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## Snow and avalanche climates of the western United States: A comparison of maritime, intermountain and continental conditions

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**ABSTRACT** The mountainous area of the western United States has long been considered to be made up of three general weather and snowcover climates: maritime, intermountain, and continental. Weather and snowcover data from high elevation sites have been collected over the past several decades through the U.S. Forest Service Westwide Data Network. The complete data set was searched for a maximum number of stations which could provide reliable, continuous data for a period of at least 15 years. A total of five sites from each climate zone met these criteria. Air temperature, precipitation, snowfall, new snow density, and snow depth data are summarized to describe average conditions for each site. Variability within and between the three climatic zones is evaluated. The weather and snow conditions of the continental zone are analysed in terms of a greater potential to develop and maintain a snowcover with a lower bulk strength. It is hypothesized that this weaker snow structure will contribute to a lower overall snow stability for longer periods of time following storm periods compared to the maritime zone. The susceptibility of the continental snow cover to skier-triggered avalanches during non-storm periods is evaluated using the avalanche accident data from the western United States.

Le climat de la neige et de l'avalanche de l'ouest des Etats Units: Une comparaison des conditions maritimes, entre-montagneuses et continentaux

**RESUME** Il y a longtemps la région montagneuse de l'ouest des Etats Units a été considéré comme trois types climatique: maritime, entre-montagneux, et continental. Les données météorologiques et neigeuses des sites de haute élévation ont été collectionné il y a des décades par U.S. Forest Service Westwide Data Network. On a examiné toutes les données a trouver les stations les plus possible qui fournissent d'information précise et continue, pour une période de 15 ans au minimum. Cinq stations par zone

climatique ont rempli ces critères. La température de l'air, la précipitation, (de la neige et de la pluie), la densité de neige fraîche, et la fonte de neige sont présentées pour montrer la condition typique pour chaque site. Les variabilités pour chaque site dans la même zone climatique et les variabilités entre les trois zones ont été évalué. Les conditions météorologiques et neigeuses de la zone continental sont analysé en relation du développement et de l'entretien d'une fonte de neige avec une force de volume plus faible. Par hypothèse la structure de la neige faible comparé à la zone maritime est responsable pour la stabilité plus basse pour une période prolongée suivant des tempêtes. La susceptibilité de la fonte de neige continentale a été évalué pendant des périodes calmes en relation des avalanches causé par des skieurs, basé sur la statistique des accidents d'avalanche de l'ouest des Etats Units.

## INTRODUCTION

Nearly four decades ago, as a result of travels in the western United States, Andre Roch (1949) called attention to the existence of three distinct climate zones: maritime, continental, and situated between these two, an intermountain zone. Although at that time no systematic research or data collection had been undertaken, it seemed obvious that these three climates should produce distinct and individual snow and avalanche conditions. As a direct result of the observations of Roch, the U.S. Forest Service designated one primary snow and avalanche study site in each of the three regions: Stevens Pass in Washington, Alta in Utah, and Berthoud Pass in Colorado (Figure 1). Data collection at these sites has been continuous from the early 1950s to the present. During the 1960s

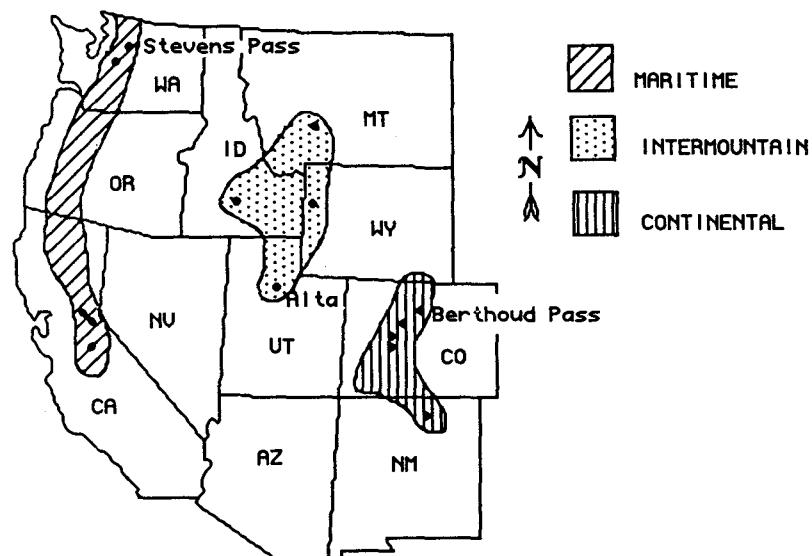


FIG.1 Location map for data collection sites within the maritime, intermountain, and continental snow climate zones.

