Snow Avalanche Climatology of the Western United States Mountain Ranges

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ABSTRACT

The snow avalanche climate of the western United States has long been suspected to consist of three main climate zones that relate with different avalanche characteristics: coastal, intermountain, and continental. The coastal zone of the Pacific mountain ranges is characterized by abundant snowfall, higher snow densities, and higher temperatures. The continental zone of the Colorado Rockies is characterized by lower temperatures, lower snowfall, lower snow densities, higher snow temperature gradients, and a more persistently unstable snowpack resulting from depth hoar. The intermountain zone of Utah, Montana, and Idaho is intermediate between the other two zones. A quantitative analysis of snow avalanche climate of the region was conducted based on Westwide Avalanche Network data from 1969 to 1995. A binary avalanche climate classification, based on well-known thresholds and ranges of snowpack and climatic variables, illustrates the broadscale climatology of the three major zones, some spatially heterogeneous patterns, and variations with elevation. Widespread spatial shifts toward more coastal conditions occurred during 1985/86 and 1991/92, and shifts toward more continental conditions occurred during 1976/77 and 1987/88. Height anomalies at 500 mb explain many of these shifts, but daily plots of climate and avalanche variables during seasonal extremes for sites in northern Utah also illustrate the importance of understanding snowpack and weather variations that occur at daily to weekly timescales. Data from several central Rocky Mountain sites indicate some relationships with the Pacific–North American teleconnection pattern and the Pacific decadal oscillation, illustrating the importance of applying long-term records in an avalanche hazard assessment.

1. Introduction

Snow avalanches are a severe natural hazard in the mountainous regions of western North America, destroying property, disrupting transportation networks and recreational facilities, and occasionally causing deaths (Voight et al. 1990; Armstrong and Williams 1992; Smith 1996). Annual numbers of avalanche accidents and fatalities in the United States have increased steadily, with the average national annual fatality rate around 25 by the late 1990s being more than five times greater than the average rate in the early 1950s (Fig. 1).

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Economic losses from avalanches are difficult to assess, but conservative estimates indicate that they amount to millions of dollars each year when accounting for property damage, snow removal from highways, and avalanche rescues (Voight et al. 1990). The avalanche hazard is greatest in the Rocky Mountain states in recent decades due to the increased popularity of skiing and snowmobiling (Fig. 1). Numerous heavily populated ski areas have significant avalanche hazards that must be monitored and controlled by highly trained ski patrols. For example, Utah's Wasatch Mountains provide backcountry skiing, snowshoeing, snowboarding, and snowmobiling to a major population center in the Salt Lake Valley, with potentially hundreds of thousands of people traveling into avalanche terrain in a given winter. The mountains of southwest Montana are also prime avalanche terrain, where over 300 000 snowmobile visits per year typically occur.

Abnormally widespread severe avalanche winters for some areas have been documented, such as the winter of 1978/79 in Glacier National Park, Montana, and Rogers Pass, British Columbia (Butler 1986;

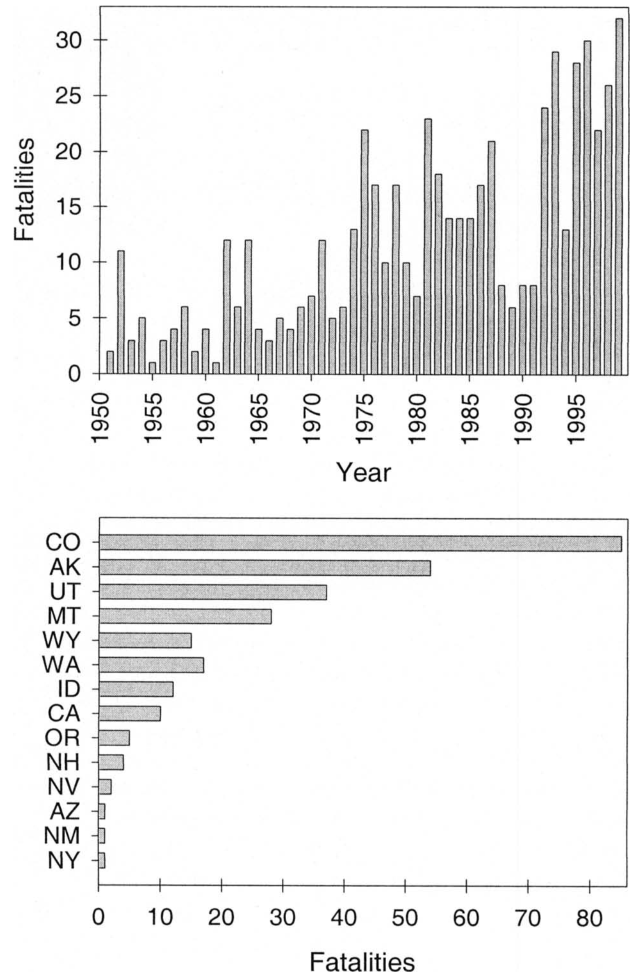

FIG. 1. (top) Annual avalanche fatalities through time in the United States from 1951 to 1999, and (bottom) avalanche fatalities by state from 1986 to 1999.

Fitzharris 1981). Calculations of probability or return intervals of such extreme avalanche winters have been conducted from analyses of tree rings and historical records for point locations (Carrara 1979; Butler 1986). However, these types of calculations do not provide much information concerning the spatial extent of avalanche severity, nor do they provide information concerning the atmospheric or snowpack processes that are responsible. Furthermore, avalanche deaths and accidents often occur during avalanche cycles that require analyses of accurate data with subseasonal temporal resolution. Numerous site-specific statistical and numerical models utilizing snowpack and weather data provide useful information concerning processes that occur at the daily timescale (e.g., Davis et al. 1996, 1998; Conway and Wilbour 1998), but are not directly applicable to larger spatial and longer temporal perspectives.

Variations in synoptic-scale atmospheric circulation affect the evolution of snowpack characteristics, which in turn affect spatial patterns of avalanche activity (Ferguson et al. 1990; Fitzharris 1981, 1987). A particular combination and/or sequence of these variations occurring at short (daily to weekly) and long (monthly to seasonally) timescales lead to severe widespread avalanche winters. Several studies have examined the relationships between atmospheric circulation and avalanche activity in Norway (Fitzharris and Bakkehøi 1986), Iceland (Bjornsson 1980), East Asia (Rangachary and Bandyopadhyay 1987), and the Swiss Alps (Calonder 1986; Hächler 1987). Fitzharris (1981, 1987) conducted a similar study for Rogers Pass in British Columbia but focused on temporal rather than spatial aspects. Mock and Kay (1992) and Mock (1995) conducted similar investigations on the avalanche climate of Alta, Utah, and the Colorado Rockies, respectively, and constructed a broadscale snow avalanche climatology of the entire western United States. However, their synoptic applications are still generally site specific, and their subseasonal analysis was conducted on a monthly rather than daily basis.

Our paper deals with several components. First, we summarize previous avalanche climate studies of the West to place this work in the context of current themes in avalanche climatology. Second, we utilize a more extensive climatic dataset at avalanche-prone sites than Mock and Kay (1992) and Mock (1995) to provide a new snow avalanche climate classification based on general snowpack processes (e.g., Roch 1949; Armstrong and Armstrong 1987; Sturm et al. 1995). This classification enables us to construct a more detailed spatial analysis of the avalanche climate zones of the West. Third, we use this classification to examine the temporal variability of snow avalanche climate characteristics over the western United States, particularly for the central Rocky Mountains, and to identify abnormal avalanche winters and their relationships to synoptic climatic patterns. Fourth, for each abnormal avalanche winter, we also examine the relationships between daily weather and snow avalanche hazard, using Alta and Snowbird in northern Utah as examples.

2. Background

Snow avalanches occur as either loose snow slides or slab avalanches (McClung and Schaerer 1993). The type of avalanche depends on the characteristics of the snowpack, which has a complex, layered structure due to variations in storms and the metamorphic processes that affect the snow once it is on the ground. Loose snow avalanches occur when the surface snow is relatively cohesionless and the slope angle is steeper than the angle of repose, and they only present a small hazard (Voight et al. 1990). In contrast, slab avalanches are more dangerous to life and property, involve more snow, run longer distances, and are more difficult to forecast; these avalanches are the focus of our research. Slab avalanches occur in snowpacks where a relatively cohesive slab overlies a less cohesive weak layer, and require that the stresses on the snow slab exceed the strength holding it in place. Common stresses that trigger slab avalanches include new or wind-blown snow, falling cornices, explosives, or the weight of a person on a slope.

Since slab avalanches require a snow structure that includes a slab overlying a weak layer, the seasonal snowpack development is critical for forecasting avalanche activity. One common scenario for a dangerous avalanche season involves meager early season snowfall and abnormally cold temperatures. Metamorphic processes resulting from these conditions turn the snowpack into cohesionless, sugary, faceted crystals called depth hoar. When subsequent new and wind-loaded snow is deposited on this weak layer, the result is often large, full-depth avalanches. Depth hoar is remarkably persistent and often causes avalanching throughout much of the winter season. Intensive snowstorms also create large avalanches if additional weight from new snowfall exceeds the strength of the bonds between the new and wind-deposited snow. Normally, most big avalanches occur from December to March with a maximum typically in January or February.

Avalanche characteristics depend on both the climate of the area and the weather preceding the avalanche. Continental climates have colder temperatures, more clear skies, and less snowfall, all of which are very conducive to the formation of depth hoar and other persistent weak layers. Due to these weak layers, large and destructive avalanches in continental areas may result from even only small snowfalls or wind events. Avalanche forecasts in these areas depend heavily on observations of structural weaknesses in the snowpack (LaChapelle 1966) as well as weather observations. In contrast, coastal climates have warmer temperatures, cloudier skies, and more copious snowfall, resulting in the formation of fewer weak layers. Avalanches in coastal climates tend to be the result of large snowfalls and they often involve only the new snowfall, therefore relying predominantly on daily precipitation variables (LaChapelle 1966). Intermountain areas have intermediate conditions between the two zones; however, intermountain areas during some winters have avalanche characteristics that can be predominately continental or coastal. Coastal conditions might spread inland or continental conditions might extend toward the coast. Since avalanche forecasting techniques vary depending on the climate type, understanding and being able to predict these seasonal shifts in climate types clearly has important implications for enhancing avalanche forecasting.

Research on the snow avalanche climate of the western United States began when Roch (1949), a researcher from the Swiss Federal Institute for Snow and Avalanche Research, classified three climate zones: the coastal, middle, and high alpine zones. LaChapelle (1966) described these three zones in further detail and noted that they correspond with the Pacific coast (coastal), Rocky Mountain (continental), and Intermountain regions (Fig. 2). He also described a fourth region, the coastal transition zone, but with the exception of it having less snowfall and rain, it is similar to the Pacific coast region. Armstrong and Armstrong (1987) were the first to examine the avalanche climate characteristics quantitatively, utilizing climatic data from the Westwide Avalanche Network (WWAN) to calculate means of temperature, precipitation, snowfall, snow depth, and snow density for each of the three climate zones. Their analyses, as well as further studies by Mock and Kay (1992), and Mock (1995), reinforce the notion of three distinct avalanche climate zones, generally following a west–east gradient (Fig. 2).

