An Analysis of Variations in Snowfall Accumulations at Flagstaff Under Similar Synoptic Settings

1) Introduction

Winter weather over the western Mogollon Rim is primarily comprised of snow, wind or a combination of the two. This study looks at the synoptic environments associated with snowfall over the western Mogollon Rim of central Arizona. Recognizing subtle but important differences between similar synoptic settings can help in making better estimates of snowfall accumulation. This information, in turn, can be used to provide emergency personnel, road crews, travelers, schools, etc., important up front guidance.

This research represents an initial step toward better documentation and understanding of northern Arizona winter weather regimes.

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 (denoted as **NS**)
2) Snow Advisory Snowfall - 3.0 to 6.0 inches (denoted as **SA**)
3) Winter Storm Snowfall - greater than 6.0 inches (denoted as **WS**)

During the above data period, around 70 percent of the identified snow storms produced less than 3 inches of snow at Flagstaff. In this paper **NS** is taken to mean a storm that produces less than 3 inches of snowfall as it moves across the Flagstaff area. The above categories were used at Flagstaff prior to the 1999-2000 winter season and do not reflect snowfall categories 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 **WS** and **SA** cases. Because so many cases fell within the **NS** category only 50 percent of these events were used to plot individual 500 mb height charts. For each snowfall category the individual 500 mb height charts were subjectively grouped based on 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

Examination of the composite charts revealed that the six most common synoptic settings for the **WS**, **SA** and **NS** categories shared many similarities. As a result, the similar synoptic settings were analyzed to identify the important differences that favor larger vs. smaller snowfall accumulations.

4) Results

a) Path of the 500 mb Low Center

When measurable snowfall occurred in Flagstaff the low center normally approached from the west through north (**Figure 1a**). However, for the **WS** cases the tendency was for the 500 mb low center to approach directly across the northern half of California and/or Nevada while deepening (**Figure 1b)**. Compare this with **NS** cases where the 500 mb low center approached either more from the north (suggesting a drier storm) or more from the west to southwest (suggesting a warmer storm and higher snow levels). Looking at **Figure 1b,** the path of the **SA** cases tended to fall between the path of the **WS** and **NS** cases. **Figure 1b** shows that, on average, there is a narrow window of approach for storms that produce large snowfall at Flagstaff. This result suggests that, no matter how strong the 500 mb low center appears, if it strays much beyond the envelope of the solid red lines (**Figure 1b)** the possibility of a **WS** category event rapidly lowers.

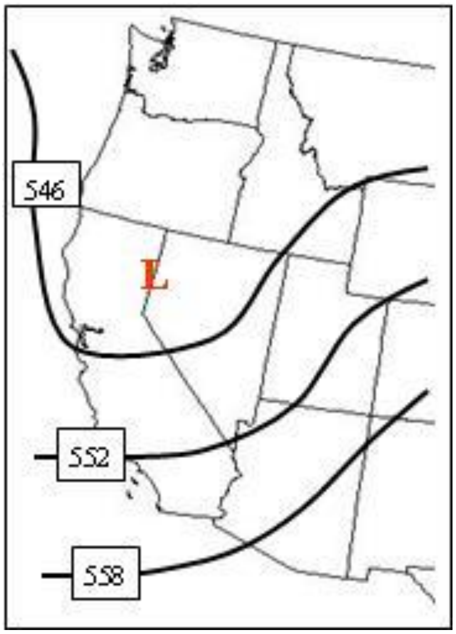

Figure 1a: The mean position of the 500 mb trough and low center around onset of snowfall at Flagstaff.