the U.S. Forest Service established a more extensive data collection system, the Westwide Data Network (Judson, 1970) at high elevation mountain sites throughout the three climatic zones. This data set contains not only weather and snow cover information, but also records of avalanche events and avalanche accidents.

Beginning with Roch's observations, and later those of E.R. LaChapelle (1966), researchers and field workers have continued to apply the concept of the three distinct snow climates. This distinction between climates is qualitatively apparent based simply on the geography and topography of the western United States. For example, the term "continental" seemed highly appropriate for sites in the Rocky Mountains. Storm systems, after leaving the moisture source of the North Pacific Ocean, may travel as far as 1800 km linear distance over the land surface, and be orographically lifted more than 3000 m, before arriving at the higher elevation sites of the Rocky Mountains.

However, to what extent do the quantitative data collected over the past several decades support the idea of three distinct climates? In order to answer this question, five observation sites with reliable data sets spanning at least 15 years were chosen from within each of the three regions. Weather and snow cover data are summarized for the 15 sites in order to describe average or representative conditions. While it is true that point measurements are being used here to represent large areas, the pattern of within-sample variance compared to between-sample variance gives credence to the concept of three distinct zones. From the generally accepted relationships between weather conditions and snow structure development, it can be hypothesized that a continental climate will produce a snow cover which has a higher avalanche potential for a greater portion of the winter season than that associated with a maritime climate.

## DATA: SOURCES AND INTERPRETATION

### Weather Data

Research in mountain weather and climatology is frequently restricted by lack of data collection at sites representing the higher elevations. Weather stations are nearly always associated with towns and villages which, although they are considered mountain sites in a general sense, are usually located on valley floors. In western North America there are very few observations comparable to those in Europe (Barry, 1981). Rarely is there the opportunity to obtain large data sets from sites 1000 m or more above the valley bottoms where distinctly different temperature, wind, and precipitation patterns prevail. The Westwide Data Network, described above, does provide this opportunity for the western United States during winter months (November-April). Data collection sites are nearly all associated with developed ski areas and measurements are generally made below timberline at a level, sheltered, study site. The geographic and elevation ranges for the sites used in this study are shown in Table 1 and Figure 2. The location of the three

climatic zones and the five sites within each zone is also shown in Figure 1. A basic assumption made at the outset of this study is that the site location and exposure on the micro- to meso-scale (1 to 100 m) of all sites is similar and that any differences found in the long-term climatic data will result from the large-scale, macro-effects of regional air mass climatology.

TABLE 1 Geographic and topographic ranges for the three climate zones

	Maritime	Intermountain	Continental
Lon. deg.	119-122	111-114	105-107
Lat. deg.	37-47	40-45	36-40
Elev. m	1200-3000	2000-3000	3100-3500
<u>Sites:</u>			
	Stevens Pass WA	Bridger Bowl MT	Berthoud Pass CO
	Mt Rainier WA	Sun Valley ID	Vail Mt. CO
	Squaw Valley CA	Jackson WY	Aspen Mt. CO
	Alpine Meadows CA	Alta UT	Crested Butte CO
	Mammoth Mt. CA	Snowbird UT	Taos NM

Sites are listed north to south according to location in Figure 1.

