# PRELIMINARY EVALUATION OF SNOW ACCUMULATION PATTERNS BASED ON STORM TYPE, MAMMOTH MOUNTAIN, CALIFORNIA, 1996-2001

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## ABSTRACT

This study examined snow accumulation at 8 sites in the subalpine zone on Mammoth Mountain, California, over the course of 67 storms during the winters 1996-1997 through 1990-2001. Locations of the field sites resulted from considering the tradeoffs between avoiding areas subject to snow erosion or wind deposition and selecting sites that exhibited little mass loss due to interception by forest canopy. The sites ranged over 500m in elevation and occurred on aspects from the east to the north-northwest side of Mammoth Mountain. Observations of snow accumulation consisted of snow depth and density measurements from snow boards, representing storm total accumulations. Measurements from the snow boards were taken at the end of each storm cycle. Synoptic variables from standard charts published by the National Weather Service formed the basis of classifying storms into four types: 1) mid-latitude front, 2) zonal, 3) cutoff or continental low and; 4) split flow. Measurements from the snow boards were related to similar observations made at a reference site by the Mammoth Mountain Ski Patrol. The analyses used regression analyses assuming linear models to evaluate trends in the accumulation measurements due to different storm types. The analyses showed that for most storms, snowfall exhibits strong correlation for specific storm types over scales of hundreds to thousands of meters, the range of distance between the sites. Storm-wise correlation among sites showed that different storm types exhibited different loading patterns. Results suggest that consideration of storm category could affect the type of interpolation one could use when dealing with operational station data.

## BACKGROUND

Mountain snowfall forecasting, an important prerequisite for snow avalanche forecasting, is difficult due to complex interactions between large-scale atmospheric circulation and topography. The Sierra Nevada is an example of these difficulties, exhibiting spatially varying snowfall accumulation patterns to patterns of synoptic scale winter storms. Analyses of relationships between regional atmospheric circulation patterns and surface climates must focus on individual locations within specific areas of interest. Research has been limited since few locations have data records longer than 15 years (Barry, 1992, Armstrong and Armstrong, 1987).

Studies that have provided useful information on patterns of synoptic scale storms that cause heavy snowfall include Mahoney, et al. (1994), Birkeland and Mock (1996), and Losleben et al. (1999). Mock and Kay (1992) analyzed snowpack, climatic data, and circulation data to determine synoptic patterns responsible for months of abnormal avalanche activity at Alta, Utah. Tollerud et al. (1994), developed useful information on the patterns of synoptic events that produce snowfall anomalies between Denver and Colorado Springs, Colorado, by comparing synoptic charts and snowfall measurements. Mahoney and Brown, (1992) and Mock (1996) also investigated these relationships for the Denver and Colorado Springs area. Denver and Colorado Springs can receive disparate snowfall amounts from the same storm, despite topographic separation of less than 100 kilometers. Losleben et al., (1999) quantified the synoptic patterns and circulation indices from gridded radiosonde data for the Niwot Ridge study site in the Colorado Rockies. Hächler (1987), examined frontal development leading to extraordinary avalanche conditions in the Swiss Alps, and found that a stationary front was involved in nearly all cases.

Mammoth Mountain lies in the Sierra Nevada, the southern part of the maritime mountain climate zone (Armstrong and Armstrong, 1987), which is characterized by deep winter snow, cover and relatively warm temperatures for an alpine zone. The rugged topography and orientation of the Sierra Nevada influences synoptic scale storm events. South of Mammoth Mountain the Sierra crest rises to over 4000 meters. This presents a formidable physical barrier to air circulation. North of Yosemite, Sierra crest elevations range from 3300 meters to 2100 meters at Donner Summit. The only break in the continuous mountain range occurs near Mammoth

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Mountain (3363 m) at Mammoth Pass. The Sierra crest at Mammoth Pass (2900 m) allows storms which otherwise lack the dynamics to reach the eastern Sierra, to deposit snow in the Mammoth area. Mammoth Mountain Ski Area is favorably situated to receive strong Pacific storms that can produce winds in excess of 45 $ms^{-1,}$ and snowfall totals exceeding one meter in a 24- hour period.

