Synoptic Patterns and Statistics Associated with Snowfall at Flagstaff from 1975 to 1995

1) Introduction

A common forecast challenge during the winter months over the western Mogollon Rim is predicting snowfall accumulation. This paper documents the synoptic patterns that resulted in 24 hour snowfall totals of over 6.0 inches at Pulliam airport in Flagstaff over a 20 year period extending from 1975 to 1995. In addition, various snowfall accumulation statistics during the same period from Pulliam airport are presented. By looking at this snowfall history forecasters will be able to increase their understanding of both the potential snowfall accumulation and the degree of uncertainty associated with various synoptic patterns.

2) Data

Historical snowfall measurements for Flagstaff were obtained from the Local Climatological Data for Arizona (LCD) for the period 1975 through 1995 for the months of November through April. Snowfall totals were based on midnight-to-midnight accumulations (local time) and grouped using the following categories:

1) Normal Snowfall - T to 2.9 inches
2) Snow Advisory Snowfall - 3.0 to 6.0 inches
3) Winter Storm Snowfall - greater than 6.0 inches

For this paper charts that were composited using events with greater than 6.0 inches of snowfall accumulation will be shown and discussed. The above snowfall categories were used at Flagstaff prior to the 1999-2000 winter season and do not reflect snowfall criteria currently being used in operations.

The National Meteorological Center Grid Point Data Set: Version III for the Northern Hemisphere was the source of data used for plotting upper air charts.

3) Methodology

Using the plotting program NMCDraw, individual 500 mb height charts were plotted for all the 6.0 inch or greater snowfall accumulations. For each snowfall category the individual 500 mb height charts were subjectively grouped based on the synoptic setting. Each group of charts was then composited using NMCComp. Composite height charts (in decameters) were plotted for the 250 and 500 mb levels. Composite wind speed (knots) and direction charts were plotted for the 250 and 500 mb levels. Composite temperature charts (Celsius) were plotted for the 250, 500 and 700 mb levels.

The resulting synoptic patterns and snowfall statistics are presented in the following.

4) Results

The patterns below were observed during winter snowfall events that produced accumulations in excess of 6.0 inches. However, it can be said that during the period studied essentially all snow producing storms approached from the northwest. The highest snowfall totals tended to occur when the mid-level low center or vorticity max approached through the northern half of California and Nevada. For the period of study it was observed that 500 mb patterns similar in appearance were associated with vastly differing snowfall accumulations. Subtle differences in the shape and position of a particular trough can be critical as to whether significant snowfall is observed at Flagstaff. The companion paper, "An Analysis of Variations in Snowfall Accumulations at Flagstaff under Similar Synoptic Settings" discusses the important features to consider when developing a "sense" of the snowfall potential for a particular storm.

In this paper, the characteristics of the synoptic patterns associated with snowfall accumulations greater than 6.0 inches are discussed. This includes the months in which each pattern was most prevalent and a few hints as to when higher snowfall amounts can be anticipated. In addition, snowfall statistics are shown to help the forecaster get a feel for what can generally be expected when a snow producing storm moves through Flagstaff.

a) Digging Troughs

Digging troughs are characterized by strong short-wave troughs that undergo strong cyclogenesis as they move across the western United States (Figures 1a, 1b, 1c and 1d). This kind of amplification can occur under a number of settings including a high amplitude eastern Pacific ridge (Figure 1a), split flow (Figure 1b), broad trough (Figure 1c) and progressive flow (Figure 1d). During the period of study digging troughs occurred throughout the snowfall season from November through April. However, early in the snowfall season, November and December, digging toughs were by far the most common pattern that produced measurable snow. In fact, during the 20 year period studied, November through mid December was the almost exclusive domain of short-wave troughs digging toward Arizona from the northwest. This tendency is likely due to November and December being a transition period into the heart of the snowfall season which is January through March. These incursions of colder air are ultimately how the mean baroclinic zone gradually moves southward. The digging trough pattern can produce snowfall accumulations of a trace to over 20 inches. These variations are based almost solely on the difference in the position and wavelength of a particular trough, as well as the position and strength of mid and upper level jet streams. The details one must analyze for the digging trough patterns are highlighted in the companion paper, "An Analysis of Variations in Snowfall Accumulations at Flagstaff under Similar Synoptic Settings" which highlights deepening troughs that move through California and Nevada.