Figure 3 provides a generalized overview of the regional variation in mean air temperature, total precipitation, mean snow depth, and mean new snow density, for the period November through April (1970-1984) for the sites listed in Table 1. For example, temperatures in the maritime average about 6.0°C above the continental zone and total precipitation is more than twice the continental value. Figures 4 through 6 contain temperature, precipitation, and snow depth data compiled by month. Table 2 contains temperature data from the three zones and shows that while the range of daily maximum and minimum temperatures is greatest in

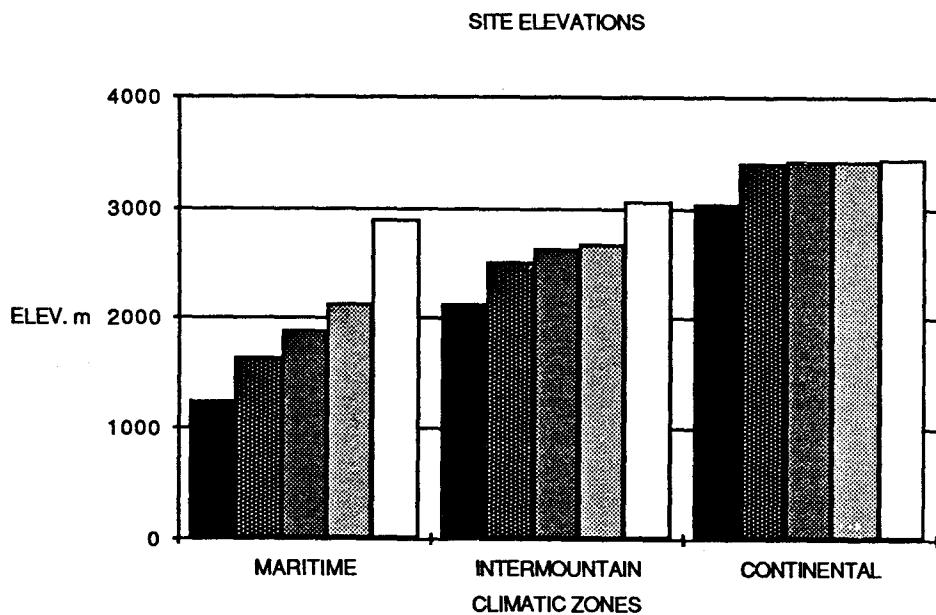


FIG.2 Elevations above sea level for the 15 data collection sites.

the continental locations, as would be expected, the standard deviations for the mean temperatures show little variation. In general, air temperatures decrease in response to the combined effect of both increasing continentality and elevation.

TABLE 2 Air temperature data, November-April

<u>Mean Elev. m</u>	<u>Maritime</u> 1965	<u>Intermountain</u> 2605	<u>Continental</u> 3350
<u>Temp °C</u>			
Mean	-1.3	-4.7	-7.3
Std. Dev.	2.1	2.2	2.0
Mean of Max.	+2.8	-1.1	-2.8
Mean of Min.	-5.6	-8.9	-12.8
Range	8.4	7.8	10.0
Abs. Max	+16.7	+13.3	+12.8
Abs. Min.	-27.2	-31.7	-33.3
Range	43.9	45.0	46.1

Table 3 contains precipitation and snowfall data including average and maximum 24 hour amounts and average number of days per year with more than 30 cm of snowfall. Here the pattern is again as expected, with all values decreasing with increasing continentality. Departure from the mean total precipitation, expressed as the coefficient of variation, remains generally consistant across the three zones.

TABLE 3 Precipitation and snowfall data, November-April

	<u>Maritime</u>	<u>Intermountain</u>	<u>Continental</u>
Mean Total			
Precip. mm	1285.5	854.1	539.3
Coeff. Var.	47.8	46.1	43.4
<u>Mean 24 hr</u>			
Snowfall cm	15.4	14.6	9.2
<u>Mean Max. 24 hr. Snowfall</u>			
	91.1	81.8	56.3
<u>Abs. Max. 24 hr Snowfall (single site)</u>			
	107.0	114.0	86.0
<u>Mean No. days/yr. &gt; 30 cm</u>			
	10.1	8.6	3.3