The results of these snow avalanche climate regionalization studies are as follows. The coastal zone, encompassing the Sierra Nevada and Cascade ranges in the Pacific coast states and extending a bit into northern Idaho, is characterized by mild temperatures, abundant heavy snowfall, a high density snowcover, and a low temperature gradient in the snowpack. Conversely, the continental zone of the Uinta Range in Utah, and the Rocky Mountains in Colorado, Wyoming, New Mexico, and parts of Montana is characterized by cold temperatures, less abundant snowfall, lower density snow cover, and a steeper temperature gradient. The intermountain zone of the northern Rocky Mountains of Montana, the Wasatch Range of Utah, the Blue Mountains of northeastern Oregon, and the mountains of southwestern Colorado is intermediate in avalanche climate characteristics between coastal and continental. Such climatic and snowpack differences are important since they determine the structure of the snow cover and the resultant character of avalanching in each zone.

The threefold classification scheme for the western United States summarizes large-scale spatial characteristics of snow avalanche climates, but smaller-scale patterns of spatial climate heterogeneity also exist (Mock 1996b). Some stations exhibit avalanche climatic conditions that deviate from surrounding areas as a result of the alignment of topography and their interactions with atmospheric circulation (Mock 1995; Birkeland and Mock 1996). For example, Mission Ridge, Washington, exhibits a more continental character as compared to the general coastal climate prevalent over most of the Cascades. A peculiar continental climatic regime, although less continental as compared to most sites in Colorado, has been documented in southern Utah and northern Arizona from limited field observations (Fig. 2; LaChapelle 1966; Dexter 1981). Changes in temperature with elevation and changes in snow depth due to wind scour can determine the formation of weak faceted crystals in isolated areas, which are often associated with more continental conditions. However, to date, the details of the spatial variability of avalanche climate over the West have not been fully examined using existing data sources. Furthermore, the spatial variability of snow avalanche conditions may vary temporally. Mock and Kay (1992), Butler (1986), and Fitzharris (1981) noted that periods of widespread severe avalanching in the interior North American mountain ranges result when persistent coastal or continental conditions are evident over a large area.

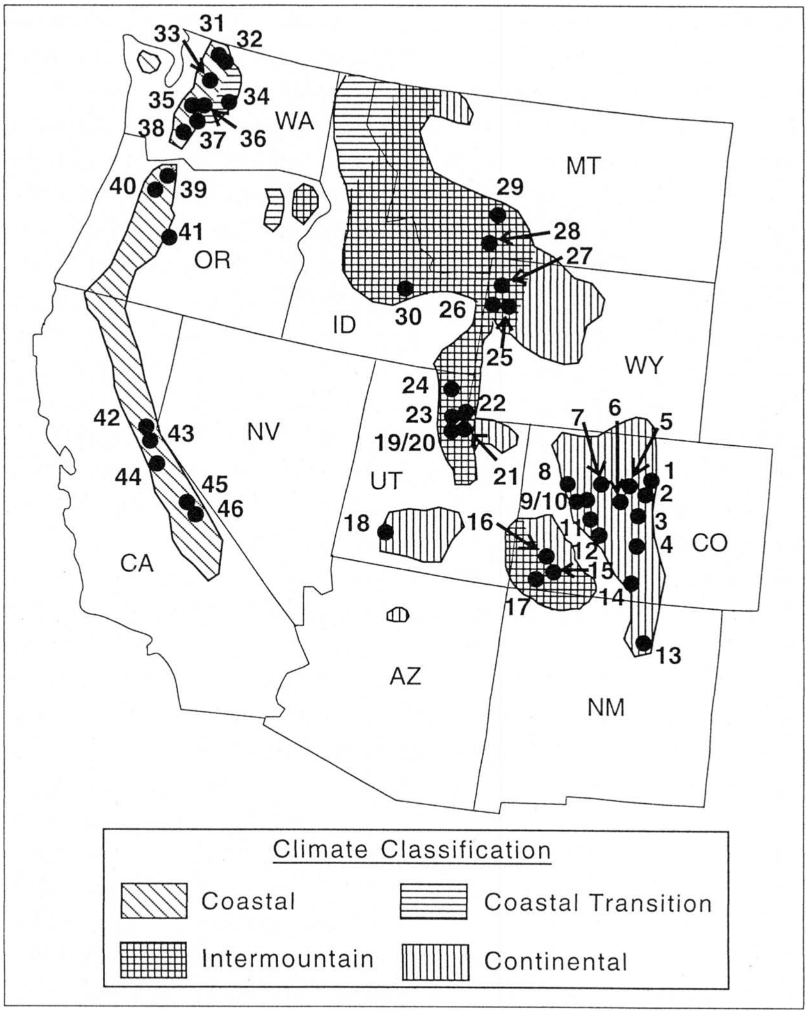

FIG. 2. Study area and zonation of avalanche climates after Roch (1949), LaChapelle (1966), Armstrong and Armstrong (1987), Mock (1995), and Dexter (1981). Numbers correspond to station locations used in our study (refer to Table 1 for station names).

We provide a first step toward a full analysis by examining all available data from the WWAN. Data collection has its origins in the early 1950s, but increased temporal coverage of data began in the late 1960s when the WWAN officially started (Judson 1970). Subsequently, the data were archived by K. Williams, initially at the U.S. Forest Service from 1971 to 1983 and then at the Colorado Avalanche Information Center from 1983 to 1995. Since 1995, D. Howlett and D. Judd of the American Association of Avalanche Professionals have managed the data. The WWAN is currently the longest established high-elevation climate and avalanche database in the United States. All WWAN sites are located close to avalanche paths and runout zones. A comprehensive analysis of WWAN data will provide an essential framework to integrate SNOTEL (snowfall telemetry) data to further examine the spatial and temporal variability of avalanche climates.

3. Description of data

We examined 48 stations with climatic and snowpack data (Fig. 2;

Table 1), including two stations in Alaska to provide additional "climate space" in analyzing the variability of avalanche climate. For 45 stations, virtually all data came directly from the WWAN, with some data provided courtesy of several ski resorts that cover a few years of missing data not included in the WWAN archives. Record lengths are not always continuous, varying from 2 to 52 yr during the 1946–98 time period. However, the majority of sites have at least 10 yr of complete data, which is not common for North American high-elevation sites (Armstrong and Armstrong 1987; Barry 1992). Most data utilized are within 1970–95 since much of the data after 1995 are still in manuscript form due to the termination of funding from the U.S. Forest Service.

We analyzed daily WWAN data for December–March. This season was chosen because early and late winter data were often incomplete for most sites since data collection reflected the business of the ski season. Six snow climate variables were chosen: minimum temperature, maximum temperature, total snow depth, daily snowfall, daily snow water equivalent, and daily rainfall. Most observers collected data using standardized instruments and data collection procedures (McClung and Schaerer 1993). Daily snowfall and snow depth were measured from snow boards and master snow stakes, respectively. Observers typically made measurements once per day during morning hours although some days included several measurements to reduce errors introduced by melting snowpack and effects of blowing snow. Daily snow water equivalent was measured from precipitation gauges, snow pillows, and occasionally by isotopic profilers (Armstrong 1976; Marriott and Moore 1984). This variable indicates the water content of new snow for the past 24 h, and it is a vital tool for avalanche forecasting since it quantifies the amount of weight, and hence stress, being added to the snowpack (McClung and Schaerer 1993). Such measurements are not a traditional requirement for many weather stations in the United States (Doesken and Judson 1996), including those at SNOTEL sites by the Natural Resources Conservation Service. SNOTEL data record the water equivalent of the snow, but their values deal with the accumulation of liquid water throughout an entire season. Furthermore, SNOTEL does not have long-term records of snow depth, which are required for calculating snow temperature gradients and new snow density, and SNOTEL data are not associated with avalanche data from nearby slopes. Thus, despite missing gaps of data, the WWAN currently possesses the largest database directly applicable for avalanche hazard research.

We also used climatic and snow data from three additional sites that are currently not part of the WWAN because they fill important spatial gaps in the network of snow climate sites in the West. These sites are Mount Bachelor, Oregon; Snowbasin, Utah; and Brianhead, Utah. The nature of the snow climate data for Mount Bachelor and Snowbasin are similar to WWAN data, including "new snow water equivalent data." The data from Brianhead comes from the National Weather Service's (NWS) Cooperative Weather Observer Program (COOP) program that comprises volunteer weather observers. We chose to use this station because it is located in an avalanche-prone area, and it fills a needed spatial gap in the avalanche climate network. Its temperature, snow depth, and snowfall data are compatible with the WWAN, but snow water equivalent was not recorded. However, winter rainfall in southern Utah and any location east of the Pacific mountain ranges is extremely rare, so our assumption that the precipitation record accurately reflects new snow water equivalent is valid and very conservative, requiring no adjustments from recorded temperatures. The lack of snow water equivalent data is also evident for other areas such as northern Idaho, but we cannot utilize other NWS COOP stations in a similar manner due to more frequent rainstorms that occur elsewhere.

Avalanche data at WWAN sites are less plentiful than weather and snowpack data, but they are currently routinely recorded at about 40 sites in the western United States. Data follow the United States reporting system (Perla and Martinelli 1978). We utilized the data indicative of size for each avalanche reported. The avalanche size is based on volume of snow as it compares with the avalanche path of interest. The size was recorded by using a relative numerical scheme from 1 to 5, with 1 indicating the smallest (any slide running less than 50 m downslope) and 5 being the maximum size avalanche expected for a given path. The use of site-specific indicator paths have been used in some avalanche research (Judson 1983), but we chose not to use this approach. A primary problem with using indicator paths is that even during large avalanche cycles, only 40% of the avalanche paths may run as a result of topographic factors (Mears 1992). The use of indicator paths may exclude some major avalanche events. Instead, we devised an avalanche hazard index that represents the total avalanche activity of a given site, which provides a much better means to assess its relationships to climatic variations.

Several problems exist with the reliability of the climatic and avalanche data. Relocation of instruments was sometimes not recorded and a variety of sensors may have been used through time, resulting in different climatic responses from similar environmental conditions (Marriott and Moore 1984). Thus, we analyzed time series of individual variables for each site ranging from daily to monthly (to account for temporal changes for stations with short records) to detect discontinuities. Any suspect data was discarded. The avalanche dataset presented more problems. The quality of avalanche control work, types of control measures used, and number of observers recording avalanche data varied with time and at different sites. Some sites also practice relatively more intensive control measures, thus setting off high numbers of artificial avalanches. Other sites may not control each small slope and, thus, may not record as many avalanches. Furthermore, the intensity of avalanche control has changed at numerous sites over time in response to the public's desire to ski additional steep and rocky terrain. The WWAN generally records few backcountry avalanches; many go unrecorded because no one observes them or because they are obscured by new or blowing snow (Armstrong and Williams 1992). Since the different terrain characteristics at each Westwide site further complicate attempts to utilize avalanche data for examining regional-scale patterns, applications of such data are mostly site specific. Thus, we focused on utilizing avalanche data for the Utah Department of Transportation (UDOT) in Alta, and Snowbird, in northern Utah. These examples demonstrate how similar applications can be conducted for other WWAN sites.