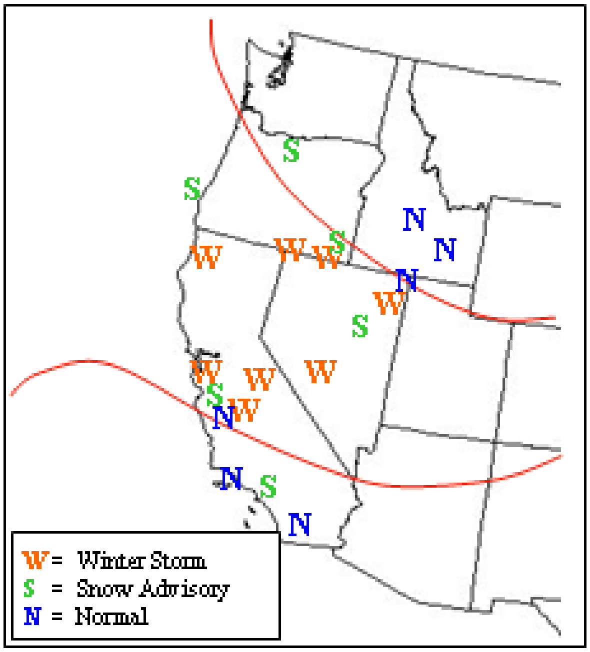

Figure 1b: The position of the 500 mb low center around onset of snowfall at Flagstaff where **W** = **WS** cases, S = **SA** cases and **N** = **NS** cases. The solid red line shows the envelope through which the 500 mb low center moved for the most frequent **WS** cases.

b) Wind Speed Gradients at 500 and 250 mb

The result of this study shows that when a storm approaches through northern California/Nevada it becomes more likely that central Arizona will be in a favorable position relative to the mid- and upper-level jet position. For **WS** cases Flagstaff was typically located on the east to southeast edge of a strong wind speed gradient at both 500 and 250 mb at the onset of snowfall with the bulk of the gradient yet to move across northern Arizona (**Figure 2a**). The 250 mb subtropical jet was strong for all **WS** cases. This gradient region is normally the most dynamic portion of a propagating synoptic-scale wave. It's easy to conclude that remaining longer under this portion of a storm would result in increased snow accumulations. For **SA** cases wind speed gradients tended to be shifted further north or south and weaker at the onset of snowfall, especially at 500 mb (see **Figure 2b** for an example). The 250 mb subtropical jet was normally strong for **SA** cases. For **NS** cases the 250 and 500 mb wind speed gradients were much weaker at both 500 and 250 mb (see **Figure 2c** for an example). In fact, the subtropical jet at 250 mb was virtually non-existent. If any significant wind speed gradient existed at all for the **NS** cases, it was shifted well away from northern Arizona.

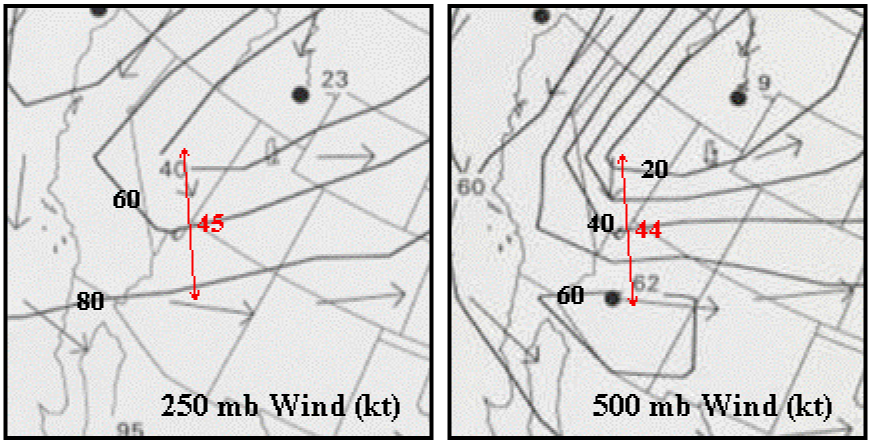

Figure 2a: The 250 and 500 mb vectors and wind speed for the **WS** cases. Wind speed is given in knots. Red arrow indicates the difference in wind speed between central Nevada and Flagstaff.