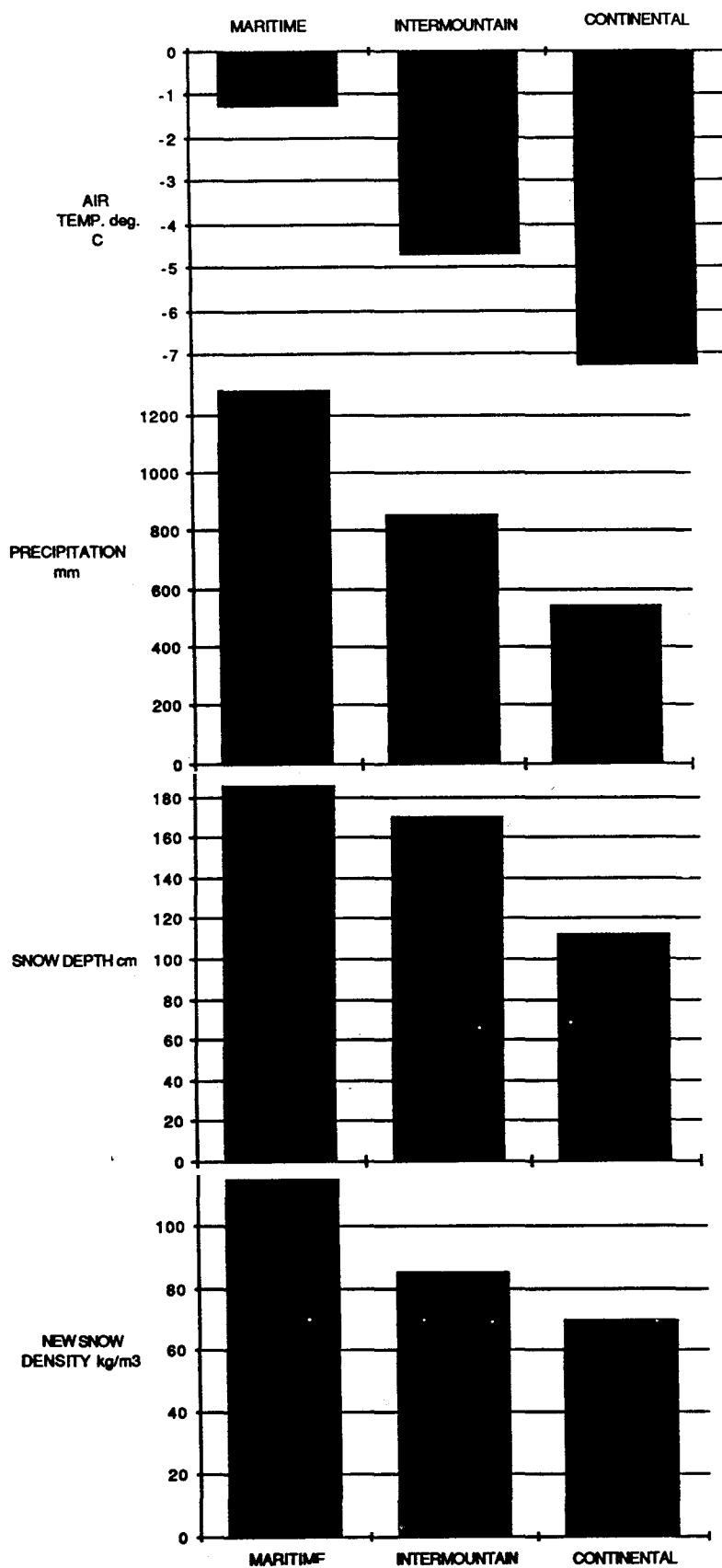


FIG. 3 Six month (Nov.-Apr.) averaged values for air temperature, total precipitation, snow depth, and new snow density for the three climate zones.