Atmospheric circulation data consist of gridded 500-mb heights (in geopotential meters) provided by the National Center for Atmospheric Research and

Table 1. Names of locations and their elevations (m) used in the study. Numbers represent locations as shown in Fig. 2. Asterisks (*) indicate the stations that have more than 15 yr of data that were used in developing the avalanche climate classification. Also shown are the number of winter seasons that each station was classified as continental, intermountain, and coastal. Alyeska is located in south-central Alaska, and Eaglecrest is located in southeast Alaska.

Id No.	Station	Elevation	Cont.	InterMt.	Coastal
Colorado and New Mexico					
*1	Berthoud Pass	3449	37	2	0
2	Loveland Pass	3575	14	0	0
3	Arapahoe Basin	3505	8	0	0
*4	Monarch	3414	16	3	0
*5	Breckenridge	3383	15	4	0
*6	Copper Mountain	3353	16	1	0
*7	Vail	3429	12	13	0
8	Sunlight	2926	4	7	0
*9	Aspen Mountain	3411	16	4	0
10	Aspen Highlands	3292	8	6	0
*11	Gothic	2890	16	4	0
*12	Crested Butte	3094	17	3	0
*13	Taos	3414	7	10	0
*14	Wolf Creek	3396	2	14	1
*15	Red Mountain Pass	3400	12	7	0
*16	Telluride	3404	11	5	0
17	Purgatory	2941	4	7	1
Utah, Idaho, Wyoming, and Montana					
18	Brianhead	2978	2	5	0
*19	Alta UDOT	2646	5	30	17
20	Alta Ski lifts	2946	1	9	1
*21	Snowbird	2865	3	17	5
22	Solitude	3011	1	1	0
23	Wolf Mt. (Park West)	2317	1	2	0

TABLE 1. *Continued.*

Id No.	Station	Elevation	Cont.	InterMt.	Coastal
Utah, Idaho, Wyoming, and Montana					
24	Snow Basin	1951	1	7	5
25	Grand Targhee	2400	0	7	0
26	Teton Pass	2440	5	9	0
*27	Jackson Hole	2493	11	14	0
28	Big Sky	2703	3	2	0
*29	Bridger Bowl	2260	4	16	3
30	Sun Valley	2743	9	6	0
California, Oregon, Washington, and Alaska					
31	Mt. Baker	1286	0	0	12
32	Washington Pass	1679	0	2	2
*33	Stevens Pass	1580	0	2	36
34	Mission Ridge	1600	1	4	4
35	Alpental	1645	0	0	3
36	Snoqualmie Pass	1158	0	0	12
*37	Crystal Mountain	2079	0	2	18
*38	Mt. Rainier Paradise	1676	0	0	26
*39	Mt. Hood	1600	0	0	19
40	Multopor Ski Bowl	1200	0	0	8
41	Mt. Bachelor	1935	0	2	7
*42	Squaw Valley	2438	0	0	23
*43	Alpine Meadows	2134	0	0	28
44	Carson Pass	2599	0	0	5
45	June Mountain	2800	1	0	4
*46	Mammoth Mt.	2900	0	6	12
Alaska	Alyeska	454	1	4	14
Alaska	Eaglecrest	799	0	3	6

covering the period from January 1946 to January 1994. The 500-mb level lies above the elevation of the highest peaks in the western United States, thereby eliminating artificial influences from the planetary boundary layer. We examined circulation data for a region covering the western Pacific to the eastern Atlantic to adequately describe large-scale atmospheric circulation features such as longwave ridges and troughs (e.g., Mock 1995). The data consist of an interpolated octagonal grid of observations at 0000 and 1200 UTC (Mass 1993).

4. Methodology

a. Regionalization of avalanche climates

We conducted our classification of snow avalanche climates over the western United States using seasonal climatic data, seasonal snowpack data, and some December data. This differed from previous approaches (e.g., Mock 1995), where multivariate statistical analyses on a monthly timescale were conducted. We chose not to use similar methods in our study for several reasons. First, climate classification by multivariate statistics does not correspond directly with important snowpack processes (e.g., temperature gradient thresholds) that are of important use for avalanche workers. Second, multivariate statistical classification approaches used to identify extremes through time, such as principal components analysis, are based on continuous time series of data, thereby eliminating the use of numerous WWAN sites with less than 15 yr of complete record. Inclusion of these data is invaluable in assessing spatial patterns of avalanche climate.

Instead, our study utilizes a binary seasonal snow avalanche classification approach derived from the possible range of winter climatic and snowpack variables (e.g., Sturm et al. 1995). Well-known criteria of defining thresholds and ranges of snow avalanche climatic variables provide the basis for classifying coastal, intermountain, and continental conditions (e.g., Armstrong and Armstrong 1987). Seasonal climatic and snowpack data were entered in a flowchart scheme, classifying the simplest snow avalanche climates initially and progressing with increasing complexity. Sturm et al. (1995) illustrated that such a classification approach can successfully represent the major spatial patterns of snow climates from the subregional to global scales. Unlike Mock and Kay (1992) and Mock (1995), we did not include avalanche data in our seasonal classification since avalanche data may be site specific and temporally inconsistent and, thus, not always accurately representative of spatial variations in the three major avalanche climate zones. Instead, we used avalanche data to indicate the response of avalanche activity to different climatic and snowpack characteristics.

We based our classification on WWAN sites with more than 15 yr of complete winter data during the period 1969–95. All seasonal data from the WWAN stations were grouped according to the general snow avalanche climatic region in which it is located (Table 1), a procedure similarly used by Armstrong and Armstrong (1987). The total numbers of cases are 152 for the coastal zone (7 sites), 91 for the intermountain zone (4 sites), and 232 for the continental zone (12 sites). To determine thresholds and ranges for the snow avalanche climate classification, we constructed box plots to compare the variability of temperature, snowfall, snow water equivalent, snow depth, December temperature gradient, and rainfall for each of the three major avalanche climate regions (Figs. 3 and 4). December temperature gradient (TG) of the snow was used in the classification because gradients exceeding 10°C m^{-1} are often associated with the formation of weak faceted crystals of depth hoar (McClung and Schaerer 1993). December temperature gradient was calculated by dividing the difference of mean December air temperature and an assumed basal temperature of 0°C by the mean December snow depth. Akitaya (1974) and Armstrong and Armstrong (1987) found this approach to calculating temperature gradient to be reasonably accurate, and it was also used by Mock and Kay (1992), and Mock (1995, 1996a). For each plot, the upper and lower boundaries of each box represent the 25th and 75th percentiles, respectively, with the box indicating the interquartile range. Whiskers above and below a box indicate the 90th and 10th percentiles, respectively.

We conducted three analyses dealing with the seasonal avalanche climate classification (described fully in section 4). First, for sites with over 15 yr of record, we input seasonally and December TG-averaged data into the classification to assess how well the classification matched up with the expected classification for each site. Second, we input seasonal and December TG data for each year for every one of the 46 sites into the classification scheme in order to

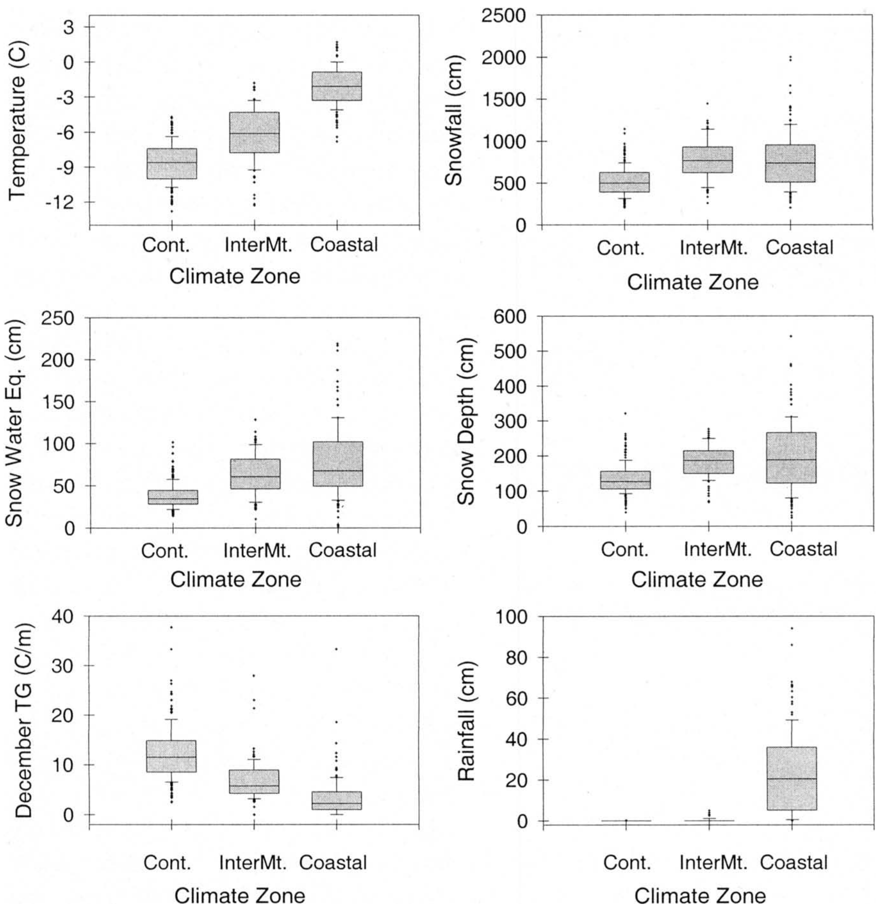

FIG. 3. Box plots illustrating the variability of temperature, snowfall, snow water equivalent, and snow depth for the three avalanche zones. Only stations with greater than 15 yr of data were used (see Table 1).

analyze the frequencies of coastal, intermountain, and continental years. Sites with shorter records were used as a means for testing the performance of the classification. Third, for each site with at least 5 yr of data (Table 1), we mapped the percentage of coastal, intermountain, and continental years, and mapped them separately. This step allowed the analysis of spatial patterns of avalanche climate characteristics, since we expected some exceptions to the west–east gradient from coastal to continental due to topographic effects. We supplemented this analysis by examining scatterplots that illustrate the relationships between elevation and the percentages of coastal, intermountain, and continental years for each site.

b. Analysis of avalanche extremes

First, we constructed a map indicating the most frequent snow avalanche climate classification for each site listed in Table 1 with records for least 5 yr. This map represents "average" conditions. Next, the spatial distribution of snow avalanche climate for each site, regardless of record length, was mapped for each year from 1969 to 1995 using symbols representing different avalanche climate types (e.g., coastal). Using symbols allowed the visualization of heterogeneous patterns occurring at smaller spatial scales that chloropleth and isoline maps do not reveal. By comparing maps for each year with the modal classification map, we identified widespread continental or coastal conditions. For these "avalanche extremes," composite anomaly maps of 500-mb heights for December–March (in geopotential meters), as well as for December continental extremes, were constructed to examine the atmospheric circulation patterns. December anomaly maps particularly provide explanations on the prevalence of depth hoar, a weakly bonded snowpack layer that forms an unstable base for future snowfall. The anomalies are relative to the period 1946–94. In the interpretation of composite anomaly maps, positive anomaly centers indicate increased clockwise flow and negative anomaly centers indicate increased counterclockwise flow.