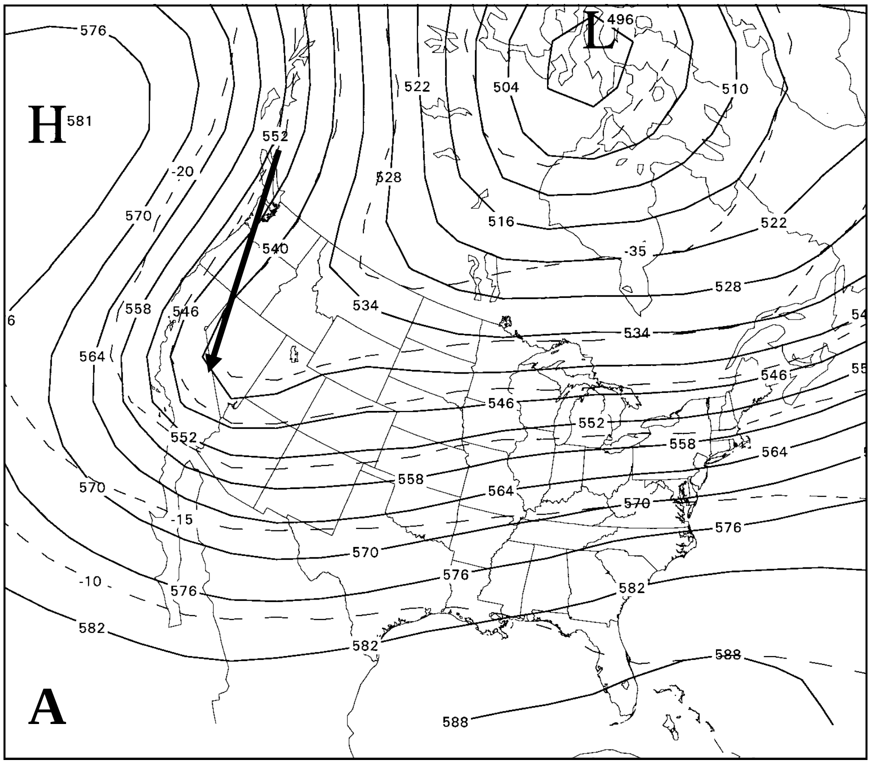

Figure 1a: High amplitude east Pacific ridge digging trough pattern around or just after the onset of snowfall at Flagstaff. Shown are 500 mb heights in dm (solid lines) and 500 mb temperatures in C. The solid black arrow indicates the movement of the vorticity max 24 hours prior to the 500 mb pattern shown.