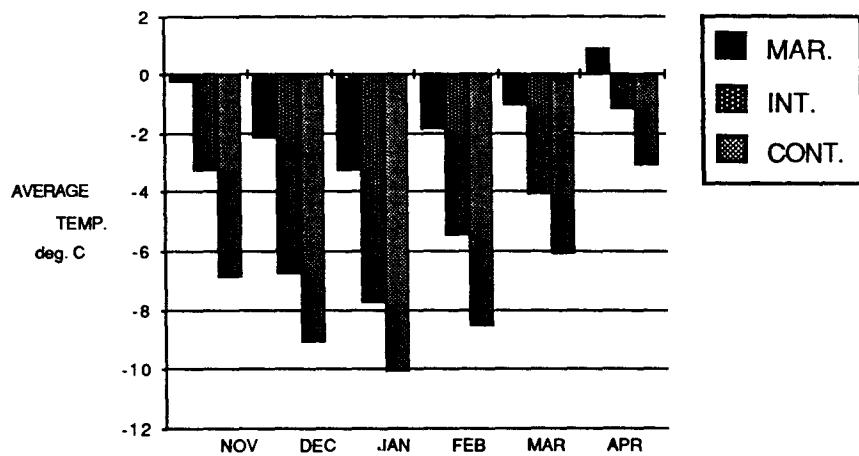


FIG.4 Average monthly air temperature for the maritime, intermountain, and continental zones.

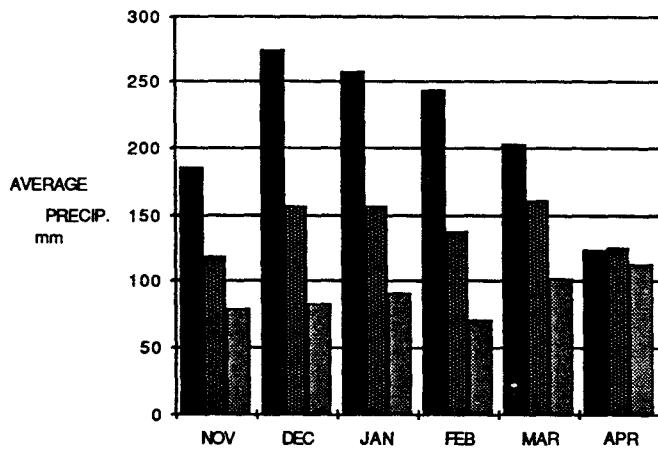


FIG.5 Average monthly precipitation for the maritime, intermountain, and continental zones.

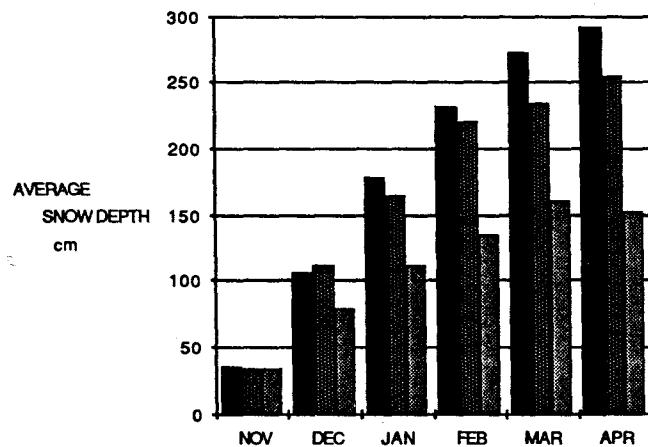


FIG.6 Average monthly snow depth for the maritime, intermountain, and continental zones.

## Snow Cover Data

Snow cover data do not follow exactly the same consistent pattern as that of precipitation. Table 4 shows that although the mean seasonal snow depth for the maritime is 1.7 times that of the continental, the coefficient of variation for snow depth in the continental is one-half that of the maritime. This relationship was consistent through each of the six months. This variation in an otherwise consistent pattern is the result of a much higher probability for above-freezing air temperatures and rain in the maritime regions, which may result in significant snow melt even during the mid-winter months. At the maritime sites, during the months of November through April, precipitation falling as rain averages 250.0 mm per year with the maximum for one site of more than 500.0 mm and the maximum 24 hour value of 200 mm. The average for the same period for the continental zone is insignificant at less than 1.0 mm.

