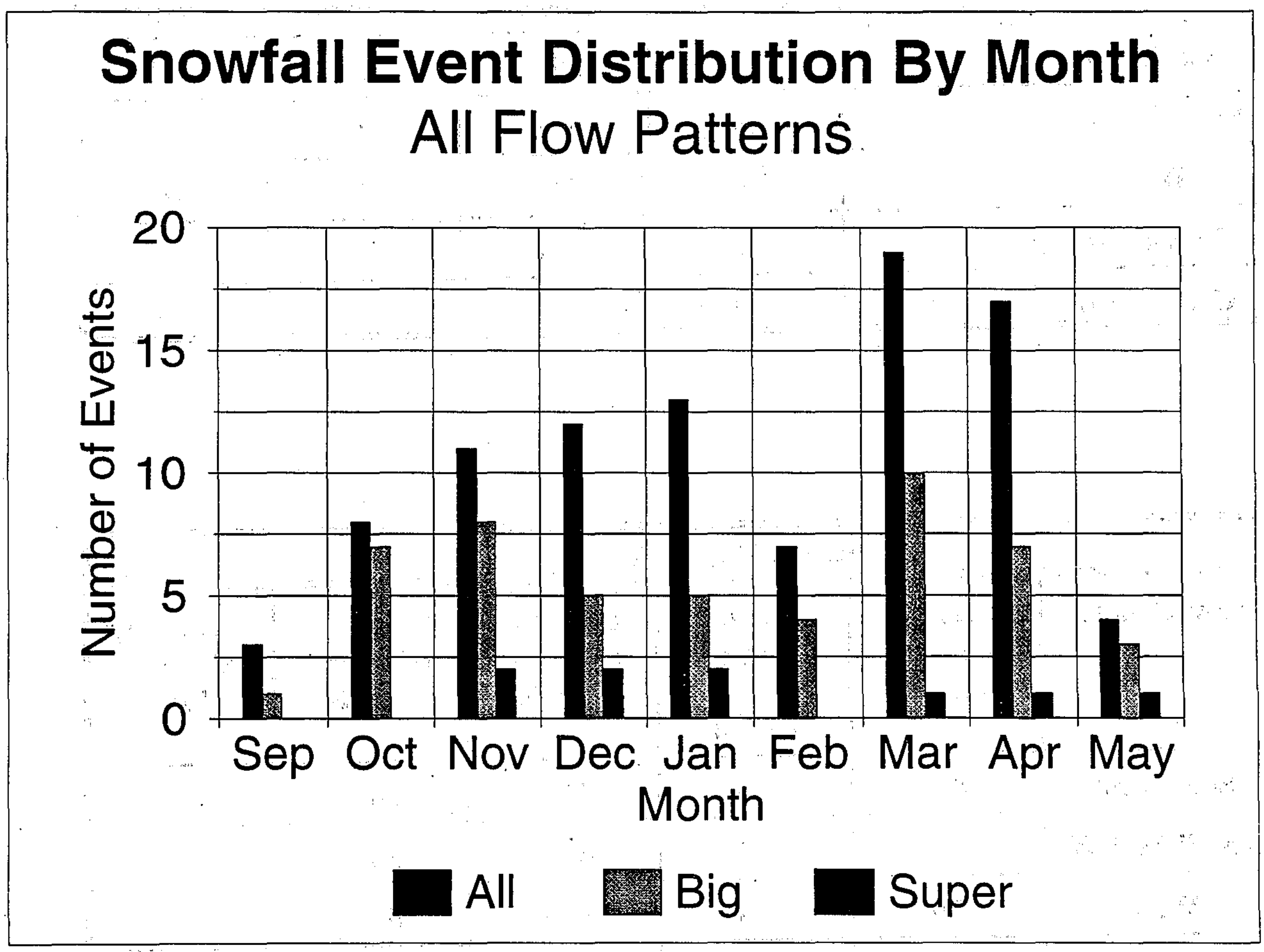


Figure 23 - Snowfall Distribution - All Flow Patterns

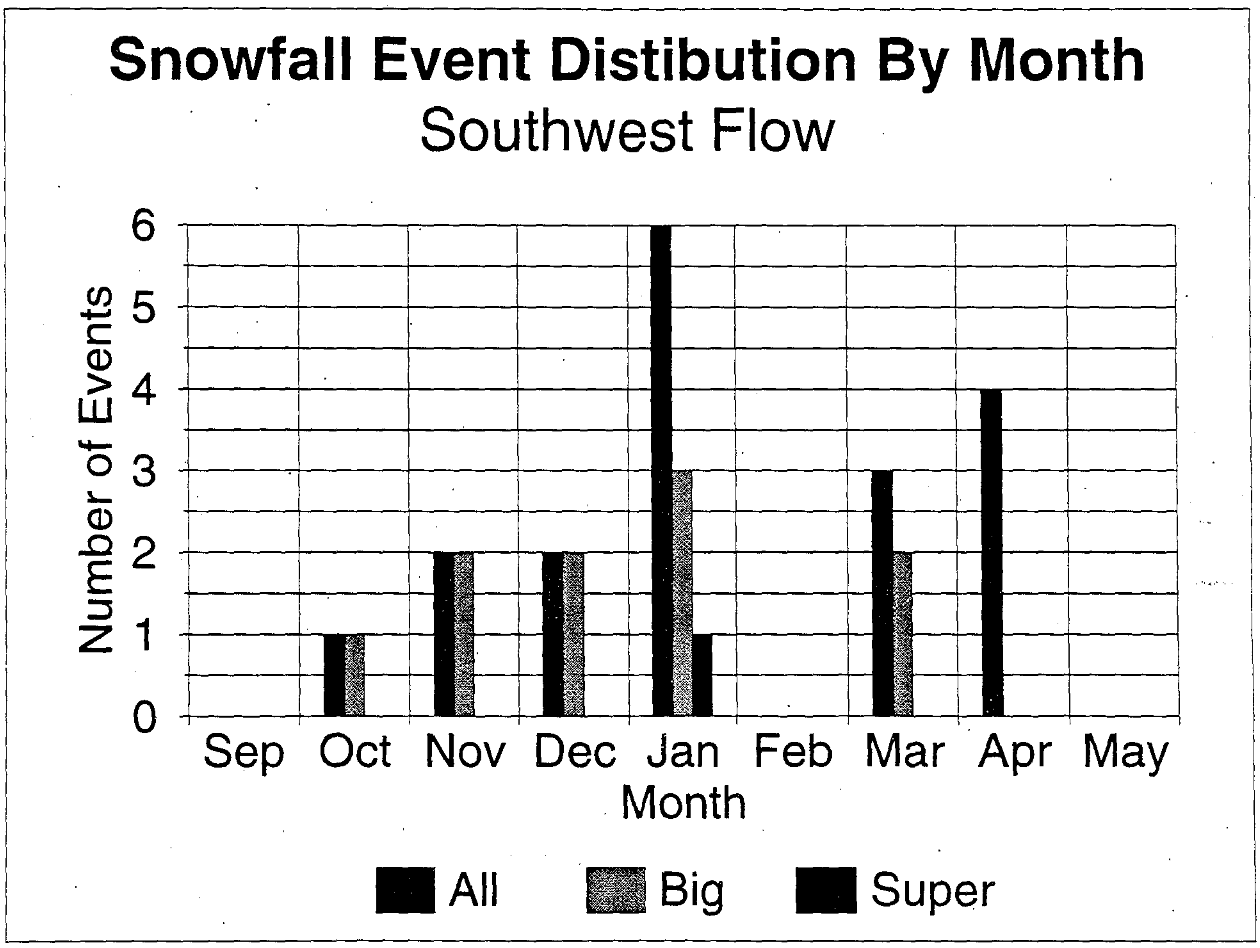


Figure 24a - Snowfall Distribution - Southwest Flow