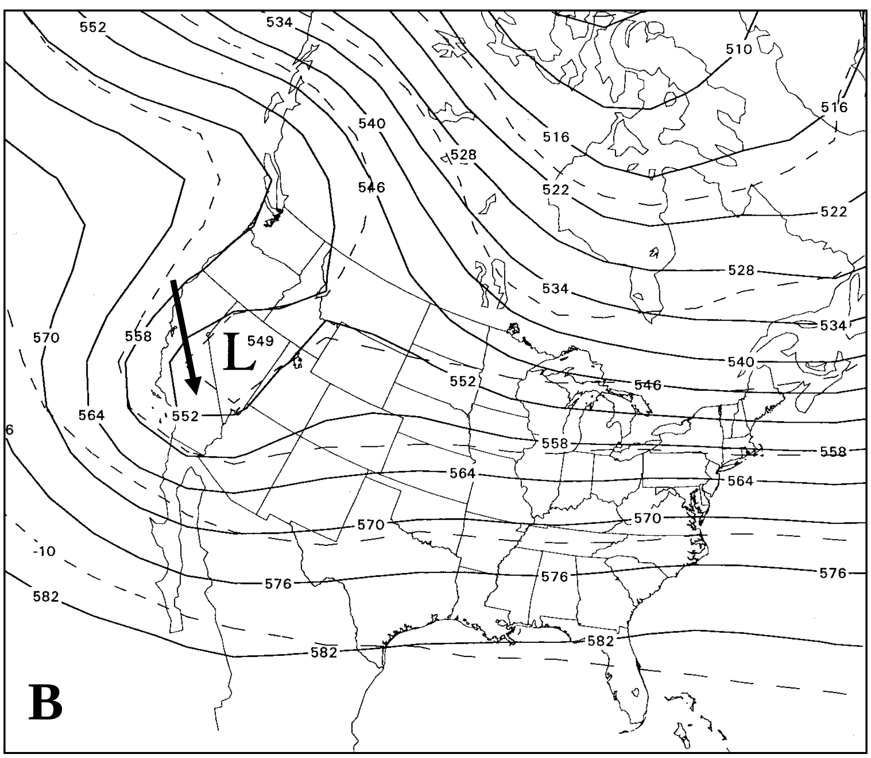

Figure 1b: Same as above except split flow.

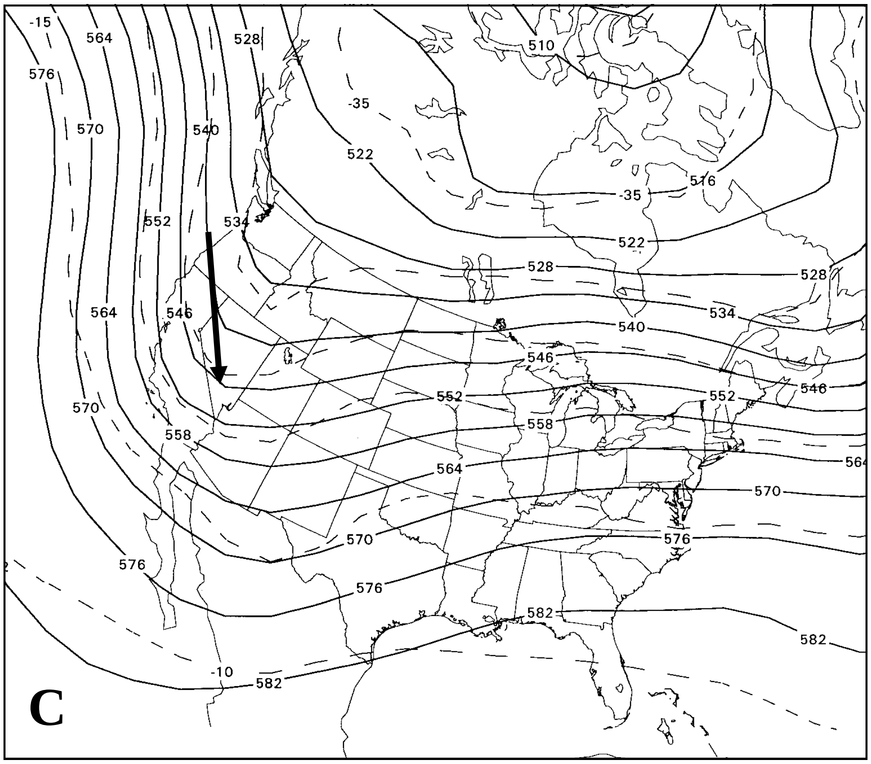

Figure 1c: Same as above except broad long-wave trough.