TABLE 4 Snow depth data

Snow Depth cm	Maritime	Intermountain	Continental
Mean Seasonal	186.3	170.1	112.8
Coeff. Var.	51.4	35.8	24.2

Table 5 contains computed snow cover temperature gradients for the period November through February for the three regions. The gradient is computed by dividing the mean monthly air temperature by the mean snow cover depth and assuming a ground temperature of 0° C. This method, suggested by Akitaya (1974), has been proven to be quite accurate, at least for mid-latitude sites (R. Armstrong, 1985). It is generally accepted that given ground temperatures of near 0° C, a temperature gradient of at least 10° per meter is required to produce depth hoar. When viewed in terms of this requirement, conditions in the continental climate are, on the average, conducive to depth hoar formation well into January. Conditions in the intermountain zone are less often conducive to depth hoar formation and such conditions are rare in the maritime.

TABLE 5 Computed snowcover temperature gradients

Temp. Gradient °C/m	Maritime	Intermountain	Continental
November	4.2	7.4	18.4
December	3.5	6.6	12.5
January	2.1	5.2	9.5
February	0.9	3.9	7.1

## DISCUSSION OF WEATHER AND SNOW COVER CONDITIONS

It can be concluded that the above data support the qualitative

observations that the snow cover of a continental climate generally has a lower bulk strength than that found in a maritime location. While snow stratigraphy at any one location, regardless of climate zone, may be highly complex and variable in both the vertical and the horizontal, conditions which favor the development of weak layers in the snow cover occur more frequently in the continental areas. For example, let us review three examples commonly observed. First, the formation of thick layers (30 to 60 cm e.g.) of depth hoar are the direct result of the thin snow cover in combination with lower air temperatures found in the continental zone. Well developed depth hoar, with grain diameters of 3.0 to 6.0 mm for example, is known to resist settlement and densification even after the process of recrystallization has ceased and overburden pressures of additional layers of new snow are added (Patterson, 1981; R. Armstrong, 1979). Therefore, these weak basal layers once formed early in the season often persist throughout the season.

Second, the environmental conditions found in the continental zone frequently favor the formation of surface hoar, a potential lubricating layer which may contribute to avalanche formation subsequent to the accumulation of additional snow layers above. Frequent clear night time skies and low absolute humidity (high transmissivity) at the high elevation continental sites allow efficient radiation cooling. Snow surface temperatures often reach the frost or ice point of the air layer just above the snow surface resulting in the formation of surface hoar. Even the statistic of fewer and smaller snowfall events (one to two cm) in a continental climate can contribute to a weak snow stratigraphy. It has been observed (Armstrong and Ives, 1976) that when these relatively thin new snow layers are monitored over time they tend to densify more slowly than adjacent thicker layers, especially in the presence of clear sky conditions and low air temperatures which often prevail between storms. Therefore, although the formation of depth hoar is generally an early season process, it is clear that additional processes which tend to promote a weaker snow structure will continue to influence the continental snow cover well into the winter.

## SNOW STRUCTURE AND AVALANCHE RELEASE

If the strength condition of the old snow structure is not considered, an inexperienced observer might expect a direct relationship between precipitation and avalanches, with the obvious conclusion that, in general, avalanche hazard would be lowest in a continental climate where total seasonal precipitation and storm totals are the least. However, considering the observations made in the paragraph above, it would seem logical to conclude that given the same increment of new snow loading, a snow slope in a continental location would actually be more likely to fail than a slope in the maritime.

One component of the Westwide Data Network is the reporting of avalanche events including information on the size and type of the release. However, due to the inhomogeneity of the individual samples monitored by the various observers, it is not possible to

make a proper statistical comparison of avalanche events. From the practical standpoint of snow safety, the primary consideration is whether or not a given snow cover will support the weight of a skier, for example, or whether it will fail as an avalanche. Within the overall data set of fracture line profiles it has been established that in a typical continental location the base of the slab involved in the avalanche is often located below the old snow-new snow interface (Armstrong and Ives, 1976) while the majority of failures in the maritime zone occur at this interface (Moore, personal commun.) The presence of distinct weak layers throughout the snow cover should create conditions where lesser amounts of precipitation are capable of producing significant avalanche activity.