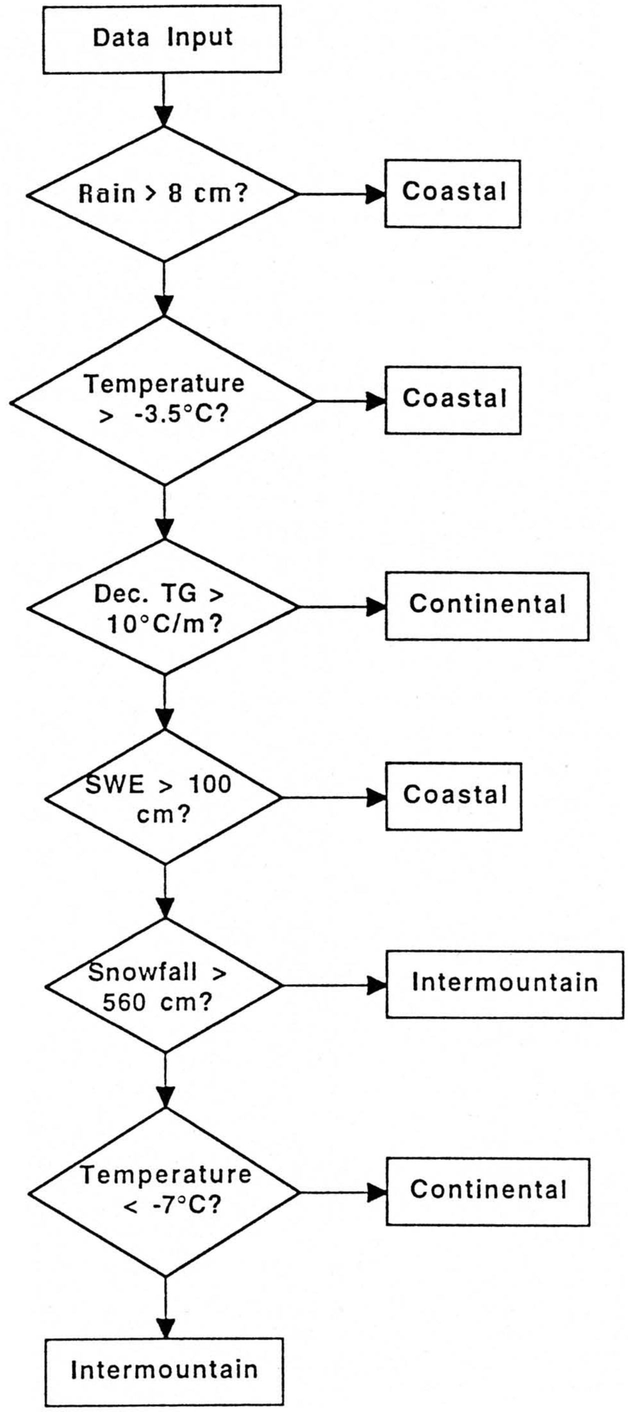

FIG. 4. Flowchart illustrating the classification procedure for the seasonal snow avalanche classification.

We used a daily timescale to analyze avalanche responses to weather and climate during selected abnormal avalanche winters at Alta UDOT and Snowbird. The size of individual avalanches (on the 1–5 U.S. scale) recorded was squared, and the daily totals were summed to construct an avalanche index. We squared the avalanche data because some conditions might lead to a large number of small avalanches, which are often relatively harmless, while larger avalanches are more indicative of conditions that might lead to damage to facilities and widespread instabilities in the snowpack in the surrounding backcountry. In addition, sometimes large numbers of small avalanches are the result of intensive avalanche control work. Next, we constructed time series for each WWAN site depicting daily trends within a particular winter. Such seasonal plots are routinely used by avalanche forecasters and ski patrollers at ski areas throughout the western United States in order to analyze the snowpack history. We selected the following variables in our graphical analyses: the avalanche index, snowfall, snow water equivalent, snow depth, and maximum and minimum temperature. Such plots then allow us to interpret the history of the snowpack for a given season.

Seasonal plots for Berthoud Pass, Colorado (a continental site), and Mount Hood, Oregon (a coastal site), for two different years demonstrate the usefulness of such analyses (Fig. 5). The 1976/77 season at Berthoud Pass started out with a thin snowpack (less than 50 cm), cold temperatures (average temperatures less than −10°C), and relatively large differences between maximum and minimum temperatures. Since the temperature of the ground stays near 0°C, the temperature gradient in the snowpack exceeded 10°C m^{-1} and was associated with the formation of weak faceted crystals. Cool temperatures and a thin snowpack throughout the 1976/77 season ensured that weak layers remained prevalent in the snowpack, and even small storms are associated with relatively high avalanche activity, as measured by the avalanche index. In fact, only one storm exceeded 20 cm during this particular season. Limited new snowfall is sufficient to overload old layers of fragile depth hoar, and avalanches releasing on this layer often run on the ground and involve the snowpack from the whole season. The situation for Mount Hood in 1982/83 is quite different and demonstrates its more coastal climate characteristics. The relatively deep snowpack (generally over 2 m and rising to well over 3 m), warm and low diurnal ranges of temperatures (average temperatures generally above or near freezing), and rain are relatively common for most coastal sites. Temperature gradients within the snowpack are minimal, and therefore weak layers of faceted crystals are limited. Periods of significant avalanching are still evident, but the avalanche characteristics differ from those occurring in more continental areas. These avalanches typically occur immediately following large and prolonged storms usually involving any recent new snow. In addition, a large rain event in early January led to a significant avalanche cycle.

Some scatterplot examples reinforce some general relationships between daily snowfall and the avalanche

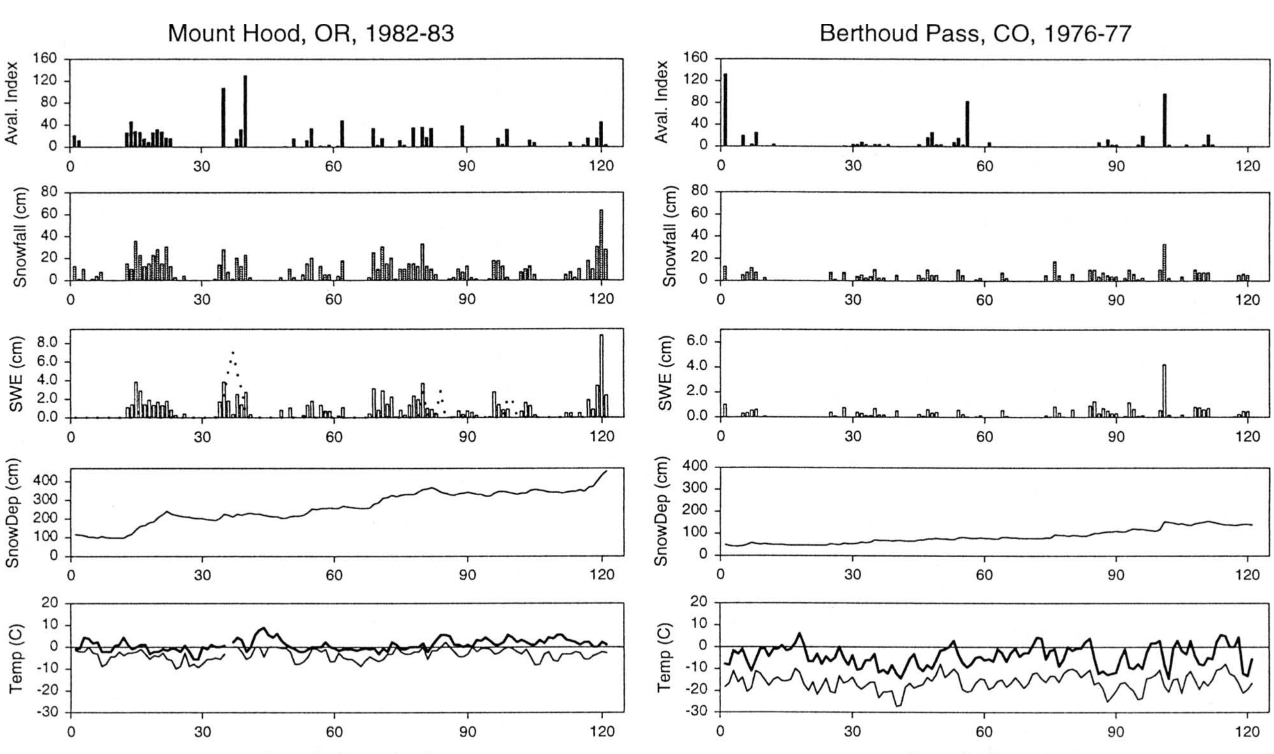

FIG. 5. Daily plots of weather and avalanche variables for Mount Hood, OR (1982/83), and Berthoud Pass, CO (1976/77). For Mount Hood in the SWE graph, dotted lines indicated rain.

index in each avalanche climate zone (Fig. 6). The example for Berthoud Pass (a continental site) indicates that high avalanche indices result from low amounts of snowfall, indicating the importance of avalanching that results from destabilization of weak layers in the snowpack. Conversely, the example for Squaw Valley, California (a coastal site), indicates that higher avalanche indices are likely due to higher amounts of new snowfall. The scatterplot for Snowbird (an intermountain site) indicates relationships that are intermediate between coastal and continental. All three examples indicate, however, that snowfall alone is not the ultimate factor in causing avalanching, as avalanche–climate relationships are multivariate in nature.