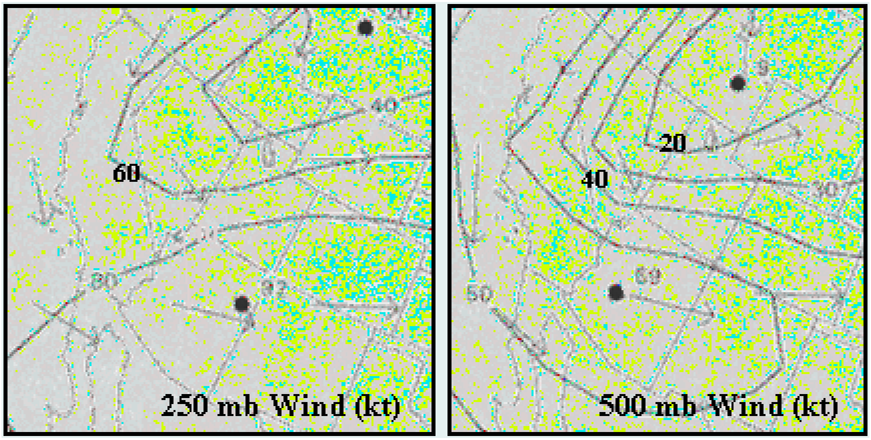

Figure 2b: Same as Figure 2a except **SA** cases.

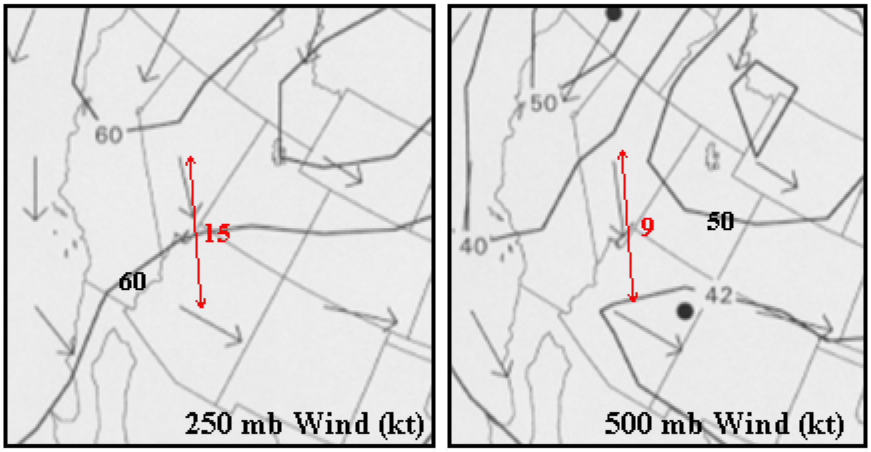

Figure 2c: Same as Figure 2a **NS** cases.

c) Mean Environmental Parameters

Around or before the onset of snowfall at Flagstaff several mean parameters were nearly identical regardless of storm strength or synoptic setting. The mean 500 mb temperature was around -20 C and the mean 500 mb height was around 559 dm over Flagstaff (**Table 1).** The mean 700 mb temperature was around -4 C (**Table 1**). The 500 mb wind was generally from the southwest with the mean wind speed for the **WS** and **SA** cases around 90 kt (**NS** cases exhibit quite a bit weaker winds). These results suggest that these values, especially temperature and height, can be used to roughly estimate the time of expected onset of snowfall at Flagstaff (and perhaps other high elevation locations) under various snowfall scenarios.

Snowfall Categories	**500 mb H (dm)**	**700 mb T (C)**	**500 mb T (C)**	**500 mb W (kt)**
Winter Storm (**WS**)	556	-4	-21	92
Snow Advisory (**SA**)	560	-3	-20	88
Normal Storm (**NS**)	561	-4	-20	64

Table 1: Mean 500mb height (**H**) in decameters, mean 500 and 700 mb temperature (**T**) in Celsius and mean 500 mb Wind Speed (**W**) in knots for the three snowfall categories.