METHODS

Daily weather and snow observations for the study period were obtained from the Mammoth Mountain Ski Patrol. Measurements of snowboards and air temperatures (maximum and minimum) at the Main Lodge snow study plot took place in the mornings, usually between 6 and 8 AM. Average wind speed, maximum gust and average wind directions are recorded from sensors displayed in the patrol room. Data was converted to Excel spreadsheet format. Storm periods were extracted from the database and analyzed for the following weather variables: depth of total snow on the ground, depth of new snow, maximum and minimum air temperatures, water content of new snow, wind speed and wind direction and barometric pressure.

Each storm was given its own unique parameters including a qualitative classification. Archived NWS fax charts were used to distinguish upper level characteristics of air temperatures, jet stream velocities, vertical velocities and dew points. Previous work done by Smith, et al. (1979) classified West Coast storms on the basis of latitude of storm formation and the type of air mass involved. These were used to identify four general storm types: 1) Mid-latitude fronts that include maritime-polar air masses and the entrainment of maritime-sub-tropical air masses, 2) Zonal storms, or confluent air masses which bring together polar maritime and maritime tropical air masses with tropical air contributing most of the moisture, 3) Cutoff or continental lows, associated with continental or modified maritime polar air masses and 4) Split flow storms, which originate as mid-latitude fronts but as the jet stream "splits" as it reaches the West Coast, storm dynamics are considerably reduced.

Storm Characteristics

- Mid-latitude storms that introduce moisture from the Gulf of Alaska and entrain maritime tropical air, are usually associated with strong upper air support, including 300mb isotachs from 75-90 $ms^{-1}$. Surface winds can be 20-40 $ms^{-1}$ from the southwest. A vigorous mid-latitude storm is accompanied by 500mb isotherms of $-25^0C$ to $-35^0C$. Vorticity intensities can range from 18 to 28 decameters/min. Surface barometric pressures are low, 720-999 mmHg. Saturation of the air mass in upper levels of the troposphere (850-700mb) is a good indicator of orographic lift enhancement of snowfall accumulations. When the temperature and dew point temperature are within $1^0C$ to $5^0C$ of each other, the air mass can be assumed to be saturated. This combination of characteristics represents a scenario typical to the formation of a full latitude trough off the West Coast and can lead to the generation of 2 to 3 short waves, or individual storm occurrences.

- Fronts with strong upper air support and more expansive air mass saturation also tend to result in greater snow deposition that increases with elevation. correlative to dynamics related to orographic lifting and the stronger vorticity inherent with frontal systems that display these intensity-inducing characteristics. This type of event is typical of significant winter storm occurrences in the Eastern Sierra. These systems can also produce areas of "jet maxes" within a prevailing upper level flow that result in high intensity, highly localized precipitation.

- Zonal storms are characterized by 300mb winds ranging from 25-55 $ms^{-1}$. The 500mb cold air component is warmer, ranging from $-5^0C$ to $-20^0C$. The 700-850mb levels are saturated. Snowline at Mammoth can be as high as 3050m. Surface winds are typically westerly from 2-5 $ms^{-1}$. Barometric pressures range from 800- 10532 mmHg.

- Cutoff, or continental lows are characterized by little, if any frontal development and involve continental polar or modified maritime polar air. 300mb jet stream winds are from 35-45 $ms^{-1}$. 500mb cold air components range from $-25^0C$ to $-35^0C$ and the 850-700mb levels show 60-80% saturation. Orographic precipitation is related to air mass saturation, the specific humidity gradient and vertical velocity. If the 700mb levels are not saturated, there is little upper air support and vertical velocity and the surface front dynamics are enhanced mainly by orographic lift. Cold air temperatures and meager snow accumulations characterize these storms.