If the snow structure of the continental zone is inherently weaker than that of the maritime, then it should be more susceptible to load-induced avalanches during non-storm periods as well. This suggests the generalized hypothesis that there is a higher probability of a skier-triggered avalanche during non-storm conditions in a continental climate than there would be in a maritime climate based on snow structure factors alone.

Intuitively, this hypothesis would seem to be correct. The next step then was to see whether or not the avalanche accident data set for the United States could provide any support for this supposition.

#### ANALYSIS OF AVALANCHE ACCIDENT DATA

The avalanche accident data used in this study are from the western United States and cover the period 1950 to 1985 (Williams, 1975; B. Armstrong, 1985). Only accidents involving at least one fatality are used in the following analysis. This is because it is felt that data describing virtually all of the fatal accidents have been submitted to the Westwide Data Network, while some unknown percentage of those accidents not involving fatalities have gone unrecorded. An equal number of accidents were randomly selected from each of the three climatic zones (maritime, intermountain, and continental), providing a total sample of 195 accidents, or 65 per climate zone.

While it is a general rule that most avalanche events occur during storm periods, this was not the case with the avalanche accidents. In all three zones, more accidents occurred during non-storm periods (less than 5.0 cm snowfall within 24 hours). Within the individual zones, for cases where data were sufficient to define storm or non-storm conditions, results showed that in the continental zone non-storm accidents were three times as frequent as accidents during storms, while this ratio was 2.4 and 1.2 for the intermountain and maritime zones respectively (Table 6). However, because there are more total days with snowfall in a maritime climate, the above data still do not provide specific information on the stability of the old snow layers with respect to skier-triggered avalanches. It is interesting to note, however, that for the accidents which occurred during storms, considerably smaller amounts

of precipitation were involved in the continental samples. Twenty-three percent of the accidents in the continental zone occurred with less than 15 cm of snowfall during the previous 24 hours, while this value was 7 and 4 percent respectively for the intermountain and maritime.

TABLE 6 Percent of accidents during storm and non-storm conditions

Weather Condition	Maritime	Intermountain	Continental
Non-Storm	41%	59%	59%
Storm	35%	25%	20%
No Data	24%	16%	21%

Another common observation is the fact that most avalanche victims trigger the avalanche which catches or buries them. The lower the snow stability, the more likely this is to occur. In all three zones there were more natural avalanches which caused accidents during storm periods than during non-storm periods, which is to be expected. However, the ratio of accidents involving triggered or artificial avalanches compared to natural events in the continental zone exceeded that occurring in the maritime zone by a factor of nearly four (Table 7). The ratio of triggered avalanches during non-storm periods compared to natural avalanches during storm periods shows a similar pattern, with the non-storm, skier-triggered accidents occurring in the continental locations at about four times the rate found in the maritime zone.

TABLE 7 Percent of accidents resulting from natural and artificial releases

Type of Release	Maritime	Intermountain	Continental
Artificial	36%	59%	56%
Natural	28%	7%	12%
No Data	36%	34%	32%

Of the total accidents for all sites, approximately one-half occurred on, or within one day following, the day of a storm event. Of the remaining accidents which occurred within one week following a storm event, twice as many were reported in both the continental and intermountain as compared to the maritime sample. These accident data provide a set of interesting comparisons. However, no truly quantitative statistical conclusion can be reached, primarily because at this time we have no detailed information on the distribution of numbers of skiers, or back-country travelers, by geographic location. However, given this test sample, using equal numbers of accidents per climate zone, it is at least qualitatively clear that the weaker snow structure of the continental zone is likely to result in a greater number of skier-triggered avalanche accidents during non-storm periods.

## CONCLUSION

This study has utilized a long-term weather and snow data set to characterize three individual snow climates in the western United States. Results presented here provide a preliminary step in the effort to evaluate the large-scale relationships between weather parameters and basic snow cover properties. Over the past several decades there have been numerous micro-scale, site specific, studies which have resulted in an improved understanding of the physical and mechanical properties of snow. Currently, there is an applied need to better describe and understand snow cover conditions on a much broader scale. This type of information is essential to further advances in such areas as hydrologic forecasting for large drainage basins and for regional avalanche prediction. The key to such temporally and spatially complete data has become satellite remote sensing. The successful development and ultimate verification of algorithms for the retrieval of snow cover parameters from high resolution satellite sensors will depend on the integration and analysis of measured data such as those used in this study.