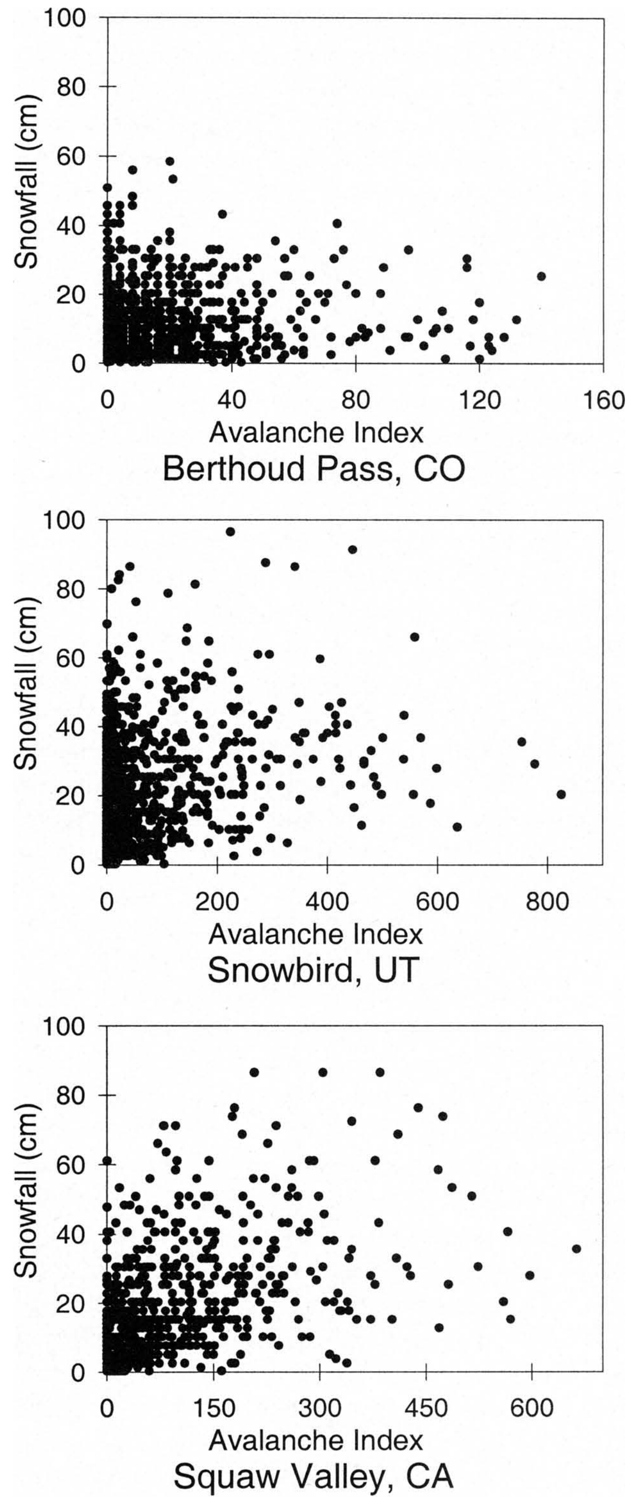

FIG. 6. Scatterplots of daily snowfall vs avalanche hazard indices for selected sites.

c. Temporal analysis of avalanche activity

Since most of the WWAN sites lack continuous records or temporal coverage, analyses of temporal trends of the avalanche index are limited to sites mostly in the central Rocky Mountains. To examine temporal trends and relationships with atmospheric circulation, we constructed a Central Rocky Mountain Avalanche Index, based on seasonal avalanche indices from the longest WWAN sites that have substantial overlap of years of record (18 yr). The WWAN sites chosen are Snowbird; Jackson, Wyoming; Berthoud Pass; and Gothic, Colorado. A principal component analysis was done on the avalanche indices to derive orthogonal variables, which are linear combinations of the original variables. This procedure also yielded principal component scores, representing a value for each orthogonal variable for each winter season. Pearson product–moment correlation analysis was conducted between each of the component scores with December Pacific–North American teleconnection (PNA) indices and December–March PNA indices to assess the relationships between avalanches and atmospheric circulation. The PNA index describes the strength of the ridge–trough–ridge system of 500-mb flow over North America (Wallace and Gutzler 1981), and indices were obtained from the Climate Prediction Center. Positive PNA indices represent ridging and negative PNA indices represent increased troughing over much of the West (Leathers et al. 1991).

An important question also exists whether such extreme coastal and continental winters were more or less frequent prior to the period 1969–95. Since high quality climatic and avalanche data are not available for many locations, such a spatial analyses prior to 1969 is not currently possible. However, a unique long climate record at Alta UDOT exists since 1946 (Armstrong and Williams 1992). We examined temporal changes of snow avalanche climate for Alta

UDOT and also compared it with the shorter record at Snowbird. Other long records extending back into the 1950s exist for Berthoud Pass and Stevens Pass, Washington, but we did not discuss results for these locations since their snow avalanche climate character remained mostly continental and coastal, respectively, through time.

5. Results

a. Avalanche climate classification

Box plots demonstrate which climate variables most effectively discriminate the three avalanche climate zones. Seasonal temperature is a good discriminator for delineating the three zones (Fig. 3). Coastal sites are clearly the warmest, with a seasonal value of around −3.5°C separating its variability from that in the intermountain zone. Warmer temperatures are important for snowpack settlement and sintering, which are important characteristics defining the coastal zone. The intermountain and continental zones possess some overlap of temperature variability, but interquartile ranges are mostly still distinct, separated at a threshold approximately −7°C. Box plots of seasonal snowfall indicate increased variability from inland toward the coast (Fig. 3). Thus snowfall is not a good discriminator between the coastal and intermountain zones, as the variability of the latter is virtually within the range of variability of the coastal zone. Snowfall for the intermountain zone, however, exhibits a different range of variability as compared to the continental zone, according to interquartile ranges, with a threshold at around 560 cm. Box plots of snow water equivalent exhibit similar results as for snowfall, but these results indicate that some of the variability in the coastal zone is a bit better discriminated from that in the intermountain zone when considering values above 100 cm. Total snow depth is a poor discriminator, with plenty of overlap of variability between the three climate zones. Results for early season (December) temperature gradient indicate a threshold of 10 C m^{-1} to discriminate the continental zone, which is well known for its weak, faceted depth hoar (Akitaya 1974). Rainfall is extremely rare in the continental and intermountain zones, but is very common in the coastal mountain ranges (Ferguson et al. 1990).

Using the above box plot results, we devised a seasonal classification scheme as represented by a flow chart (Fig. 4). The simplest coastal conditions were classified based on rainfall and temperature characteristics. As a first step, we selected a conservative criteria of 8 cm of seasonal rainfall because rare, big rainstorms (generally below 5 cm) occur over the interior western United States during late winter and early spring. We did not want to bias our classification due to a single rainstorm toward coastal conditions if mostly intermountain or continental conditions predominated during a given season. The second step of the classification identifies coastal conditions as being associated with average December–March temperatures of greater than −3.5°C. Third, continental conditions were classified adhering to the well-known early season (December) temperature gradient threshold of 10 C m^{-1}, needed to form weak, faceted depth hoar (Armstrong and Armstrong 1987).

If none of the seasonal conditions have rainfall greater than 8 cm, temperatures greater than −3.5°C, or a December temperature gradient of 10 C m^{-1}, then the following variables factor into the classification. The fourth step in our classification identified coastal conditions mostly at intermountain sites with lower temperatures than most cases in the Pacific mountain ranges but with higher amounts of precipitation. These conditions of high snow water equivalent primarily pertain to locations in northern Utah, where coastal-type conditions are not uncommon (Mock and Kay 1992). Fifth, some intermountain conditions were classified based on their higher snowfall as compared to the continental zone; this is shown in the box plots (Fig. 3). We chose not to use additional snow water equivalent in this discrimination procedure because it would simply duplicate the same information as for snowfall. Finally, a temperature threshold value provided further delineation for classifying intermountain and continental conditions. Generally, average temperatures exceeding −7°C are not particularly suitable for widespread formation of depth hoar unless the snowpack is very thin.

b. Performance of the classification and spatial variations of snow avalanche climates

Analysis of the results for individual WWAN stations used to derive the classification generally show excellent correspondence with the three broadscale avalanche climate zones constructed by LaChapelle (1966) and others (Fig. 2; Table 1), demonstrating that the classification scheme used is effective. Nine of the 12 Colorado and New Mexico sites were most frequently classified as continental. Telluride and Red Mountain Pass, Colorado, generally get more frequent intermountain conditions than other continental sites due to their relatively warmer temperatures and because they are more susceptible to snowstorms moving from the southwest (Armstrong and Williams 1981). Vail, Colorado, and Taos, New Mexico, have slightly higher values of intermountain classifications than continental, which is not surprising given that these sites often experience relatively higher snowfall than most other sites in Colorado. Wolf Creek, Colorado, clearly classifies as intermountain, similar to Mock's (1995) results. This site is particularly vulnerable to heavy snowfall from southwesterly flow since there are not many formidable mountain barriers that intercept Pacific moisture (Armstrong and Williams 1992). All four intermountain sites with records greater than 15 yr show intermountain snow climate as the most frequent classification. Results for Bridger Bowl, Montana, and Snowbird illustrate that they occasionally experience continental and coastal conditions (Table 1). Alta UDOT tends to experience more coastal extremes than other sites due to abundant snowfall. The steep rise and favorable orientation of Little Cottonwood Canyon, where both Alta and Snowbird are located, allows for unusually copious snowfall, even during relatively small storms. Further, Alta's higher elevation allows it to consistently receive more snow than nearby Snowbird. Conversely, Jackson tends to be more continental in character than some predominantly intermountain sites due to colder temperatures that prevail. With the exception of Mammoth Mountain, California, the six other coastal sites rarely or never experience intermountain conditions due mostly to relatively greater rainfall and mild temperatures. Mammoth Mountain lies east of the Sierra Crest, so it receives some rainshadow effects and does not always behave as coastal in character as sites west of the Sierra Crest (Mock and Kay 1992).

A second way that we verified the performance of the classification utilized WWAN sites with shorter data records (Table 1). Arapahoe Basin and Loveland Pass, Colorado, classified as predominantly continental, which is expected since they are located along the Continental Divide at a high elevation, cold, and relatively dry location. Grand Targhee, Wyoming, and Alta Ski Lifts, Utah, are two good examples that clearly classify as intermountain. Grand Targhee is classic intermountain, experiencing warmer temperatures than Colorado yet not having as much snowfall as Alta UDOT and the coastal sites. Alta Ski Lifts is approximately 1000 ft higher in elevation than Alta UDOT; this difference shows the importance of elevation, which lowers temperatures and thus changes avalanche climate characteristics. Mount Baker, Washington, and Carson Pass, California, provide additional examples of coastal sites that only classify as coastal. Alyeska, Alaska, which was not used in devising the classification, shows mostly coastal characteristics, with some occasional continental characteristics, consistent with results by Mock (1996a). Overall, when looking at the spatial distribution of the most frequent classification for all sites with at least 5 yr of record (Fig. 7), the performance of the classification appears robust. Some sites further inland show mixed combinations of classifications, but these results are expected due to spatially heterogeneous snow patterns resulting from topographic effects.

We calculated the percentage of winters for each site that is classified as a particular avalanche climate, and mapped the results to summarize the major spatial patterns of avalanche climate characteristics over the West (Fig. 7). Sites in the Pacific mountain ranges illustrate high percentages of coastal classifications, with rare classifications of intermountain and continental for Mount Bachelor, Oregon; Mission Ridge, Washington; and Mammoth Mountain. Mount Bachelor and Mission Ridge are east of the Cascade Crest and, therefore, receive less precipitation. Mission Ridge's temperatures are also cold since it is frequently under a temperature inversion that dominates the Columbia Basin. Almost all of the sites in Colorado have the highest percentages for continental classifications, with some moderate percentages of intermountain classifications in the western and southwestern portions of the state. Sunlight, Colorado, classifies as intermountain more frequently than continental, perhaps because of its warmer, low-elevation location. Purgatory, located in southwestern Colorado, also classifies as intermountain more frequently. It is also a lower-elevation site, and it is more susceptible to snowstorms traversing from the southwest.