- Excessive cold air at upper levels can result in the eventual formation of cutoff lows, with extremely cold temperatures and the suppression of dynamics confined to lower levels. The cut off low typically separates from jet stream support due to this suppression of dynamics and follows a path of least topographical resistance. These systems have historically produced snowfall at very low altitudes (down to sea level on the California Coast), including significant amounts at high desert locations and higher coast range locales

- Split flow storm are similar to a mid-latitude front, but lose upper level jet stream support when the jet stream splits into two branches as it approaches the West Coast. Initially, 300mb isotachs are strong, from 75-90 $ms^{-1}$ but diminish to 45-60 $ms^{-1}$ as the jet stream splits. The accompanying cold air component is –$25^{0}$C to –$35^{0}$C. Saturation levels are lower, 60-80%. Surface winds at Mammoth are southwest to west at 8 m/s. Barometric pressures remain high at 10400mm Hg or higher.

To determine if there is a storm type effect on total seasonal loading, the frequency and mean accumulation for each storm type was tabulated. Next, to determine correlation between sites for all storms, a linear model was constructed to examine the relative trends in loadings among the sites compared to the reference site. Storm-wise correlation among sites was tested using dummy slope variables.

Snow Board Measurements

Total storm snowfall and snow water equivalence were measured for 86 winter storms during the winters 1996-1997, 1997-1998, 1998-1999, 1999-2000 and 2000-2001. Six snowboards were placed on the north, east and west slopes of Mammoth Mountain. Sites were selected to represent general aspects and exposures of large areas on Mammoth Mountain and ranges of subalpine elevations. Locations were selected to be relatively free of guest traffic and to have easy access from the lifts normally open during the season, including storms.

Snow depth and density on the snowboards were measured after frontal passage. Total storm depth and snow water equivalent (SWE) were measured from the surface of each board. Ten total depth measurements were averaged to obtain estimates of total snow depth at each site.

Figure 1 shows the locations of study sites on Mammoth Mountain, California. Black arrows show measurements sites; the white arrow shows the reference site.