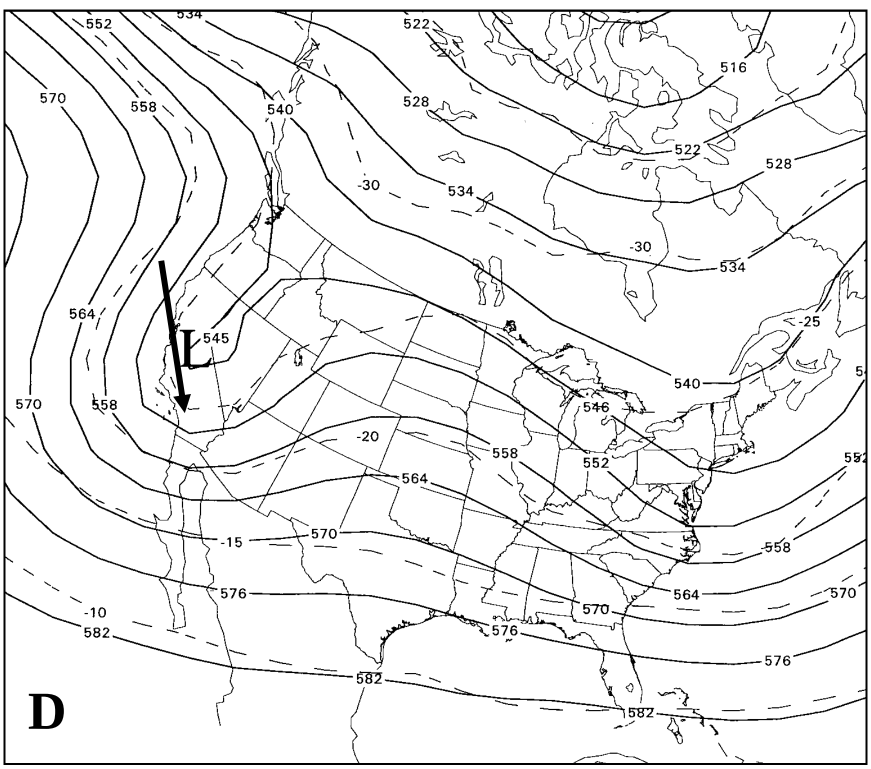

Figure 1d: Same as above except progressive pattern.

b) **Deep long-wave Troughs**

The deep long-wave trough pattern was observed almost exclusively in January and February during the period of study. The deep long-wave trough pattern was seldom seen early in the snow season (November and December) or late in the snowfall season (March and April). There are two flavors of the deep long-wave trough. Figure 2a illustrates the broad deep trough and Figure 2b shows the deep high amplitude trough. The broad deep trough (Figure 1a) is characterized by a far southward shift of the polar low and well below normal heights across all of the western United States. The long-wave trough and cyclonic curvature is on the scale of several thousand miles. Snowfall is enhanced by the approach of a strong jet max embedded in the general flow. The deep high amplitude trough (Figure 2b) is associated with major ridging over the eastern Pacific Ocean and a semi permanent positive tilt long-wave trough across the western United States. The data set shows that the big snow occurs when a strong jet max moves through the west side of the long-wave trough and approaches Arizona.

Interestingly, these patterns are almost exclusively associated with snowfall accumulations of greater than 6.0 inches over a 24 hour period. In other words, the deep long-wave trough pattern was rarely associated with mundane 1 or 2 inch snowfall events during the 20 year period studied. But there is a caveat, the deep high amplitude trough (Figure 2b) is extremely sensitive to trough position as detailed in the companion paper.