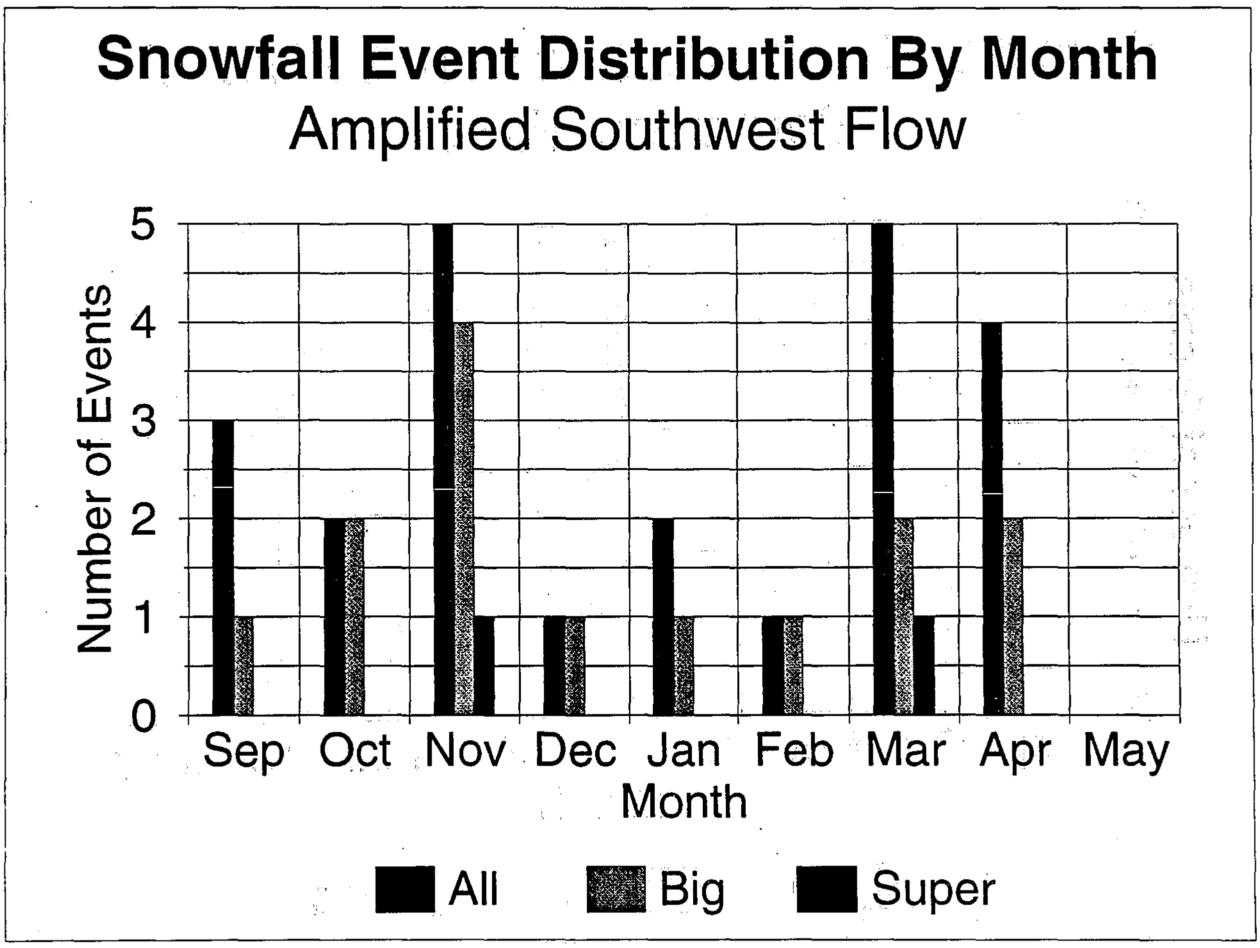


Figure 24b - Snowfall Distribution - Amplified Southwest Flow

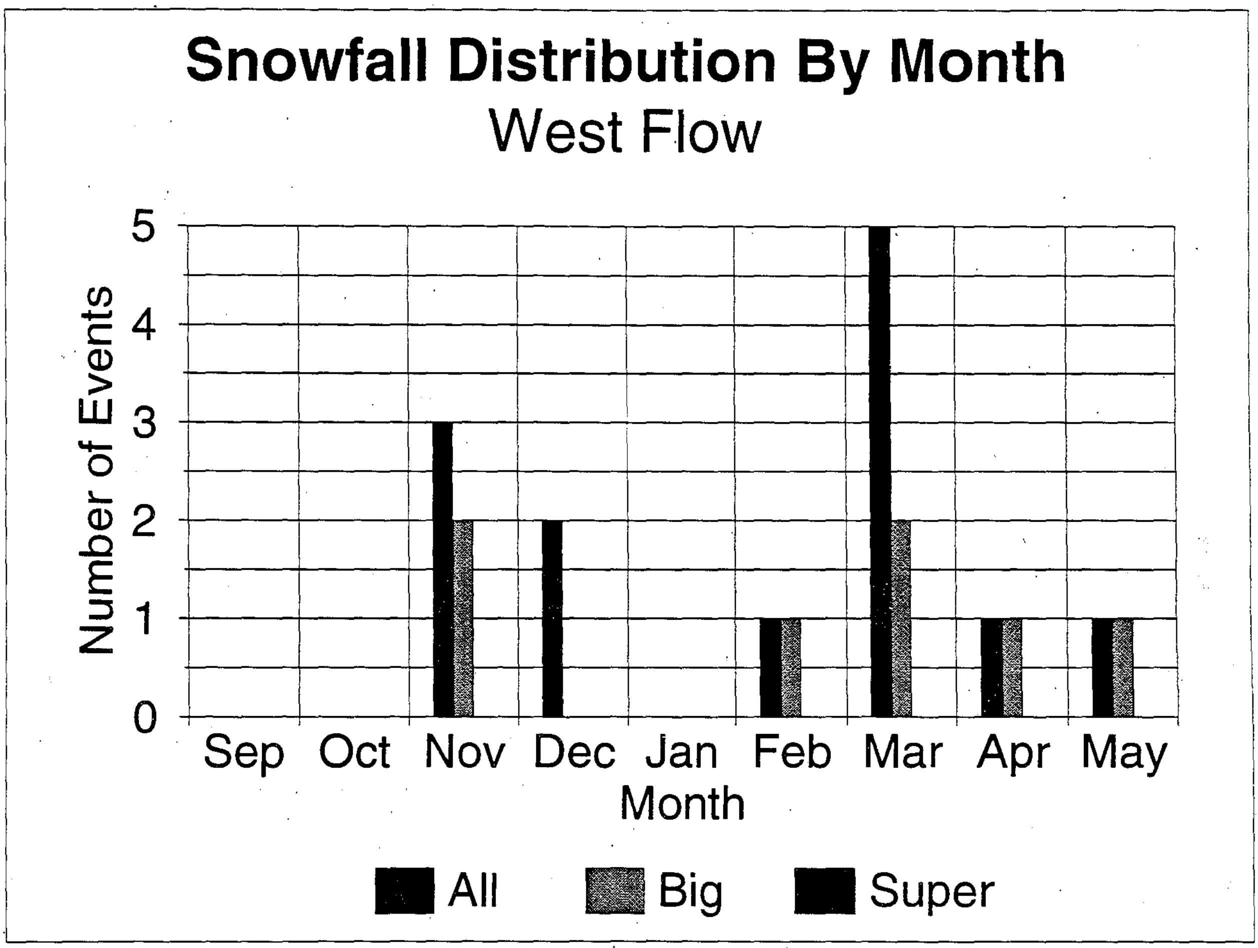


Figure 24c - Snowfall Distribution - West Flow