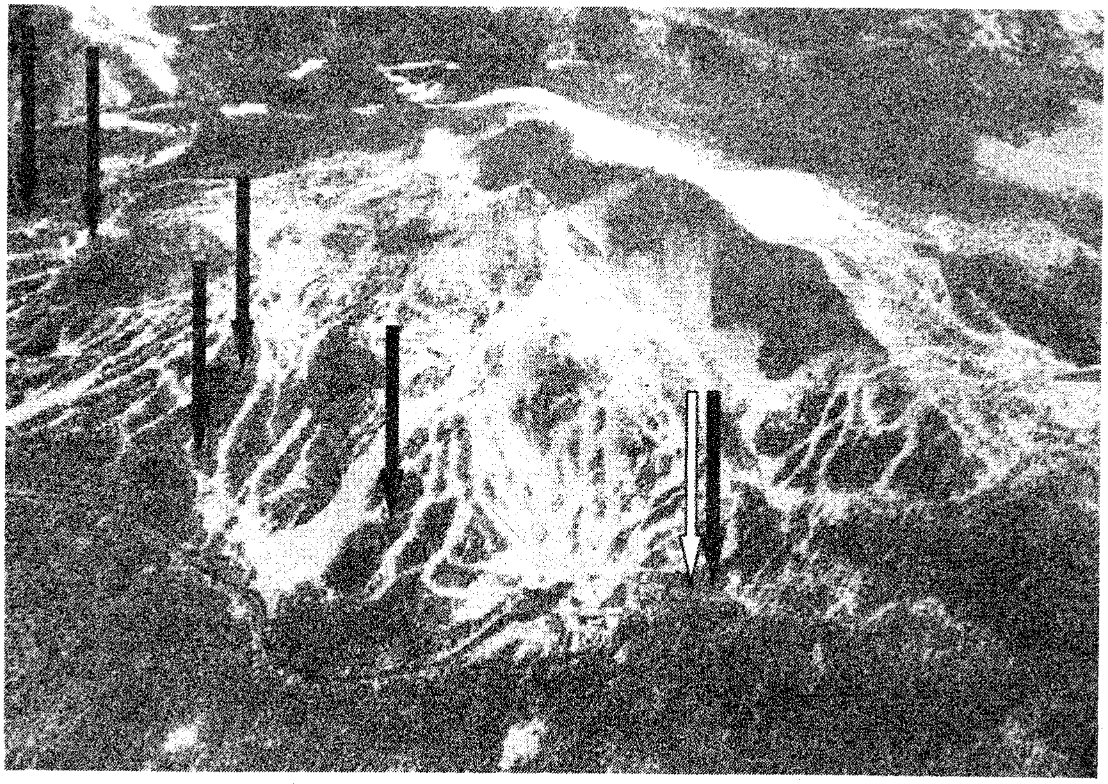

Table 1. Study plot site characteristics.

| Site | Aspect | Elevation | Average Seasonal SWE |
|---|---|---|---|
| | | | **1996-2001** |
| Chair 15, top | $90^{0}$ | 2750 m | 71.7 cm |
| Chair15, bottom | $90^{0}$ | 2600 m | 68 cm |
| Chair 21, top | $20^{0}$ | 2800 m | 91.1 cm |
| Chair21, bottom | $20^{0}$ | 2710 m | 75.6 cm |
| Chair 2 | $18^{0}$ | 2800 m | 87.1 cm |
| Chair 11 | $0^{0}$ | 2780 m | 91.4 cm |
| Reference Site | $0^{0}$ | 2780 m | 92 cm |

Standard linear regression was used to find overall trends between snow accumulation at these sites, relative to the reference site. Storm SWE was lumped together for all storms at the sites and trend line slopes and correlation coefficients were compared between the sites. In order to test the qualitative attribute of storm type, four slope dummy variables were created. Slope dummy variables allow the slope of the relationship between the SWE at the reference site and SWE at a study plot to be different depending on whether the condition specified by the dummy variable is met. Slope dummies provide a way to determine the hypothesized impact of an independent variable on the dependent variable if the qualitative condition of storm type is met (Studenmund, 2001).

## RESULTS

The Main Lodge site was used as a predictor for SWE at the measurement sites. Table 2 shows the equations resulting from simple linear regression analysis, $n = 91$. Figure 2 shows the relationships between the reference site and the study plot SWE's. Over all storms, all sites show high correlation to the reference site.

Table 2. Trend lines fit through snow accumulation data for each site.

| Site Name | Regression Equation | $R^2$ |
|---|---|---|
| 15 top | $Y=0.16 + 0.77x$ | 0.78 |
| 15 bottom | $Y=0.24 + 0.70x$ | 0.79 |
| Chair 21 top | $Y=0.76 + 0.903x$ | 0.79 |
| Chair21 bottom | $Y=0.98 + 1.02x$ | 0.77 |
| Chair 2 | $Y=0.11 + 0.92x$ | 0.84 |
| Chair 11 | $Y=0.01 + 0.933x$ | 0.81 |