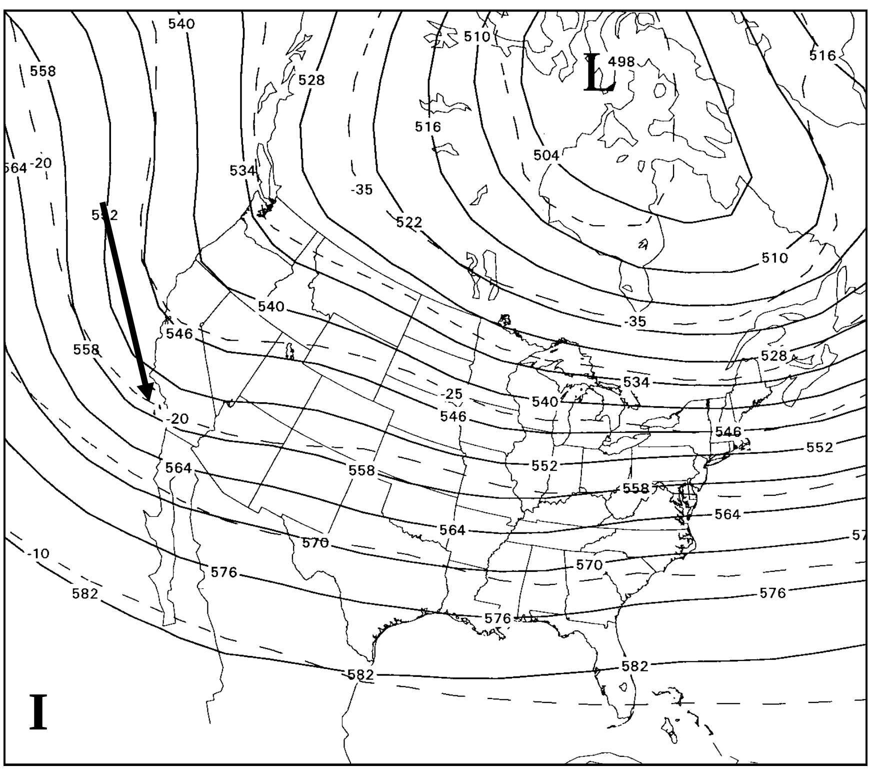

Figure 2a: The broad deep long-wave trough pattern around or just after the onset of snowfall at Flagstaff. Shown are 500 mb heights in dm (solid lines) and 500 mb temperatures in C. The solid black arrow indicates the movement of the vorticity max 24 hours prior to the 500 mb pattern shown.

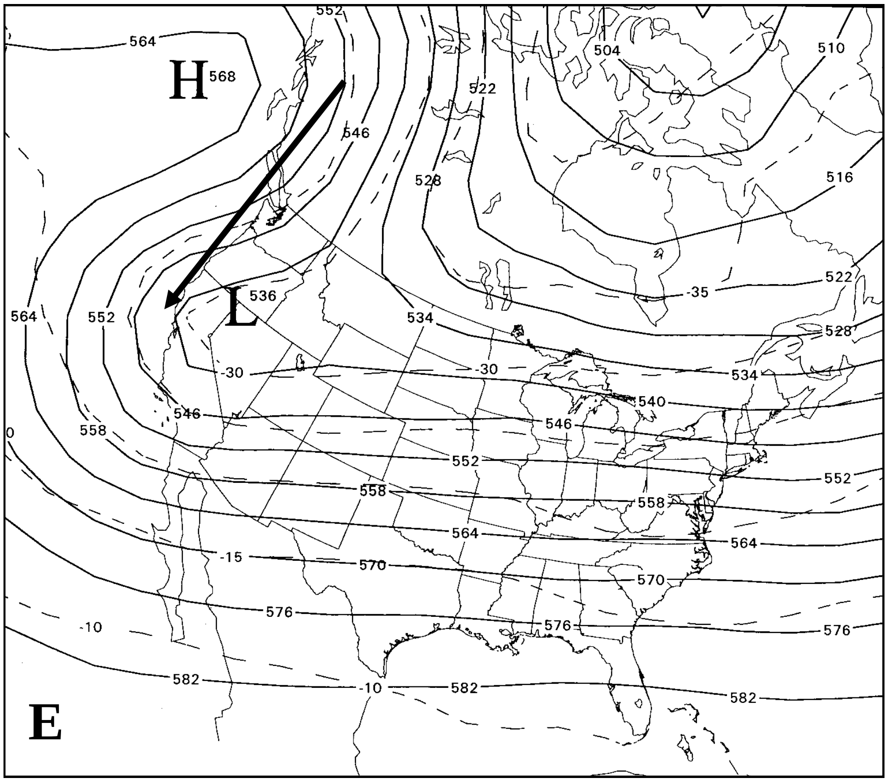

Figure 2b: Same as Figure 2a except deep high amplitude long-wave trough.

c) High over Low pattern

The high over low pattern was a frequent visitor during January and February during the period of study. The low typically forms over the eastern pacific or along the California coast as upstream trough energy undercuts an existing ridge (Figure 3). A split flow develops with the high over low pattern forming (also known as a rex type blocking pattern). This pattern was also used in the companion paper comparing lows that move through central California into Nevada.

This appears to be a difficult pattern to get a handle on and not likely associated with widespread heavy snowfall. However, if enough energy is transmitted to the low it will be cold enough and contain enough baroclinicity for relatively strong low-level flow and decent chance at snow amounts over 6.0 inches. However, the more "cut-off" the low is from the flow the less likely snow amounts over 6.0 inches will be observed with 1 or 2 inch totals becoming more likely. Not really sure why this pattern doesn't show up more late in the snowfall season but it could be this pattern becomes more of a rain producer from March into April.