All of the Utah and Wyoming sites, and Bridger Bowl show highest percentages as intermountain. Brianhead, located in southwestern Utah, perhaps deviates from the more predominate continental conditions farther east due to its relatively higher snowfall (Greer et al. 1981). Percentage maps also show that northern Utah sites (Snowbasin, Alta, and Snowbird) receive more frequent coastal years as compared to continental years. Continental extremes tend to be more frequent northward in the intermountain zone, with Big Sky, Montana, and Sun Valley, Idaho, exhibiting fairly frequent continental classifications. These isolated continental conditions are due to a higher elevation at Big Sky that results in colder temperatures, and relatively low snowfall at Sun Valley, both of which enhance snow temperature gradients (Mock 1995).

Elevation plays an important control on the spatial variations of percentages of avalanche climate, but it alone is not the determining factor (Fig. 8). Sites above 2500 m generally are colder and have higher percentages of continental conditions, but some of these high-elevation sites also are intermountain and coastal. Sites that have high percentages of intermountain vary from 2000 to 3500 m. However, sites that have high percentages of coastal conditions exhibit marked vertical variability from around 500 to 3000 m, indicating the additional importance of synoptic-scale atmospheric circulation features and their interactions with topography, creating some patterns of spatial climate heterogeneity (Cayan 1996; Mock 1996b; Birkeland and Mock 1996).

Table 2 illustrates the number of cases involved with each type of criteria used in the avalanche climate classification, while Table 3 provides some representative examples. The criterion "rain > 8 cm" applies almost exclusively to the coastal zone, as demonstrated by data from Stevens Pass. Most of the occasional classifications of coastal conditions in the intermountain zone are due to "temperatures > −3.5°C," with "SWE > 100 cm" being important only for heavy snowfall-prone sites such as Alta UDOT. The criterion "December TG > 10 C m^{-1} plays the key role in defining continental conditions in both the continental and intermountain zones, with Berthoud Pass being a prime example. Although "temperature < −7°C" classifies some continental conditions, most of these are for sites within the continental zone. The criterion "snowfall > 560 cm" classifies the majority of the intermountain conditions that occur in the continental zone, and this classification criteria is normally common for Alta UDOT, Snowbird, Jackson Hole, and Bridger Bowl. The criterion "temperature > −7°C" tends to classify intermountain conditions more frequently when they occasionally occur at coastal sites such as Mission Ridge, Mount Bachelor, Eaglecrest, and Mammoth Mountain; and at low-latitude continental sites such as Taos, Sunlight, and Purgatory.

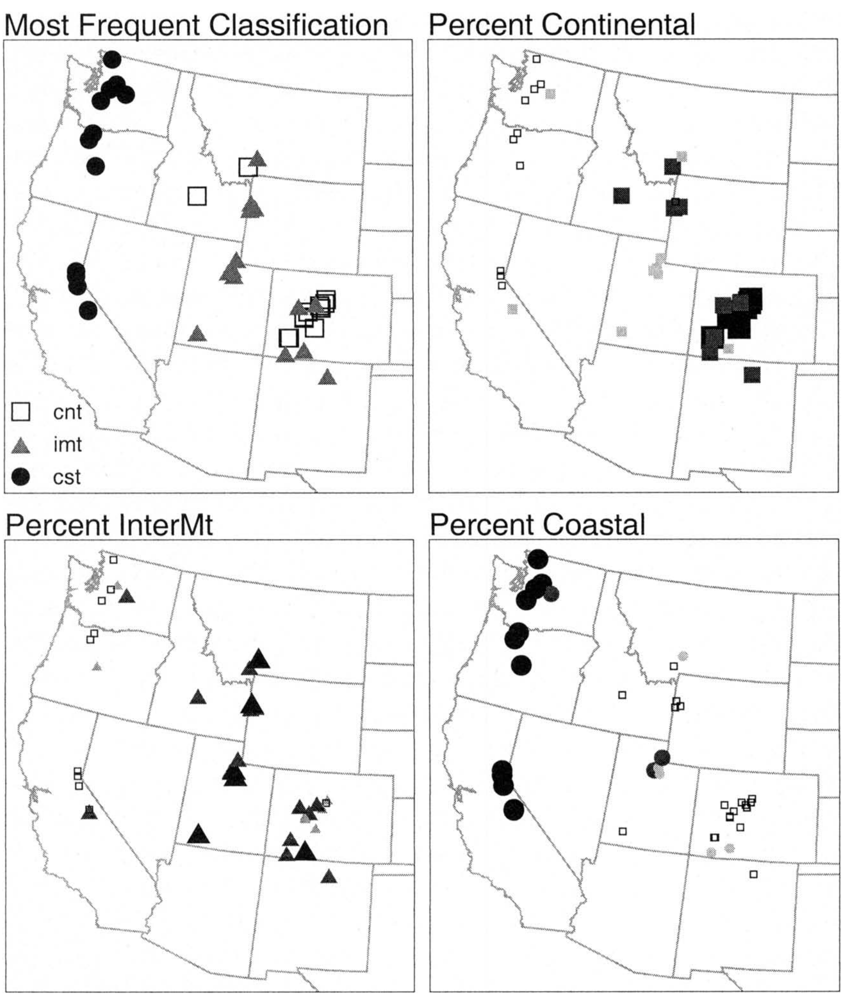

FIG. 7. (top left) Maps illustrating seasonal avalanche climate characteristics by the most frequent classification, (top right) the percent of continental classifications, (bottom left) the percent of intermountain classifications, and (bottom right) the percent of coastal classifications. For the three percentage maps, unfilled small squares represent 0%, small filled symbols represent 1%–33%, medium filled symbols represent 33%–66%, and large filled symbols represent 66%–100%: Cnt = continental, Imt = intermountain, and Cst = coastal.

c. Coastal extremes

Two widespread coastal winters were detected: the winters of 1985/86 and 1991/92. For both winters, the spatial distribution of coastal conditions spread inland to western Montana and northern Utah (Fig. 9). Several sites that are normally continental in character, such as Sun Valley and sites in southwestern Colorado, classify as intermountain. The 500-mb height pattern is similar for both winters as well (Fig. 10). The distribution of seasonal (Dec–Mar) 500-mb height anomalies shows a negative center in the North Pacific and a positive center over the western United States, indicative of a positive mode of the Pacific–North American teleconnection pattern (Wallace and Gutzler 1981). The negative anomalies correspond to an intensification of a trough in the North Pacific, enabling warmer and wetter southwesterly flow to enter the western United States (e.g., Klein and Bloom 1986; Mock and Kay 1992; McCabe and Legates 1995; Cayan 1996). The positive heights over the West are generally not too strong to cause widespread dryness, but sufficient enough to illustrate the predominance of a ridge at times, which would cause increased warmth (Arkin and Janowiak 1987).

Shifting from the regional to the local scale shows how avalanche climate extremes affect avalanche conditions at individual sites. We emphasize Snowbird as an example for its long-term high quality data record, and because it is located in the intermountain avalanche climate zone which will be affected by more subtle climate fluctuations than either coastal or continental sites. Snowbird classifies as coastal during both the 1985/86 and 1991/92 winters. Coastal winters are commonly typified by a deep snowpack, abundant snowfall, warmer temperatures, and avalanches that are associated with large storms or continual snowfall. An analysis of the daily data from Snowbird for the 1985/86 winter shows an example of a coastal year at a predominantly intermountain site (Fig. 11). Snowfall starts early, with total snow depth exceeding 1 m by 1 December. Such rapid increases in snow depth in the early season are important because this limits temperature gradients within the snowpack, preventing the formation of weak, faceted crystals or depth hoar. The existence of a relatively strong snowpack is demonstrated in the storm from early Decem-

TABLE 2. Number of cases classified by climate criteria in the seasonal avalanche climate classification. Refer to Fig. 4 for more detailed information.

Criteria for classification	Climate classification	No. of cases
Rain > 8 cm	Coastal	164
Temperature > −3.5°C	Coastal	94
Dec. TG > 10 C m^{-1}	Continental	232
SWE > 100 cm	Coastal	19
Snowfall > 560 cm	Intermountain	162
Temperature < −7°C	Continental	32
Temperature > −7°C	Intermountain	78

TABLE 3. Number of cases classified by climate criteria in the seasonal avalanche climate classification for selected WWAN sites.

Criteria for classification	Stevens Pass, WA	Alta UDOT, UT	Berthoud Pass, CO	Mammoth Mountain, CA	Taos, NM
Rain > 8 cm	30	1	0	1	0
Temperature > −3.5°C	5	6	0	10	0
Dec. TG > 10 C m^{-1}	0	5	35	0	5
SWE > 100 cm	1	10	0	0	0
Snowfall > 560 cm	2	28	2	3	3
Temperature < −7°C	0	0	2	0	2
Temperature > −7°C	0	2	0	3	7

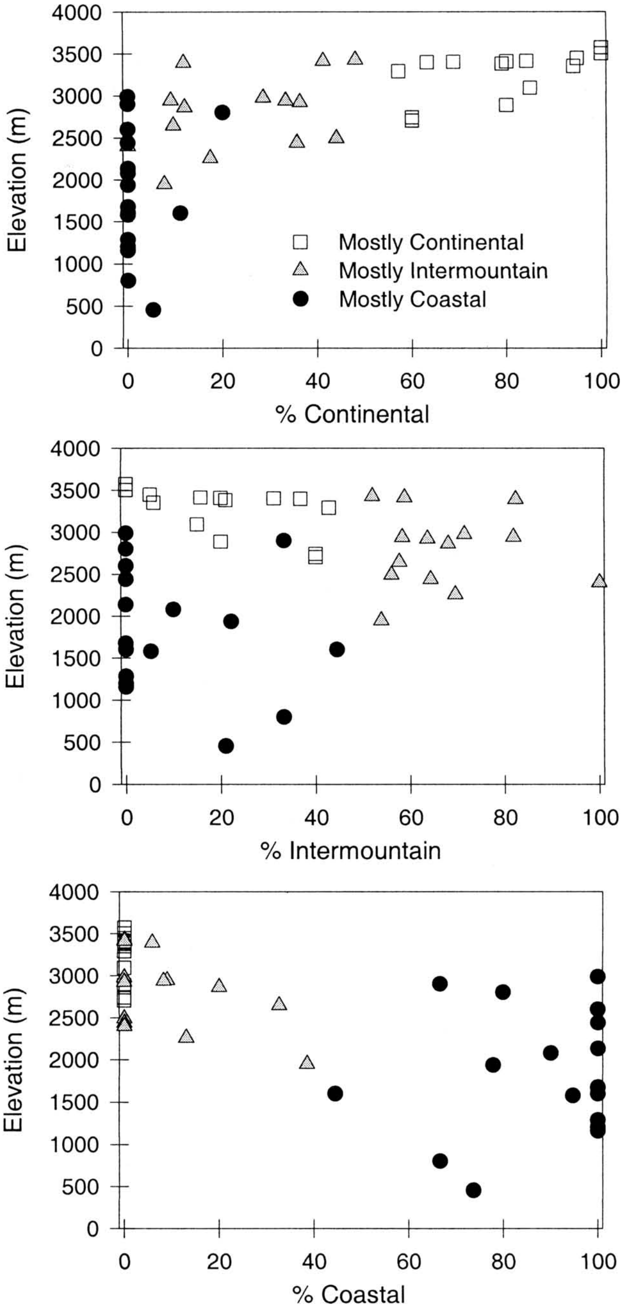

FIG. 8. Scatterplots illustrating the relationship between elevation and percentages of continental, intermountain, and coastal classifications. Sites are represented by their most frequent classification (mostly continental, mostly intermountain, and mostly coastal) as shown in Fig. 7.

ber. Despite snowfall greater than 1 m over two days, avalanche activity is limited (avalanche index < 50). Later in December, there is no new snow, and it is possible that some weak layers formed near the snow surface. If the weather had been clear, conditions would have been ideal for forming near-surface faceted crystals, a potentially dangerous midpack weak layer (Birkeland 1998). Thus, several days of snowfall in early January are enough to trigger a fairly decent avalanche cycle (avalanche index > 200). The rest of the season is punctuated by small- to medium-sized storms, moderate to warm temperatures, and only moderate avalanche cycles. The largest avalanche cycle occurred in mid-February when continuous, dense snowfall triggered a number of large avalanches throughout the western United States, including most of northern Utah. Avalanche data for Alta UDOT exhibit similar results as for Snowbird concerning the large February avalanche cycles (Fig. 12).