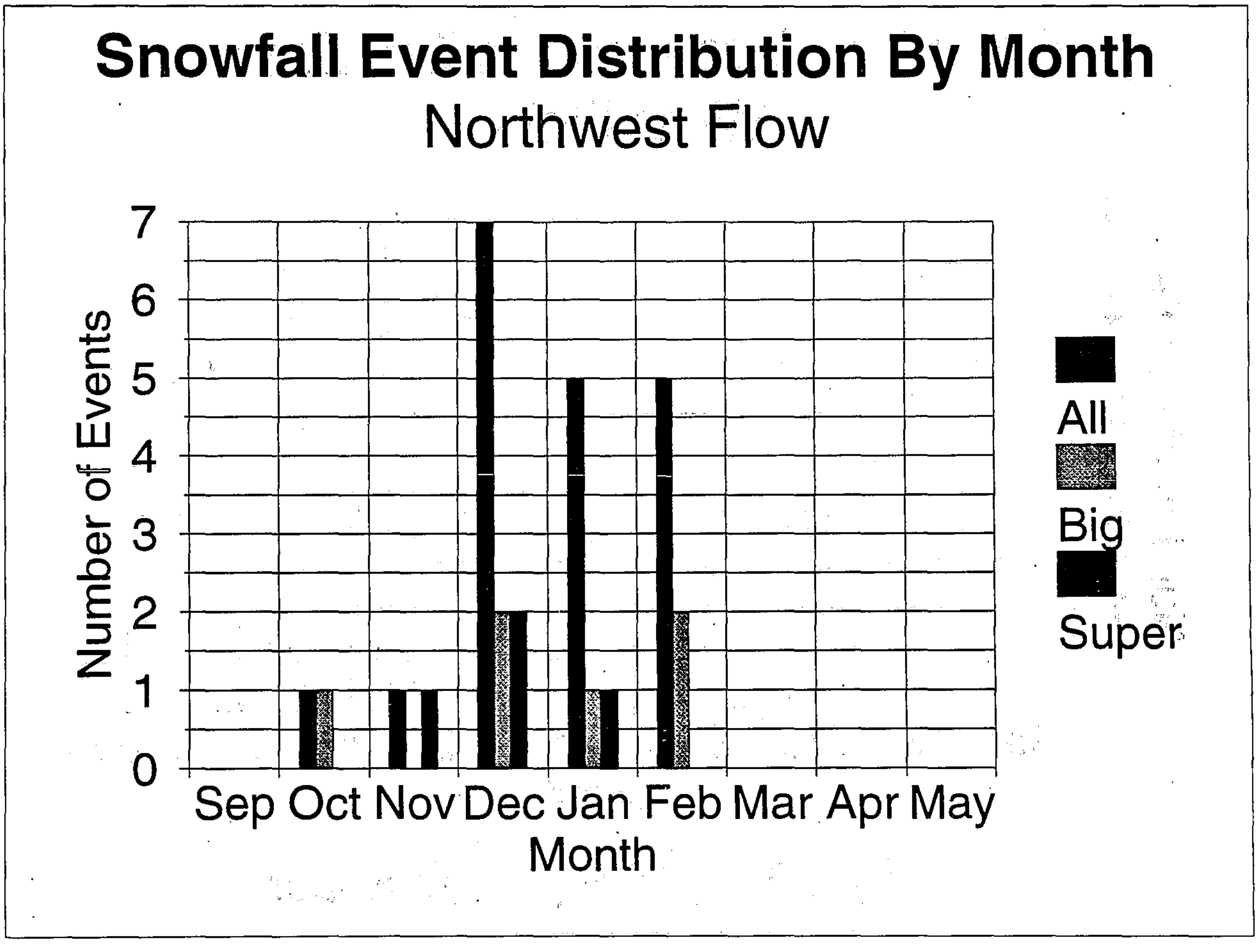


Figure 24d - Snowfall Distribution - Northwest Flow

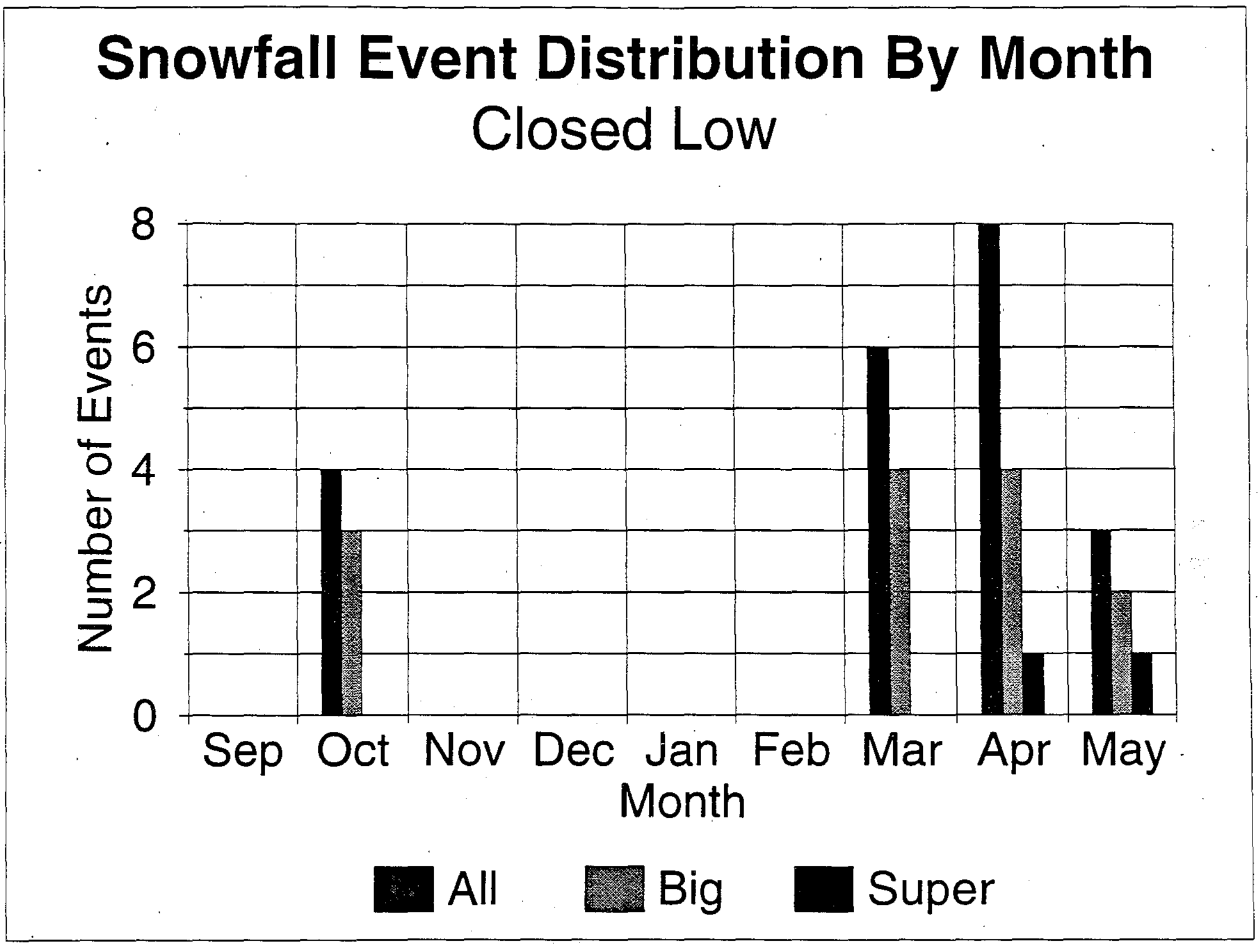


Figure 24e - Snowfall Distribution - Closed Low

APPENDIX A - LIST OF EVENTS AND SNOWFALL AMOUNTS

Southwest Flow Cases			
Date(s) of Event	**Snowfall (inches)**	**"Big" Event**	**"Super" Event**
December 3-4, 1948	8.2	✔	
January 7-8, 1949	8.0	✔	
January 13-16, 1954	13.2	✔	
December 23-24, 1955	7.4	✔	
March 12-13, 1957	8.4	✔	
April, 22-23, 1958	6.1		
April 23-25, 1961	9.7		
April 9-10, 1963	6.5		
March 12-13, 1967	7.6		
January 26-28, 1968	6.8		
October 15-16, 1971	7.4	✔	
January 2-3, 1973	6.1		
January 25-26, 1975	14.0		✔
November 18-19, 1977	11.0	✔	
November 17-19, 1978	10.8	✔	
April 2-4, 1982	6.6		
January 22-23, 1989	10.2	✔	
March 22-23, 1994	6.7	✔	