5) Important Details to Consider

a) Trough Wavelength at 500 mb

Even when a storm approached between the solid red lines shown in **Figure 1b** differences in the wavelength of a trough resulted in variations in snowfall amounts. **Figure 3** shows a common synoptic setting that produced snowfall in Flagstaff. A long-wave trough was located across the west half of the United States with a ridge over the northeast Pacific Ocean. This pattern produced significant snow when a short-wave trough propagated through the long-wave trough. For **WS** cases the deepening short-wave was on the order of the long-wave trough and actually caused the entire long-wave pattern to amplify. For **NS** cases the short-wave was a much shorter wavelength and primarily propagated <u>through</u> the long-wave pattern. As a result, for the **NS** cases, the short-wave traveled more quickly and shortened the time under favorable dynamics and likely lowered the potential for northward advection of moisture. Storm characteristics associated with the **SA** cases fell between the extremes of the **WS** and **NS** cases.

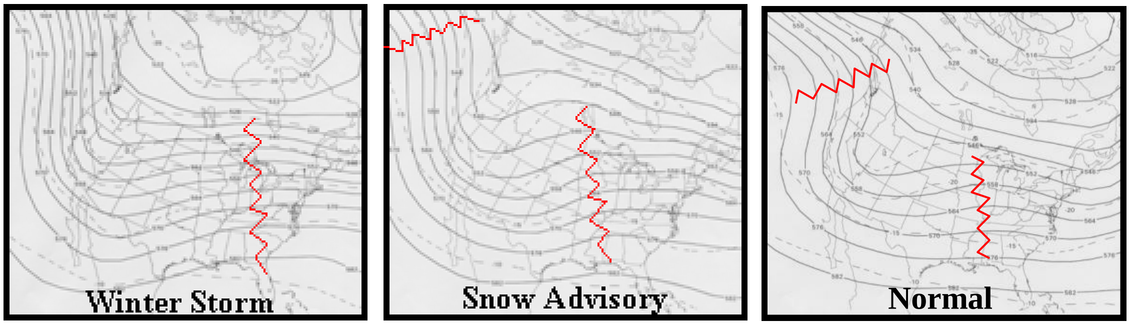

Figure 3: Shown is the 500 mb height chart for **WS**, **SA** and **SN** cases. The red zig-zag lines denote the ridge axis on either side of the trough and serve as markers to depict the shortening of wavelength from **WS** to **NS** cases.

b) Temperature and Temperature Gradients at 700 and 500 mb

Shown are composite charts for snowfall cases where the trough was located along the southern boundary of the solid red lines shown in **Figure 1b**. In these cases temperature and temperature gradients appeared to be the main difference between getting **WS** or **NS** accumulations. Looking at **Figure 4** the two main differences between the **WS** and **NS** cases are: 1) **WS** cases exhibited colder temperatures aloft 2) **WS** cases exhibited stronger low-level baroclinicity. The warmer temperatures in the **NS** cases could result in a later onset of snowfall as well as a shorter period of snowfall. In addition, the stronger low-level baroclinic zone exhibited in **WS** cases would support stronger southwest upslope winds and perhaps large-scale dynamics.