The winter of 1991/92 also demonstrated coastal avalanche climate conditions throughout much of the western United States. During this winter, Snowbird classified as coastal, and a daily analysis of the Snowbird data more clearly demonstrates the nature of the winter (Fig. 11). Like the 1985/86 winter, air temperatures were relatively warm and the snowpack was deep, exceeding 1 m on 1 December. The snowpack was probably fairly strong, since numerous small- to medium-sized storms through mid-January caused almost no significant avalanche activity. A stretch of dry weather through early-February may have created surface snow weaknesses that led to the obvious peak in avalanche activity in mid- to late February (peak avalanche index > 400) caused by a series of storms. Further snowfalls through the year did not cause widespread avalanching, indicating a relatively strong snowpack.

d. Continental extremes

Two widespread continental winters were detected: the winters of 1976/77 and 1987/88. Mock and Kay (1992) and Butler (1986) suggested extremely continental conditions in northern Utah and Glacier National Park, respectively, during 1978/79; however, our classification for that year indicates the spatial distribution of continental conditions was not as widespread as 1976/77 and 1987/88. For both 1976/77 and 1987/88, the spatial distribution of coastal conditions remains largely unchanged compared to normal. However, all the intermountain sites classify as continental (Fig. 9). The synoptic patterns, however, differ between one another for these two winters, indicating two different types of continental extremes (Fig. 13). December–March 500-mb height anomalies for 1976/77 indicate increased troughing over the North Pacific, increased ridging off the west coast, and increased troughing over the southeastern United States. Similar, but much stronger anomaly signs are evident

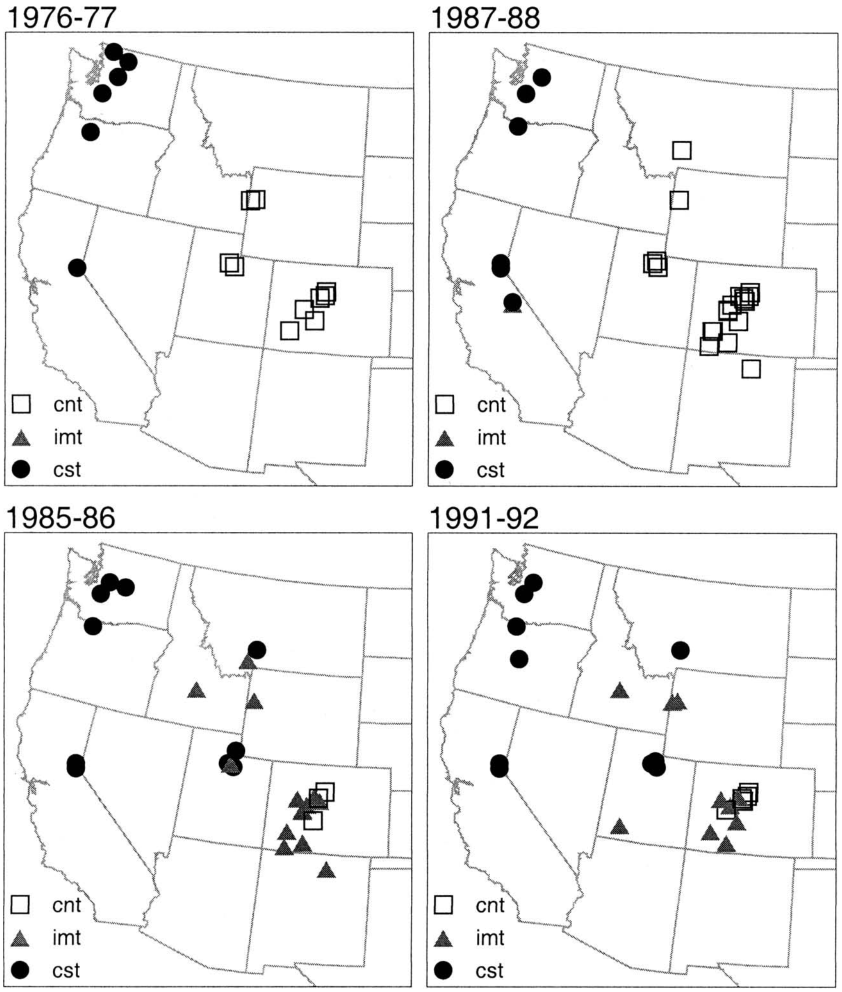

FIG. 9. Seasonal avalanche climate characteristics for the continental avalanche extreme winters of 1976/77 and 1987/88, and the coastal extreme winters of 1985/86 and 1991/92.

in the pattern of December 500-mb anomalies. This synoptic pattern indicates a strong positive mode of the PNA pattern, with some anomalous colder northwesterly flow over the far interior West and widespread lower snowfall (Wagner 1977). The widespread below normal snowfall provided conditions conducive to very steep snow temperature gradients and formation of depth hoar in the shallow early season snowpack. In addition, virtually the entire West experienced persistent severe drought—such widespread anomalous conditions are not evident at any other time in the twentieth-century climate record (Meko and Stockton 1984). These abnormal conditions are attributed to a change from a strong west–east SST cold–warm gradient in the North Pacific, which in turn led to the persistent configuration of the upper-level trough–ridge–trough pattern (Namias 1978). Thus, although several intermountain sites classified as continental for multiple winters, no other winter resembled that of 1976/77.

The December–March 500-mb anomalies for 1987/88 show weak anomalies throughout most of the North American sector (Fig. 13). However, the December 500-mb anomaly map provides the primary information defining this season as widespread continental. Positive height anomalies are evident over most of northern North America, indicating a weakened circumpolar vortex. Four negative anomaly centers are apparent along the West Coast, the North Atlantic, western Eurasia, and the northwestern Pacific Ocean. These negative centers show a shift of the 500-mb longwave pattern, with a trough over the Far West causing colder temperatures and thus steeper snowpack temperature gradients. As a result of the weakened circumpolar vortex, this synoptic pattern did not bring widespread early season heavy snowfall.

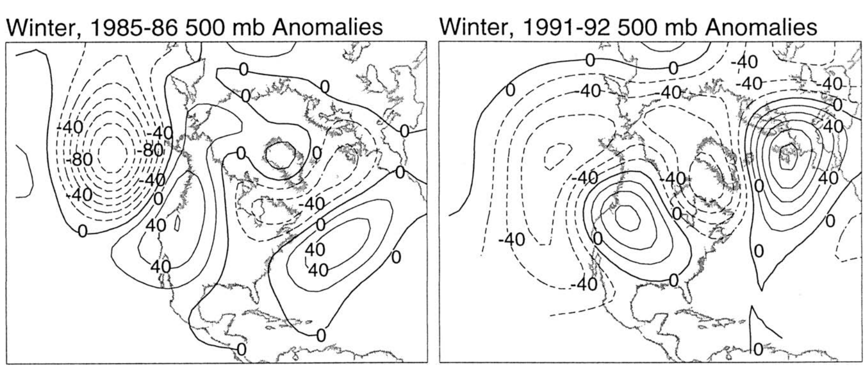

FIG. 10. The 500-mb anomalies for the coastal winters of 1985/86 and 1991/92. Units are in geopotential meters.

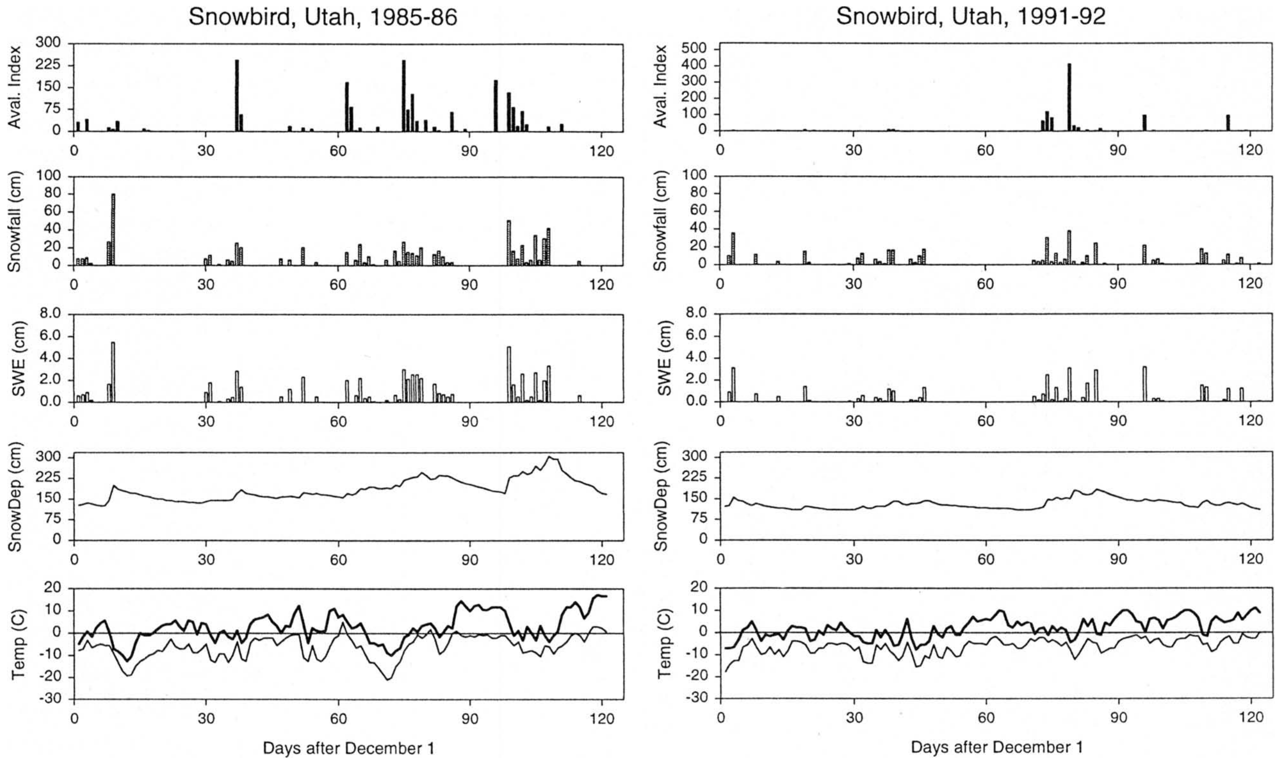

FIG. 11. Daily plots of weather and avalanche variables for Snowbird, UT, for the coastal extreme winters of 1985/86 and 1991/92.