Amplified Southwest Flow Cases			
Date(s) of Event	Snowfall (inches)	"Big" Event	"Super" Event
February 26-27, 1951	7.2	✔	
March 24, 1954	6.9	✔	
March 2-4, 1955	8.7		
April 1-2, 1956	6.7		
November 1-2, 1957	6.0	✔	
November 15-17, 1958	7.8	✔	
March 9-10, 1962	6.3		
September 7-8, 1962	6.3		
March 22, 1964	10.5		✔
December 6-7, 1971	7.1	✔	
April 17-18, 1972	7.2	✔	
November 26-28, 1975	7.4		
November 19, 1979	6.0	✔	
January 17-18, 1980	7.6	✔	
September 18-19, 1983	7.5		
September 23-24, 1984	6.9	✔	
October 7-8, 1985	6.0	✔	
April 12-13, 1986	7.3		
March 7-9, 1987	6.1	✔	
April 25,1988	6.6	✔	
October 27-28, 1991	9.6	✔	
January 11-12, 1993	7.1	✔	
November 17, 1994	12.4		✔

West Flow Cases			
Date(s) of Event	**Snowfall (inches)**	**"Big" Event**	**"Super" Event**
February 8-9, 1955	9	✔	
May 2-3, 1956	6.7	✔	
March 4-5, 1957	7.7		
November 14-15, 1961	8.5		
November 22, 1962	6.3	✔	
March 3, 1972	7.5	✔	
December 2-3, 1972	7.6		
December 10-13, 1975	10.7		
November 17-19, 1978	10.8	✔	
March 3-5, 1980	7.5		
March 1-2, 1989	7.5		
March 22-23, 1990	7	✔	
April 28-29, 1990	6.2	✔	

Northwest Flow Cases			
Date(s) of Event	**Snowfall (inches)**	**"Big" Event**	**"Super" Event**
December 16-17, 1955	21.3		✔
February 13-16, 1958	8.1		
Dec 4-7, 1958	11.3		
February 16-18, 1959	9	✔	
November 10-12, 1959	18.8		✔
January 6-8, 1962	10.6	✔	
January 21-22, 1963	6.5		

Northwest Flow Cases			
Date(s) of Event	**Snowfall (inches)**	**"Big" Event**	**"Super" Event**
December 16-17, 1963	13	✔	
February 27-28, 1970	6.1		
December 31, 1971 - January 2, 1972	17.6		✔
October 31 - November 4, 1973	12.8	✔	
December 27-29, 1973	9.3		
February 24-25, 1978	8.4	✔	
December 4, 1978	13.7		✔
December 23, 1984	7.9	✔	
February 3-5, 1988	6.6		
December 19-21, 1989	7.1		
January 16-17, 1994	5.9		

Closed Low Cases			
Date(s) of Event	**Snowfall (inches)**	**"Big" Event**	**"Super" Event**
October 17-20, 1949	8	✔	
March 11-12, 1954	7		
October 23-25, 1954	8.6		
April 2-5, 1955	42.3*		✔
March 1-3, 1966	14.2	✔	
April 29-30, 1967	9	✔	
April 26-28, 1970	19.2	✔	
April 19-20, 1973	9.6		

Closed Low Cases			
Date(s) of Event	**Snowfall (inches)**	**"Big" Event**	**"Super" Event**
March 25-27, 1975	6.8		
April 7-8, 1975	8.7	✔	
March 28-29, 1977	6.7	✔	
October 15-16, 1980	14.7	✔	
March 17-18, 1981	9.3	✔	
May 11-12, 1981	15.6		✔
March 19-20, 1982	11.8	✔	
May 11-12, 1983	11.9	✔	
May 8-9, 1986	8.3	✔	
April 27-28, 1989	6		
April 10-13, 1991	22.7	✔	
October 7-8, 1993	7.8	✔	

* - Largest Billings snowfall on record

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