SNOW CLIMATOLOGY OF THE EASTERN SIERRA NEVADA

Susan Burak, graduate student
Hydrologic Sciences
University of Nevada, Reno

David Walker, graduate student
Department of Geography/154
University of Nevada
Reno, NV 89557-0048

ABSTRACT: The Sierra Nevada mountain range of California lies between 35° and 40° N latitude and is located within 320 km (200 miles) of the Pacific Ocean. The steep, high elevation (3000-4000 m) eastern slopes of the Sierra Nevada lie between 37° and 38° and are less exposed to moderating maritime influences of Pacific storms due to the orographic effect of the Sierra Crest. Previous investigators have classified the snow avalanche climate of the Sierra Nevada as a coastal climate zone, with mild temperatures, large quantities of snowfall and precipitation, low temperature gradients and higher numbers of avalanches than intermountain and continental locations. Most avalanches are storm or solar radiation induced.

Long term snowpack records and climate data suggest that the orientation of synoptic scale circulation interacts with the Sierra Crest and the diverse topographic relief to produce a latitudinal gradient of SWE on event and seasonal timescales. Results from this study show considerable variation in snowpack characteristics between field stations spanning less than a degree of latitude. Avalanche danger ratings applied on a regional scale are problematic for an area that exhibits considerable climatic and snowpack variation over a short between reporting stations.

Our research investigates the spatial variability of the snowpack along the eastern slope of the Sierra Nevada on a daily and seasonal timescale. Weather and climate records are utilized to produce a snow climate classification for four east-side recording stations. The classification is based on general snowpack processes used by Mock and Birkeland (2000).

KEYWORDS: Eastern Sierra, snowpack climatology, temperature gradient, avalanche forecasting

1. INTRODUCTION

The eastern Sierra lies between 37^0 and 38^0N and is located within 320 km (200 miles) of the Pacific Ocean. Mountain weather and avalanche forecasting is difficult due to complex interactions between large scale circulation and topography. Like other mountain ranges, the eastern Sierra exhibits spatially varying snowfall accumulation patterns due to elevational gradients that range from 1500 to 2700 meters of relief and the orientation of the numerous east side canyons to the previaling storm track winds.

The rugged eastern escarpment of the Sierra Nevada provides winter recreation opportunities for an increasing number of skiers, snowboarders and snowmobiles. Despite the fabled “bomber” snowpack of the area, the number of avalanche accidents

Corresponding author address:
Susan Burak, P.O. Box 8544, Mammoth Lakes, CA. 93546
Email:sburak@psln.com

and close calls is increasing and three fatalities occurred during the 2005 and 2006 seasons. Avalanche forecasting is complicated by the diverse topography and differences in snowfall and SWE accumulation on a storm by storm basis for each study location.

This paper uses daily weather and snowpack data from four reporting stations to develop a snowpack climate classification for each location. The spatial analysis was done for the eastern Sierra from Bishop Creek north to Tuolumne Meadows. Data records span a period from 1983 to 2006, with the shortest record from 1992-1993 to 2006.

2. BACKGROUND

The snow avalanche climate of the western United States includes three major zones following a west-east gradient: coastal, intermountain, and continental (Roche 1949, Armstrong and Armstrong 1987, Mock and Kay 1992, Mock and Birkeland 2000).

The coastal zone is characterized by abundant snowfall, higher snow densities, higher temperatures, and higher numbers of avalanches (Mock and Birkeland 2000). The continental zone is characterized by cold temperatures, lower snowfall, lower snow densities, extensive faceted crystal growth due to high temperature gradients in the snowpack and a greater number of hard slab and climax avalanches than the coastal zone (Mock 1995). Relatively low numbers of avalanches occur in a continental climate, but there is a higher avalanche hazard potential due to difficulties in predicting the behavior of buried layers of faceted crystals (Armstrong and Armstrong 1987). Average monthly precipitation for continental climates is about 50% of coastal climates during the December to April 1 time period. Snow depths are about 40% less (Armstrong and Armstrong 1987).