## ACKNOWLEDGEMENTS

Without the foresight, planning, and organizational efforts of M. Martinelli, A. Judson, and K. Williams of the U.S. Forest Service, the unique data set used in this study would not have been available. Credit must also go to the hundreds of individual observers, mostly volunteers, who have made many thousands of measurements, often under adverse environmental conditions. M. Whitfield provided professional programming assistance with the climate data set and R. Trahan was a student assistant for the analysis of the accident data. Initial work on this study was performed while the authors were employed at the U.S. Forest Service, Rocky Mountain Station, Ft. Collins, Colorado with additional support provided by the Division of Atmospheric Resources Research, U.S. Bureau of Reclamation, Denver, Colorado.

## REFERENCES

Akitaya, E. 1974. Studies on depth hoar. Publication 144, International Assoc. of Hydrological Sciences, Gentbrugge, Belgium, p. 42-47

Armstrong, B. R. 1985. Avalanche Accident Victims in the U.S.A. Journal of Ekistics, No. 309, Nov./Dec., p. 543-546.

Armstrong, R. L. 1985. Metamorphism in a subfreezing, seasonal snowcover: the role of thermal and vapor pressure conditions. Unpublished Doctoral Dissertation, University of Colorado, Boulder, 175 p.

Armstrong, R. L. 1979. Analysis of compressive strain in adjacent temperature-gradient and equi-temperature layers in a natural snow cover. Journal of Glaciology, Vol. 26, No. 94, p. 283-289.

Armstrong, R. L. and Ives, J. D. (Eds.) 1976. Avalanche release and snow characteristics, San Juan Mountains, Colorado. Institute of Arctic and Alpine Research Occasional Paper No. 19, University of Colorado, Boulder, 256 p.

Barry, R. G. 1981. Mountain Weather and Climate. Methuen, London, 313 pp.

Judson, A. 1970. A pilot study of weather, snow, and avalanche reporting for western United States. National Research Council of Canada Tech. Memo. 98, Ottawa, p. 123-134.

LaChapelle, E. R. 1966. Avalanche forecasting -- a modern synthesis. Publication 69, International Assoc. of Hydrological Sciences, Gentbrugge, Belgium, p. 350-356.

Patterson, W. S. B. 1981. The physics of glaciers. Pergamon Press, Oxford, 380 p.

Roch, A. 1949. Report on snow and avalanche conditions in the U.S.A. Western Ski Resorts. From the 26th of January to the 24th of April, 1949. Swiss Federal Institute for Snow and Avalanche Research Report No. 74., Davos, 44 p.

Williams, K. 1975. Avalanche fatalities in the United States, 1950-1975. USDA Forest Service Research Note RM-300, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colorado, 4 p.

#### DISCUSSION

##### R.D. Faisant

Graph of fatalities by state may lead to erroneous conclusions, e.g. Colorado is twice as dangerous as other states. If fatalities were charted by climatic zone (e.g. California, Alaska, Washington, Oregon combined), would not gross number of fatalities for maritime zone about equal the number for continental?

##### R.L. Armstrong

This part of the study was designed to investigate the relationship between snow climate and fatal avalanche accidents. Therefore equal sample sizes. (65) of accidents were selected from each climate zone.

##### N. Rangachary

1. What is your definition of non-storm avalanche accident? Further it appears to contradict the present concept of direct action avalanches.
2. The climatic zone should have been maritime, inter mountain and mountain (instead of continental) as the elevation increases from west to east.

##### R. Armstrong

1. A storm was defined as being at least 5.0 cm of new snow in the previous 24 hours. Within this study both storm and non-storm accidents may be either natural or triggered events, so the single term direct action was not appropriate here.
2. All of the sites used in this study are in mountain locations. In order to describe the prevailing weather and snow cover conditions typical of these locations, the terms maritime and continental were used. These are standard terms in the field of climatology.