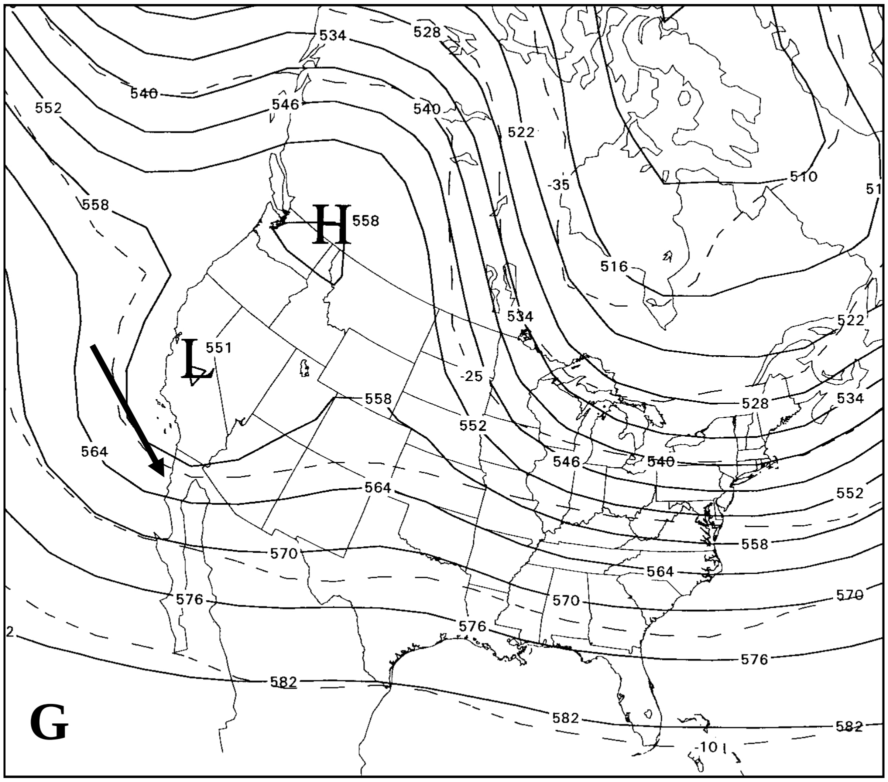

Figure 3: The high over low pattern around or just after the onset of snowfall at Flagstaff. Shown are 500 mb heights in dm (solid lines) and 500 mb temperatures in C. The solid black arrow indicates the movement of the vorticity max 24 hours prior to the 500 mb pattern shown.

d) Kamikaze Trough

During the period of study the kamikaze trough generally made its appearance from late December through the remainder of the winter season. This pattern also had a tendency to make its appearance during El Nino years and was much less frequent during normal or La Nina phases of the ENSO. The kamikaze trough is characterized by a trough from the Pacific moving directly into a long-wave ridge over the western United States (Figure 4). The ridge typically bends but doesn't break and the trough ultimately shears-out, de-amplifies and is absorbed into the large-scale flow. How much snow is produced depends on how much energy and jet max forced upward motion can make it through the ridge before the trough/jet max is essentially absorbed by the large-scale flow and dies (thus the name "kamikaze trough"). Because of the rapid weakening of the kamikaze trough it is probably difficult to judge if the dynamics for snowfall will last long enough for a greater than 6.0 inch snow accumulation or simply a good old fashioned 1 .0 or 2.0 inch jobber. If there was any tendency associated with the kamikaze trough it was that a stronger mid- and upper-level jet was associated with a better the chance for higher snowfall accumulations. However, this was not an absolute, and quite a bit of variability was associated with this pattern. The best advice, don't get to upset when a kamikaze trough inevitably "sinks" your forecast!