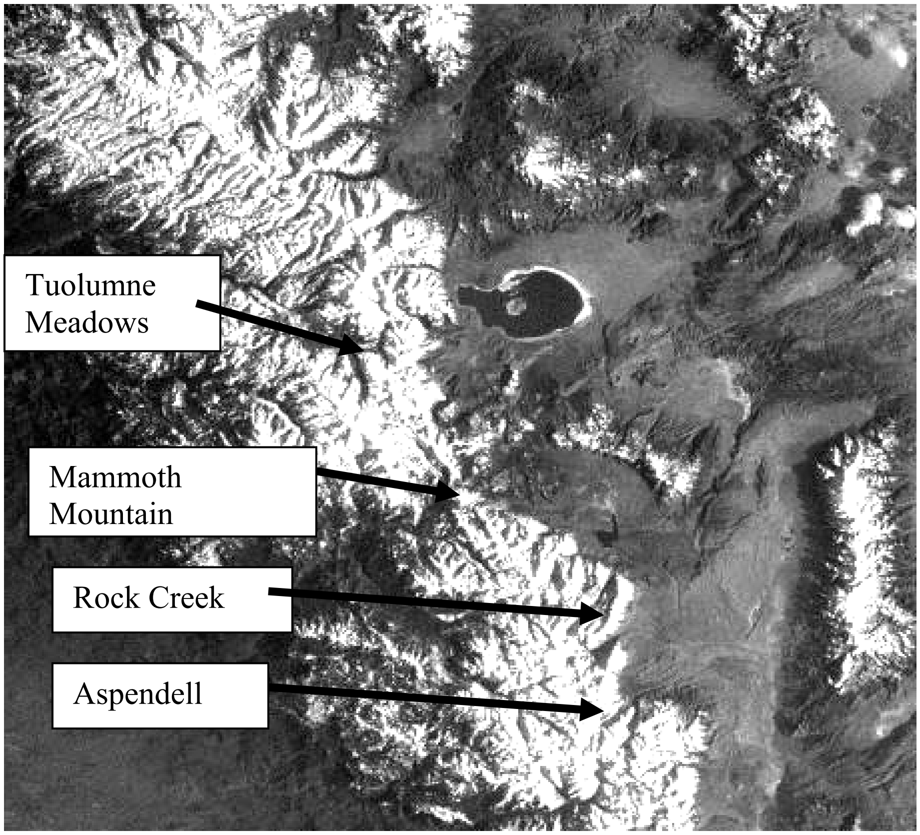
The intermountain zone is intermediate between the coastal and continental types. LaChapelle (1966) noted that the intermountain zone is typified by the Wasatch Range in Utah, the northern Rocky Mountains in Montana and the mountains of southwestern Colorado. The difference in snowpack characteristics between each climate zone determine snowpack characteristics such as the presence of depth hoar or surface hoar, persistence of weak layers and the character of avalanche activity.

Variations in snowfall and SWE in mountain regions depend on the position of synoptic scale circulation which determines the position of storm trajectories (Mock 1995). Storm tracks in the eastern Sierra originate in sub tropical regions that have a westerly or southerly flow (Losleben et al 2001) or storms that originate in the Gulf of Alaska that typically have a more southwesterly flow (Losleben et al 2001). Historic records of snow depths and SWE compiled by the California Data Exchange Center (CDEC) show a latitudinal gradient in snow depths and SWE with the southern portion of the range receiving an average of 30 to 40 cm of SWE. Similar elevations 40 to 50 km north receive an average of 75 to 100 cm of SWE (CDEC 2006). The likely cause for this observed trend in precipitation patterns is the stronger deflection of wind flow along the southern half of the range which leads to enhanced convergence toward the north (Reeves et al., 2006, Nieman et al 2004). dettinger.