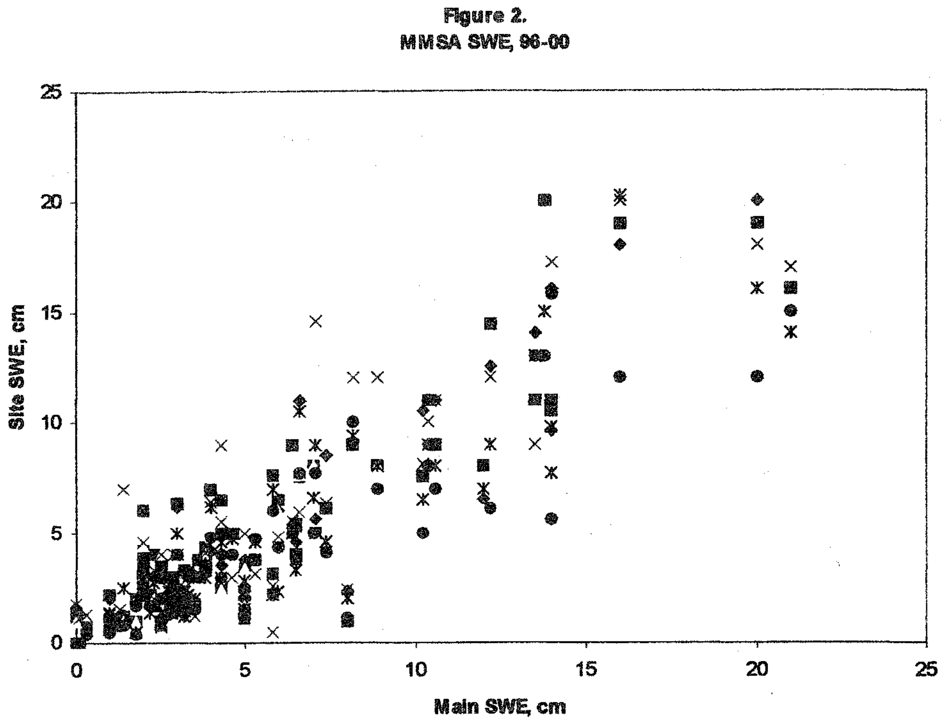

Figure 2. Scatter plots of measurements from the test sites compared with the reference site at the Main Lodge, Mammoth Mountain.

Next, the frequency of different storm type occurrence over the study period was tabulated and presented (Table 3). Different seasons had significantly different storm types.

Table 3. Frequency of storm type occurrence.

| Storm Type | 1996-1997 | 1997-1998 | 1998-1999 | 1999-2000 | 2000-2001 |
|---|---|---|---|---|---|
| Mid-latitude | 3 | 7 | 4 | 3 | 3 |
| Zonal | 4 | 5 | 1 | 4 | 2 |
| Cutoff | 3 | 1 | 1 | 0 | 1 |
| Split flow | 0 | 1 | 6 | 11 | 5 |

The trend lines for each site changed slope when recalculated using data only from a particular storm type. Four dummy variables were created for each storm type. Resulting regression equations were tested with F-tests for joint significance of the dummy storm type variables. The results of the F-tests showed that the differences in trend line slope were highly significant at a= 0.05, p= 0.0000001. The results are shown in Table 4.

Table 4. Results of the storm-wise regressions using 4 dummy variables. There are significantly (a= 0.05) different slopes for different storms.

| Site | Constant | Test constant | Coefficient | Test coefficient |
|---|---|---|---|---|
| Ch2 | 0.11 | .82 | 0.92 | 0.11 |
| 21 top | 0.76 | 0.80 | 0.90 | 0.84 |
| 21 bottom | 0.98 | 1.38 | 1.02 | 0.87 |
| Ch11 | 0.93 | 0.72 | 0.01 | 0.86 |
| 15 top | 0.16 | 0.71 | 0.77 | 1.12 |
| 15 bottom | 0.24 | 0.60 | 0.7 | 1.17 |

## DISCUSSION

The analyses described here used a linear model to fit a trend line to the scatter plots of storm SWE at each of the remote sites, compared with the reference site on Mammoth Mountain. The resulting regression equations show the general pattern of SWE loading for all storms, and the relatively high correlation coefficients suggest close relationships between the remote and reference sites. Thus, for each trend line, the slope shows the overall loading amount at each remote site compared with the reference site.

Each winter has a different frequency of storm type. For example, winters characterized as strong El Niño winters are predominated by mid-latitude and zonal storms. Winters characterized by La Niña episodes are predominated by split flow storms. The dummy variable analyses comparing each site to the reference site, showed significant differences between loading patterns due to the different types of storms. This suggests that consideration of storm category could affect the type of interpolation used for making snow maps from operational station data. This result also indicates that one should consider storm type when assessing avalanche hazard from measurements from a single study plot.

## ACKNOWLEDGEMENTS

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