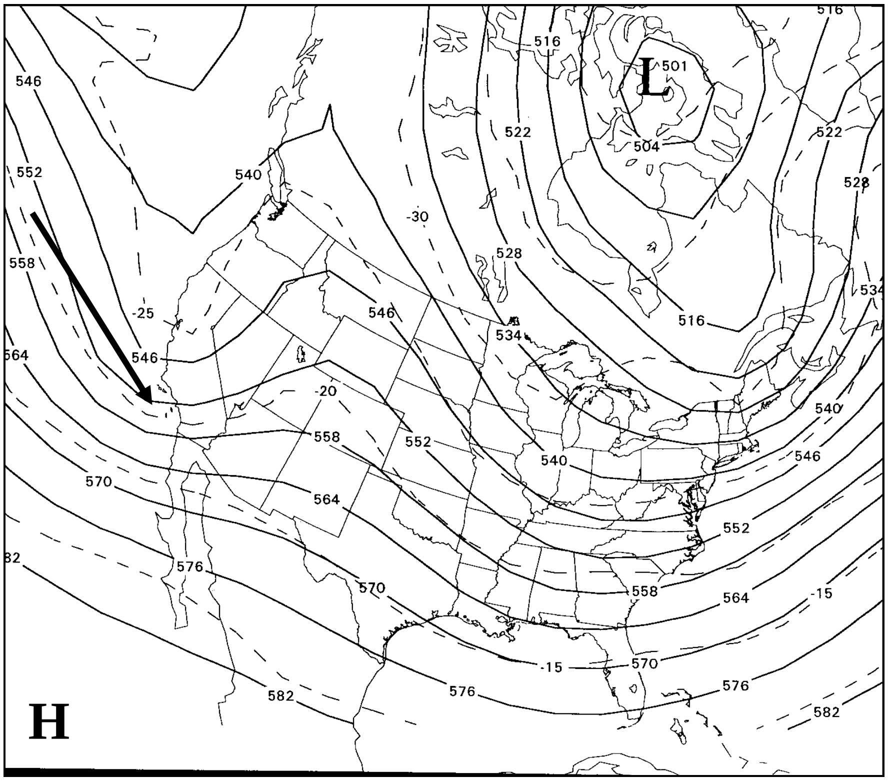

Figure 4: Kamikaze trough pattern around or just after the onset of snowfall at Flagstaff. Shown are 500 mb heights in dm (solid lines) and 500 mb temperatures in C. The solid black arrow indicates the movement of the vorticity max 24 hours prior to the 500 mb pattern shown.

e) Broad Closed-Low Over the Great Basin

During the period of study the broad closed-low over the Great Basin was observed primarily from later in March into April (Figure 5). This pattern was rarely seen during the early to mid portion of the snowfall season (November through February) in terms of snowfall accumulation. In addition, when this pattern was observed, it was generally associated with snowfall accumulations of over 6.0 inches over a 24 hour period. Only 2(??) out 12 cases were associated with lighter snowfall amounts. This pattern appears to characterize the last gasp cyclogenetic troughs that can occur at the end of the snowfall season and are often doozies!

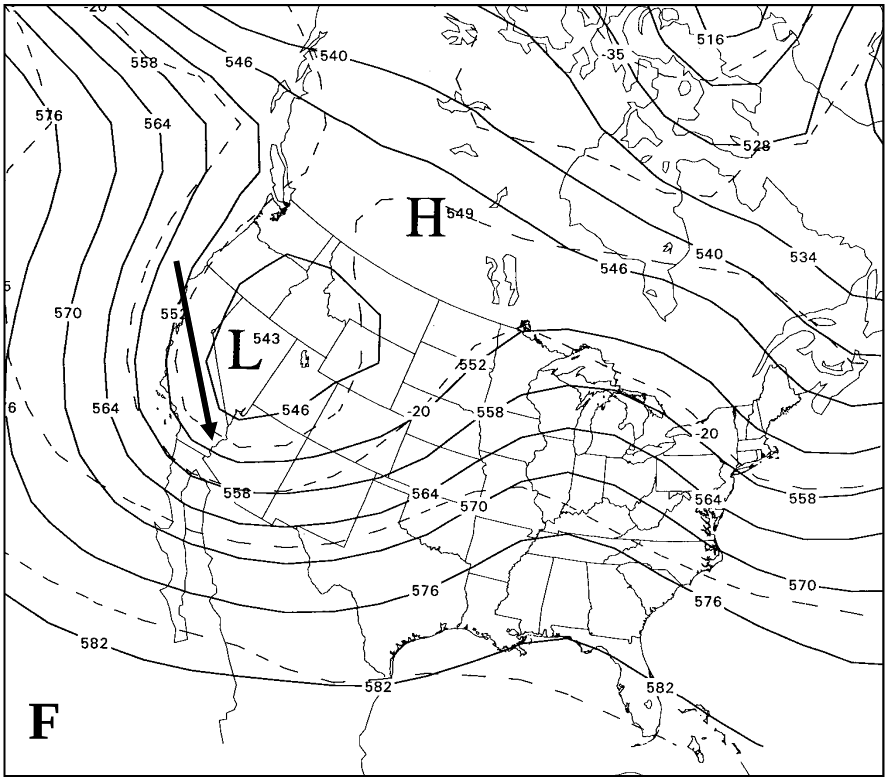

Figure 5: Broad closed-low over the Great Basin pattern near or after the onset of snowfall at Flagstaff. Shown are 500 mb heights in dm (solid lines) and 500 mb temperatures in C. The solid black arrow indicates the movement of the vorticity max 24 hours prior to the 500 mb pattern shown.