We provide a first step toward a spatial analysis of small scale patterns of snowpack climate heterogeneity that exist within the braod coastal classification of the Sierra Nevada. We focus on 4 individual locations with snowpack and climate records spanning 13 to 24 years. Analyses of relationships between regional circulation patterns and surface climates using 500 and 700 mb height anomalies were conducted for the period 1990- 2006.

The eastern Sierra is defined in this paper as the eastern slopes from the Bishop Creek drainage to Tuolumne Meadows. Figure 1 provides the location of the study sites.

Figure 1. Location map, eastern Sierra Nevada.



3. PREVIOUS WORK

The Sierra Nevada has long been classified as having a coastal snowpack (eg. Roche 1949, Armstrong and Armstrong 1987, Mock and Birkeland 2000). Andre Roche was the first researcher to classify the western United States into three snow and avalanche climates representing generally a west-east gradient: the coastal, middle and high alpine zones. LaChapelle (1966) noted that the coastal zone generally corresponds to the Sierra Nevada and Cascades. The Unita and Rocky Mountains typify the continental zone and the intermountain zone is typified by the Wasatch Range in Utah, the northern Rocky Mountains in Montana and the mountains of southwestern Colorado.

Armstrong and Armstrong (1987) summarized weather and snowpack data from western locations to characterize the three snow climates in the western United States. They quantified the characteristics of each snow climates by using the means of temperature, precipitation, snowfall, snow depth and snow density (Armstrong and Armstrong 1987).

More recent work by Mock and Kay (1992), Mock (1995), Mock and Birkeland (2000) has provided an understanding how climate variables influence snowpack characteristics and avalanche activity. Mock and Birkeland (2000) used climate variables to classify regions of the western mountains as coastal, intermountain or continental snow climate zones. A binary classification system was created using an extensive data set from the Westwide Avalanche Network (WWAN) data. A flow chart using rainfall, air temperature, December temperature gradients, season SWE and snowfall was used to classify snow climates from 48 stations.

Other related work has focused on differences and similarities in atmospheric circulation associated with snowfall occurrence. Losleben et al (2001) compared snowfall occurrence, snow pack, and the atmospheric circulation conditions associated with snowfall at Mammoth Mountain and Niwot Ridge, Colorado. Increased vorticity, at both 700mb and 850mb, was identified as the strongest and most significant index associated with snow occurrence at both sites.

Burak and Davis (2001) used regression analyses to evaluate trends in the accumulation measurements due to different storm types. The analyses showed that for most storms, snowfall showed strong correlation for specific storm types over scales of hundreds to thousands of meters, the range of distance between 8 study plots on Mammoth Mountain. Storm-wise correlation among sites showed that different storm types exhibited different loading patterns.

Recent work by Nieman et al (2004) used the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) dataset for December through March 1996-2006 to classify 63 storm types. Three track types produce three distributions that effect the distribution and amount of precipitation occurring in the Sierra Nevada.

4. METHODS

We selected 4 stations with snowpack and climate records dating from 1983 to 2006. Observations of the each site location We assume that the location and exposure of the four sites on a scale of 1- 100 m (Armstrong and Armstrong 1987) is similar and that classification differences between the sites are due to synoptic scale effects.

The Mammoth Mountain data set was in digital form. The other site records were handwritten and were entered into Excel spreadsheets. Snow and weather variables included minimum temperature, maximum temperature, total snow depth, daily snowfall, daily snow water equivalent (SWE) and daily rainfall.

Measurements were made on a daily basis between 0700 to 0800. December through March data was analyzed because many east side locations do not receive snowfall until mid to late December. During dry years, the more southern sites, Rock Creek and Aspendell, often do not receive snowfall until January. As a result, December temperature gradients often exceed the threshold value for the continental classification of 10^0C per meter. We used the binary seasonal snow avalanche classification developed by Mock and Birkeland (2000). The names of the sites, their elevations and the number of seasons classified as coastal, intermountain and continental are shown in Table 1.