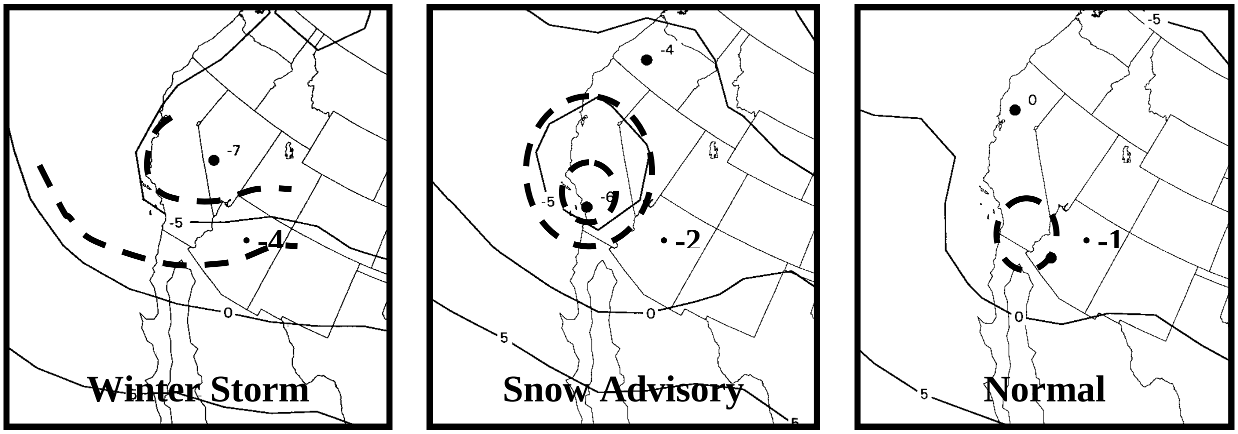

Figure 4:.Composite temperature charts for a common snow producing setting at Flagstaff. Shown is 700 mb temperature in Celsius (solid contours). The black numbers over Arizona shows the mean 700 mb temperature for each composite chart at Flagstaff. The dashed black lines indicate the relative shape and strength of temperature gradients.

c) Position of 500 mb Trough Axis and Low Center

Shown in **Figure 5** are snowfall cases where the **SA** and **NS** troughs were of similar strength to the **WS** cases but moved just along the northern periphery of the solid red lines shown in **Figure 1b**. In **Figure 5** the shape of the height field for each of the composite snowfall charts is similar. The main difference is where the trough deepens. For the **WS** cases the trough axis moved across far northern California and then deepened as it moved into central Nevada. For the **SA** cases the short-wave was as strong as in the **WS** case but moved further to the north. For the **NS** cases the trough axis approached almost directly from the north and deepened over Utah and Arizona. One impact of this difference is that moisture would have a better chance of being advected northward with the low center approaching through Nevada as in the **WS** cases. This is because when the low approaches through Nevada a moistening south to southwest low-level flow would be more likely. An approach through Nevada also places central Arizona under the prime dynamic region of the approaching wave. Any storm path further north or northwest and central Arizona would be on the southern fringe of the best dynamics.

This research suggests that if a trough deepens directly over Arizona/Utah or deepens too far to the north lower snowfall accumulations are to be expected. One exception to this rule is if significant moisture already exists over Arizona and height falls and upper dynamics are all that is needed to produce heavy snow, this scenario can occur in November when a system dives from the north.