f) Snowfall Statistics

Tables 1, 2 and 3 below summarize various snowfall statistics calculated for the 20 year period of study. Table 1 shows the average snowfall accumulation associated with measurable snowfall events (no trace events). In general the typical snowfall at Flagstaff was around 3 inches with a standard deviation of +/- 3 inches. The snow accumulation observations were not normally distributed with the peak of the distribution curve (not shown) shifted to the left of the average and weighted toward the lower snowfall amounts. This is illustrated more concretely in Table 2.

	Nov	Dec	Jan	Feb	Mar	Apr
Average Snowfall per Event (inches)	3.8	2.4	3.2	3.2	3.1	2.7
Standard Deviation (+/- inches)	4.2	2.9	3.5	3.8	3.3	3.0

Table 1: Shown are the average snowfall per event and standard deviation by month for snowfall events greater than a trace. Distribution curve for this data set is not normally distributed with the curve skewed toward accumulation less than 3.0 inches.

Table 2 shows the percentage of 24 hour snowfall accumulation that fell within the various categories listed. In general, only 12% percent of all storms exceeded 6.0 inches of snowfall accumulation in 24 hours. About 14 % percent of the storms produced snowfall totals in the 3-6 inch range. However, 74% percent of the storms produced snowfall amounts of less than 3 inches. Considering the winter storm/heavy snow criteria at Flagstaff is now 8 inches or greater probably less than 10% percent of all storms exceed this 24 hour accumulation.

	Nov	Dec	Jan	Feb	Mar	Apr	Avg
>6 inches	16%	8%	16%	13%	11%	12%	12%
3-6 inches	10%	10%	12%	17%	19%	14%	14%
<3 inches	74%	82%	72%	70%	70%	75%	74%

Table 2: Shown are the percentage of events that exceeded the given snowfall accumulation categories by month.

Table 3 translates the percentages above into actual numbers of events per month. It can be seen that on average there was only 1 snowfall event of 6 inches or greater per month during the period studied. What does this say? All the synoptic signals must be positive to exceed the highest snowfall criteria at Flagstaff.

	Nov	Dec	Jan	Feb	Mar	Apr	Average
>6 inches	1	1	2	1	1	1<	1 per month
3-6 inches	1	1	1	2	2	1	1 per month
<3 inches	4	7	8	6	8	4	6 per month
	5	9	11	9	11	6	

Table 3: Shown are the average number of events per month by category during the period studied.

5) Conclusions

The synoptic patterns associated with snowfall accumulations of greater than 6.0 inches at Flagstaff from 1975 through 1995 were presented. In general, snowfall at Flagstaff occurred with a short-wave trough approaching from the. It was shown that certain patterns are more dominant during differing portions of the snowfall season or during El Nino years. A general conclusion that can be drawn from this study is that the largest snowfall accumulations are associated with storms that approach through a very narrow range of directions. In the companion paper, “An Analysis of Variations in Snowfall Accumulations at Flagstaff under Similar Synoptic Settings” it is shown that storms that stray away from this distinct line of approach rapidly lose the potential to produce over 6.0 inches of snowfall in 24 hours. The statistics support this conclusion in that such a low percentage of storms produce snowfall accumulations of greater than 6.0 inches in 24 hours. This suggests that conditions need to be just right for the higher snowfall totals and for the western Mogollon Rim (and other similar areas of northern Arizona) the northwest approach is critical. The companion paper details these aspects in more detail.

	Nov	Dec	Jan	Feb	Mar	Apr	Avg
WS (>6 in.)	16	8	16	13	11	12	12
SA (3-6 in.)	10	10	12	17	19	14	14
NS (<3 in.)	74	82	72	70	70	75	74
	108	177	218	182	220	118	