Avalanche occurrence records were recorded for the Mammoth Mountain Ski area but avalanche records from Aspendell, Rock Creek and Tuolumne Meadows span a short period or were recorded sporadically. Despite the lack of avalanche occurrence data, the snowpack climate classifications provide information regarding snowpack and avalanche conditions in each location.

Table 1. Site elevations, period of record, and snow avalanche climate classifications.

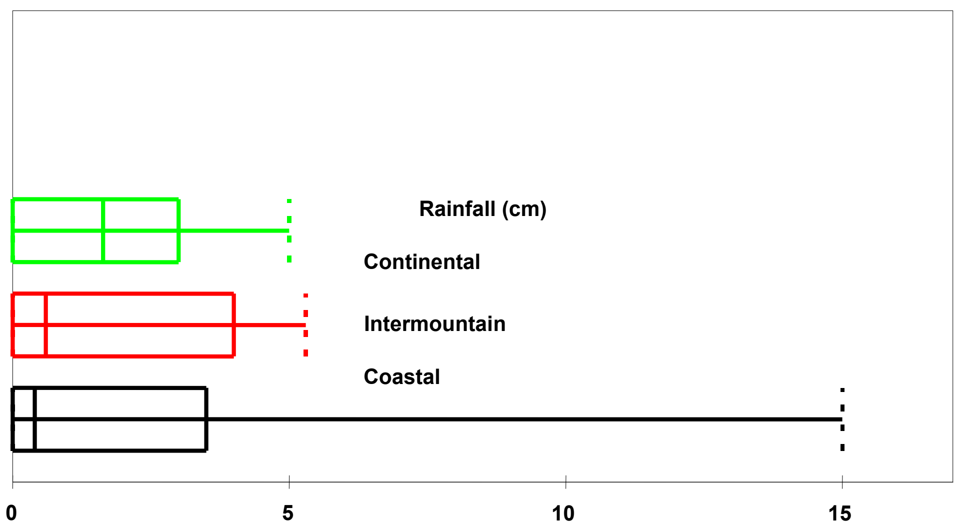
Site	Years of record	Eleva-tion meters	Con-tinental	Inter-mountain	Coastal
Mammoth Mountain	1982-2006	2725	0	2	22
Tuolumne Meadows	1987-2006	2650	2	7	10
Rock Creek	1992-2006	2865	3	8	2
Aspendell	1985-2006	2621	4	4	13

6. RESULTS

6.1 Boxplots

Boxplots of snowpack and climate data were constructed to compare the variability of temperature, December temperature gradient, snowfall, snow water equivalent and rainfall. The results are displayed in figure 2 and figure 3.

Figure 2. Boxplots of rainfall and air temperature.