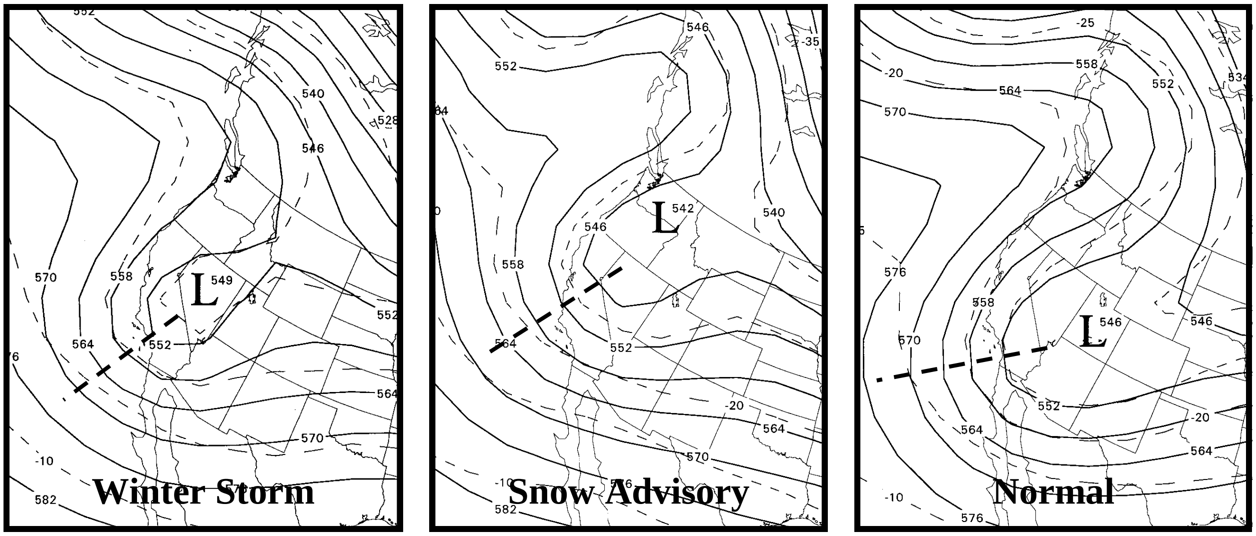

Figure 5: Shown are 500 mb heights in dm and trough axis (dashed black line) for **WS**, **SA** and **NS** cases. Subtle differences in the position of very similar troughs can be important to snow accumulations.

5) Conclusions

There are a number of characteristics that must be considered when determining potential snowfall accumulations. The most interesting aspect of this study is how similar synoptic settings can produce such varied snowfall amounts at Flagstaff. Subtle differences in the position, wavelength and depth of the approaching wave result in important differences in snowfall accumulation. It was found that identifying specific synoptic patterns is probably not an effective way to determine potential snowfall accumulations. It is better to look at the details of an approaching trough to estimate how long northern Arizona will remain under favorable storm dynamics (larger snowfall amounts are almost directly proportional to time spent under favorable dynamics).

It has been shown that **WS** cases tended to occur with deepening troughs that approached through northern California and Nevada. This is not surprising since the approach through California/Nevada is likely to place northern Arizona under the prime dynamic region of an approaching trough. Deepening storms that approached through California/Nevada and produced **SA** or **NS** snow amounts occurred with faster moving, shorter wavelength troughs (i.e., less time under favorable dynamics). This study shows that as a trough approaches from an increasingly northerly or southwesterly direction the chance for a **WS** snowfall event at Flagstaff rapidly diminishes with an **SA** or **NS** event becoming more likely.

For the cases where storms approached more from the south (**WS**, **SA** and **NS** storm centers near the southern boundary in **Figure 1b**) one main difference appeared to be that the **WS** cases were colder than the **SA** and **NS** cases (-4 C vs. -2 or –1 C at 700 mb) which suggests a later onset of snowfall for the **SA** and **NS** cases. An additional difference was that a low-level baroclinic zone was present for the **WS** cases but virtually non-existent for the **SA** and **NS** cases. This suggests that localized low to mid level upslope flow was enhanced for **WS** cases. These differences are subtle but are the features that need to be analyzed closely, especially when a weaker storm approaches along the southern boundary in **Figure 1b**.

For cases where storms approached more from the north (**WS**, **SA** and **NS** storm centers near the northern boundary in **Figure 1b**) one main difference appeared to be lack of time in the prime dynamic region of a storm. This was especially true for **SA** cases which tended to be as strong as **WS** cases in terms of trough dynamics but the main dynamic center skirted too far to the north. Another difference was dry air which was most common for the **NS** cases. These tended to be storms that moved into Arizona almost directly form the north. Plenty of dynamics moved across the area but moisture was lacking. Storms that approach from the direct north from about December onward are hard pressed to generate even **SA** amounts of snowfall due to the lack of moisture. The only exception to this morphology was in November when storms descending from the north moved over moisture that was already in place across Arizona and resulted in significant snowfall.

The main point of this study was to investigate the synoptic features that lead to higher or lower snowfall amounts. However, synoptic influences are always subject to smaller scale influences that can result in locally higher snowfall amounts than the synoptic scale indicates. The two main features in this category are frontal boundaries and orographic effects. Slow moving strong cold fronts or cold fronts undergoing frontogensis can result in extreme localized accumulations of snowfall, well above what would be expected from the synoptic input. Research to address cold front enhanced snowfall accumulations could be approached on a case study basis. Also, localized orographic effects can result in high local accumulations. Research to address orographic influences would need to be conducted using a mesoscale model.

Future research will address the influence of frontal strengthening/weakening and local orographic influences. Further study will also go into identifying and better understanding the synoptic settings favorable to significant snowfall across a number of geographic regions in northern Arizona.