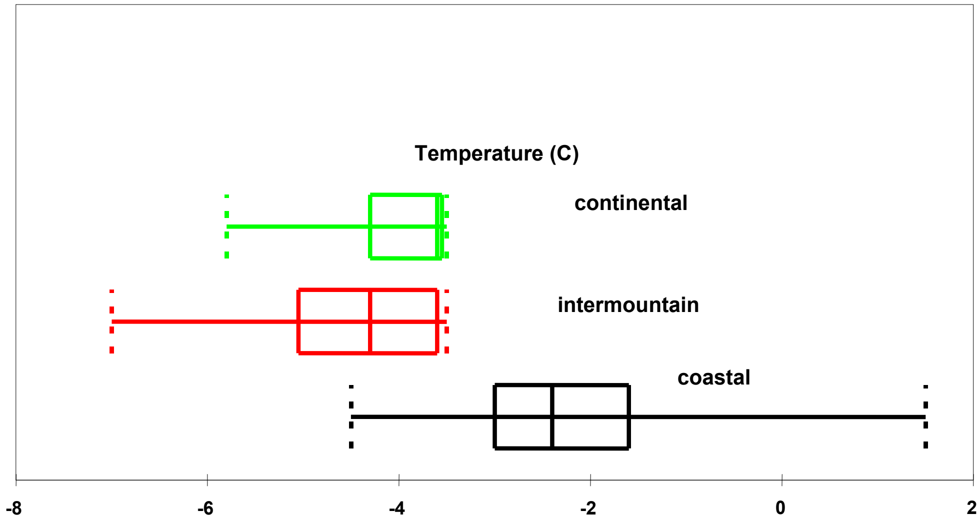
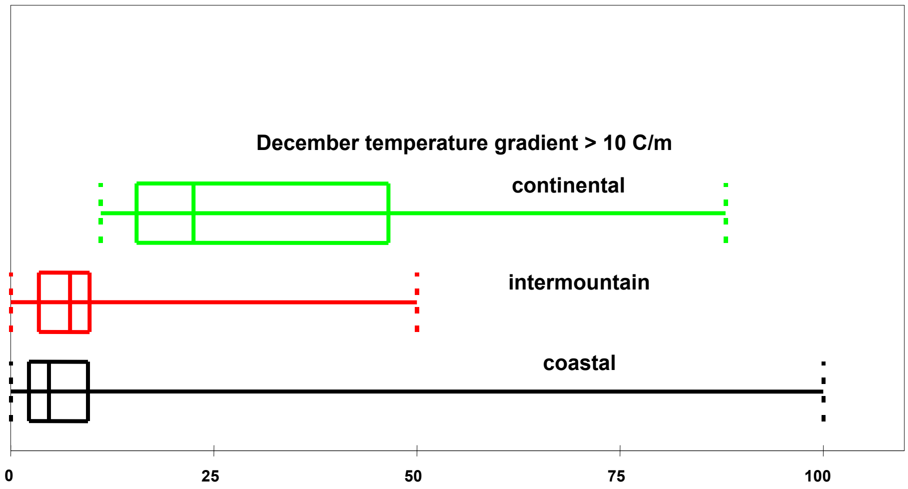
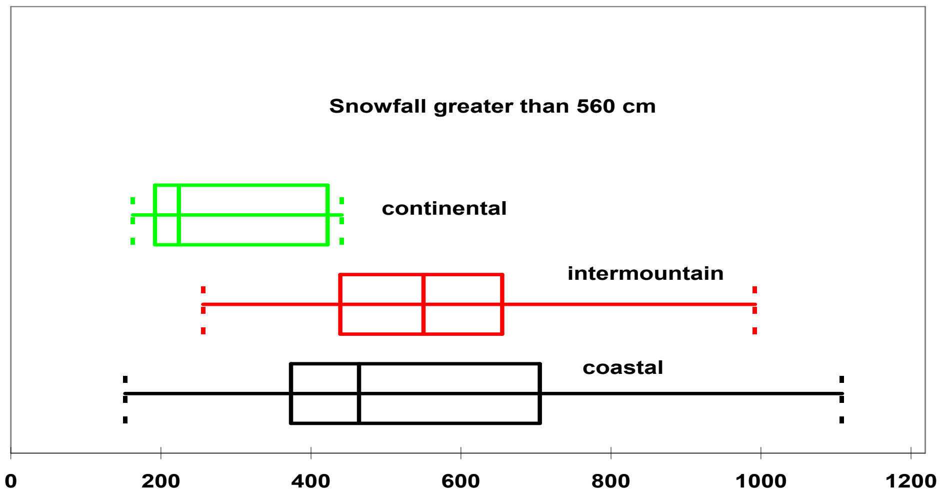
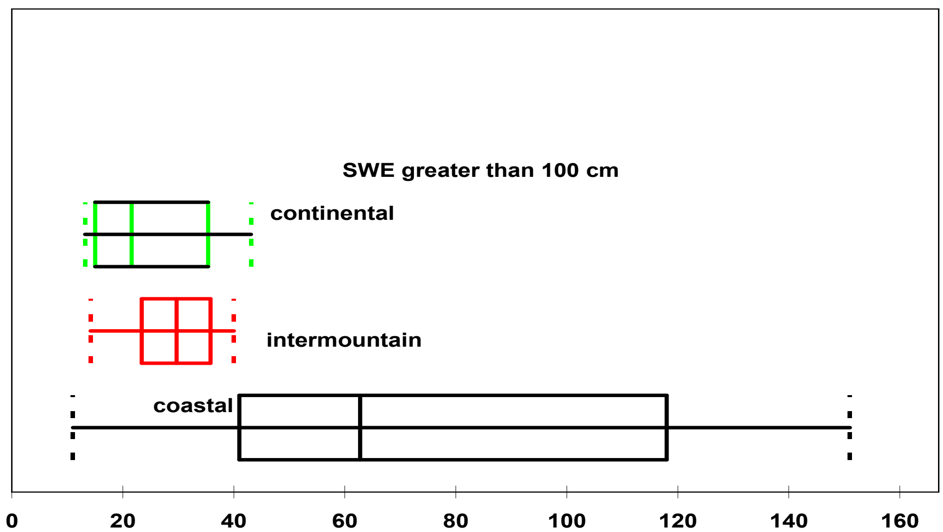


Figure 3. Boxplots of December temperature gradient, snowfall and snow water equivalent







The boxplots demonstrate the variability of thresholds and ranges which could lead to misclassification errors. For example, the median air temperature is -2.4^{0}C for the coastal classification, -4.3^{0}C for intermountain and -3.6^{0}C for continental. Air temperature less than -3.5^{0}C can separate coastal and intermountain conditions but can be misleading as a single designator for the continental classification. This is due to the fact that warm winters support sintering and low temperature gradients in the snowpack.

6.2 Snow avalanche climate classification

The binary classification scheme was applied to seasonal means of the four study locations.

Table 2 presents the results of the initial classification.

Table 2. Initial classification, 77 cases

Criteria for classification	Climate classification	No. of cases
Rain > 8 cm	Coastal	7
Temperature> -3.5^0 C	Coastal	40
Dec. TG> 10 C m^{-1}	Continental	13
SWE > 100 cm	Coastal	1
Snowfall > 560 cm	Intermountain	6
Temperature < -7^{0}C	Intermountain	10

Climate classifications in Table 2 suggest continental winters in the eastern Sierra are determined by the December temperature gradient. However, examination of individual cases revealed that five seasons initially classified as continental began with below average December snowfall that resulted in large December temperature gradients (14.5 to 50 C m^{-1}). Heavy snows arrived around the first of the year and continued through February and March. Total season snowfall was close to or exceeded the threshold snowfall value of 560 cm. Avalanche records at Rock Creek noted numerous soft slab avalanching that occurred during storms and immediately after storms in January and March 1995 when 234 and 327 cm of snow fell, respectively. Avalanche activity during heavy Sierran winters usually involves new snowfall rather than structural weakness in the snowpack.

Using snowfall greater than 560 cm, the continental designations were revised to reflect the substantial snowpacks of these heavy snow years. Table 3 presents the individual cases.

Table 3. Snow avalanche climate revisions

Location	Season	Dec. TG	Snow-fall	Clim-ate class	Revised class
Rock Creek	1992-1993	16	746 cm	Cont	Inter
Rock Creek	1994-1995	14.5	649 cm	Cont	Inter
Rock Creek	1995-1996	41	550 cm	Cont	Inter
Rock Creek	1997-1998	17	584 cm	Cont	Inter
Aspendell	1994-1995	50	565 cm	Cont	Inter

The revised classification is shown in Table 4.

Table 4 . Revised classification

Criteria for classification	Climate classification	No. of cases
Rain > 8 cm	Coastal	7
Temperature> -3.5^0 C	Coastal	40
Dec. TG> 10 C m^{-1}	Continental	8
SWE > 100 cm	Coastal	1
Snowfall > 560 cm	Intermountain	11
Temp >-7^{0}C	Intermountain	10

A compilation of the results of the binary classification for each location are presented in Table 5.

Table 5. Snow avalanche climate classifications

Year	Mammoth Mountain	Aspendell	Rock Creek	Tuolumne Meadows
1984-1985	intemountain			
1985-1986	coastal	coastal	coastal	coastal
1986-1987	coastal	continental		
1987-1988	coastal	coastal		coastal
1988-1989	coastal	coastal		
1989-1990	coastal	continental		coastal
1990-1991	coastal	intermountain		continental
1991-1992	coastal	continental		coastal
1992-1993	coastal	intermountain	intermountain	intermountain
1993-1994	coastal	coastal	intermountain	coastal
1994-1995	coastal	intermountain	intermountain	coastal
1995-1996	coastal	coastal	intermountain	coastal
1996-1997	coastal	coastal	coastal	coastal
1997-1998	coastal	coastal	intermountain	intermountain
1998-1999	coastal	coastal	continental	intermountain
1999-2000	coastal	coastal	coastal	coastal
2000-2001	coastal	coastal	intermountain	intermountain
2001-2002	intermountain	continental	intermountain	intermountain
2002-2003	coastal	coastal	Missing	coastal
2003-2004	coastal	coastal	intermountain	intermountain
2004-2005	coastal	coastal	intermountain	coastal
2005-2006	coastal	intermountain	intermountain	intermountain

If we assume that the location and exposure of the four sites on a scale of 1- 100 m (Armstrong and Armstrong 1987) is similar, then differences between the sites could be due to the interaction of synoptic scale effects on topography. The study locations do not represent similar conditions because smaller scale climatic controls over ride the effects of larger scale controls on both event and seasonal time scales. Diverse classifications over a short distance is probably a result of small scale circulation features interacting with local topography.

7. Conclusions

The diversity of snowpack conditions in the eastern Sierra present a challenge for operational forecasting. Avalanche danger ratings are general descriptions and do not provide detailed information on snowpack and weather conditions within the forecast area. Forecasters utilizing data from a variety of locations can include more detail within the format of a standard avalanche forecast.

8. LITERATURE

Armstrong, R. and B.R. Armstrong, 1987. Snow and avalanche climates of the western United States: A comparison of maritime, intermountain and continental conditions. Avalanche Formation, Movement and Effects. Proceedings of the Davos Symposium, September 1986. IAHS Publication. No. 162, 1987.

Burak, S.A. and R.E. Davis. Preliminary Evaluation of snow accumulation patterns based on storm type, Mammoth Mountain, California, 1996-2001. 2001. Proceedings of the Western Snow Conference, Sun Valley, Idaho.

LaChapelle, E.R. 1966. Avalanche forecasting, a modern synthesis. Publication69, International Association of Hydrologic Sciences, Gentbrugge Belgium, p. 350-356.

Losleben, M., S. Burak, R.E. Davis and K. Adami. Snowfall occurrence at two lee-side mountain locations: Comparing the Sierra Nevada, California and the Rocky Mountains, Colorado. 2001. Proceedings of the 18th Annual Pacific Climate Workshop.

Mock, C.J. 1995. Avalanche climatology of the continental zone in the southern Rocky Mountains. Physical Geographer, 16, 165-187.

Mock,C.J. and K. Birkeland. 2000. Snow Avalanche Climatology of the Western United States Mountain Ranges. Bulletin of the American Meteorology Society. V 81, no. 10.

Mock, C.J. and P.A. Kay. 1992. Avalanche climatology of the western United States, with an emphasis on Alta, Utah. Professional Geographer, 44, 307-318.

Nieman, P., P. Ola, G. Pearson, F. Martin, P. Jorgensen, A.B. White and D.E. Kingsmill. 2004. Modification of fronts and precipitation by coastal blocking during an intense landfall winter storm in southern California: Observations during CALJET. Monthly Weather Review, Vol. 132.

Roche, A. 1949. Report on snow and avalanche conditions in the U.S.A.,Western Ski Resorts. From the 25th of January to the 24th of April, 1949. Swiss Federal Institute for Snow and Avalanche Research. Report # 74. Davos, 44 p.