As with the coastal years, a closer look at the data from an individual site during a widespread continental year demonstrates how regional patterns affect individual locations. Locations experiencing continental conditions should have shallow snow depths, weak snow layers, and widespread avalanching even with small storm events. Snowbird and Alta UDOT data for the 1976/77 winter clearly demonstrate these patterns—the former again emphasized here for brevity of discussion (Figs. 12 and 14). The season at Snowbird starts with an extremely thin snowpack; for the entire month of December, the total snow depth remained below 0.50 m (Fig. 14). Such thin snow cover contributes to maximizing temperature gradients within the snowpack, which, in turn, results in the metamorphism of weak, faceted crystals and depth hoar. These crystals then form an unstable base for subsequent snowfall that can last through the season. Relatively modest snowfall in early January led to some small avalanche cycles, but one of the more telling days of the season comes in early February. At that time a modest snowfall of about 0.40 m resulted in an extremely active day of avalanching (avalanche index > 400). The characteristics of this winter are further emphasized in the dramatic avalanche cycle of late February. A large storm of nearly 1 m followed by several smaller storms kicked off a large avalanche cycle, with avalanche indices approaching 500 for two days followed by two days with indices from 250 to 300. This winter demonstrates continental conditions, which comprise long periods of dry weather and large diurnal temperature ranges, punctuated by storms that cause widespread avalanching.

The 1987/88 winter also classifies as continental at Snowbird, but the daily data do not demonstrate continental nature of the season as clearly as 1976/77 (Fig. 14). Still, through the first two-thirds of December snowfall is meager (total depths < 0.5 m) and temperatures throughout most of the winter are relatively colder than normal (some daily averaged temperatures are less than −10°C). These conditions are clearly sufficient to cause the widespread formation of faceted crystals typically found in continental climates. Some small snowstorms lead to a modest avalanche cycle in late December (avalanche index around 200). In January a series of small storms (all less than 0.3 m of snow in 24 h) cumulatively result in one large avalanche day (avalanche index around 300). Through most of the rest of the winter, conditions are relatively dry and there are just a few days with significant avalanche activity. Warm weather and longer days of solar radiation in March also resulted in stronger

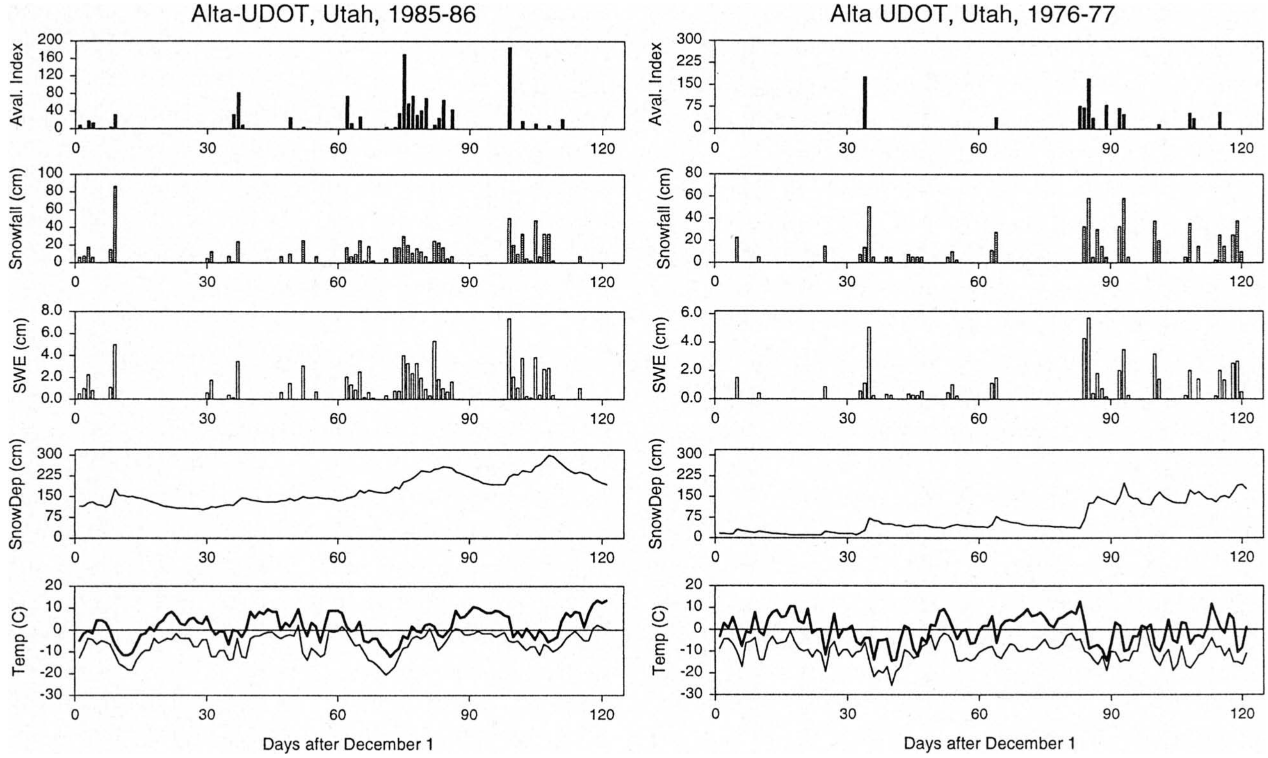

FIG. 12. Daily plots of weather and avalanche variables for Alta UDOT during the coastal extreme winter of 1985/86 and the continental extreme winter of 1976/77.

bonding of the snowpack, also enabling only minor avalanche activity.

e. Temporal trends of avalanche activity in the central Rocky Mountains

Temporal trends of seasonal avalanche indices for selected sites in the central Rocky Mountains indicate an interesting peak during the mid- to late 1970s, and generally decreasing thereafter until around 1992 (Fig. 15). We do not believe this is due to changes in avalanche control, particularly since Gothic records only "natural avalanches." The principal component analysis, based on the four central Rocky Mountain sites, yields three main components that explain 97% of the total variance. The first component explains 73% of the variance and its component scores relate inversely with the overall trend of decreasing seasonal avalanche activity (Fig. 15). The component scores correlate significantly with corresponding December PNA indices ($r = 0.411$, $p = 0.09$). The amplified positive December PNA pattern since the early 1980s suggests an increased prevalence of an upper-level ridge over the West, which explains warming over much of the region and causing more stable snowpack conditions from increased settlement and sintering, resulting in less avalanches. The second component explains 13% of the total variance but its component scores indicate no distinctive trends nor does it exhibit statistically significant relationships with circulation indices. It most likely represents some aspect of avalanche control. The third component explains 11% of the variance. The scores for this component correlate significantly with seasonal (Dec–Mar) PNA indices ($r = -0.616$, $p = 0.006$). The low (reverse) PNA indices suggest an upper-level pattern of increased troughing over much of the central Rocky Mountains, which is conducive to increased snowfall and thus also avalanche activity. Although the correlation concerning the first component and the variance explained for the third component are somewhat low, these relationships are rather robust considering that avalanche control has substantially affected the dataset. Longer and more plentiful WWAN records would provide further insight on these avalanche–climate relationships.

El Niño–Southern Oscillation (ENSO) events and sea surface temperature linkages have been suggested as perhaps an important cause of avalanche variations in the western United States (Fox 1973). Such an ENSO–avalanche relationship, unfortunately, is too simplistic due to important snowpack characteristics that additionally respond to climate and cause avalanching. For example, the widespread continental winter of 1976/77 was largely due to meager snowfall, which was induced by anomalous ridging over the West related to a warm ENSO event. The winter of 1991/92, also related to a warm ENSO event, was an extreme coastal year over much of the West due to the anomalously warm temperatures, which stabilized the snowpack. Some studies indicate that periods of strong and moist southwesterly flow from the subtropics tend to develop during winters preceding warm ENSO events (e.g., Rasmusson and Carpenter 1982; Wang 1995). Interestingly, the winter of 1985/86 preceded the moderate warm ENSO event of 1986/87 (Kousky and Leetmaa 1989), and similarly the winter of 1991/92 preceded the warm ENSO event of 1992/93 (Bell and Basist 1994). These relationships suggest that some shifts to more coastal conditions may precede warm ENSO events. However, widespread coastal shifts were not detected for winters preceding the warm ENSO events of 1976/77, 1982/83, and 1993/94. The very strong warm ENSO event of 1982/1983, as illustrated by June–November values of the Southern Oscillation index (SOI; Fig. 15), only caused a very small shift in coastal conditions into northern Utah despite a very highly positive PNA winter index. The winters of 1980/81 and 1976/77 also have high PNA indices but no coastal shifts. Therefore, the magnitude of seasonal climate anomalies, the intraseasonal variability of synoptic-scale circulation and surface climatic responses, and potential snowpack processes need to also be addressed in order to predict potential avalanche responses.

f. Temporal variations of avalanche climate at Alta UDOT and Snowbird

Overlapping of the Alta UDOT and Snowbird records indicate that three continental winters occurred within the time frame 1973–98, and both sites have all three winters in common within a 25-yr period (Table 4). This comparison suggests that continental winters at Alta may be representative of northern Utah. Examination of the Alta UDOT record for 1946–73 reveals two continental winters within a 28-yr period—a bit lower frequency than the latter period but not dramatically different (Table 5). Clearly continental winters at Alta are relatively rare, generally occurring once every 10 yr. The overlapping records of coastal events for Alta UDOT and Snowbird for 1973–98 indicate that coastal winters are more frequent at Alta UDOT (11), as discussed previously. A coastal winter at Snowbird always corresponds with a coastal winter at Alta UDOT, but not necessarily vice versa (Table 4).

Classification of data at Alta UDOT for 1946–73, however, indicates only six coastal winters, with no coastal winters occurring in consecutive years (Table 5). These results suggest that Alta UDOT perhaps had a much more stable character of snow avalanche climate during 1946–73, with few coastal and continental winters. These changes may perhaps be related to decadal changes in the snow climate of the region (e.g., Karl et al. 1996), associated with changes in the frequency of zonal 500-mb synoptic patterns (Changnon et al. 1993) and perhaps also the Pa-

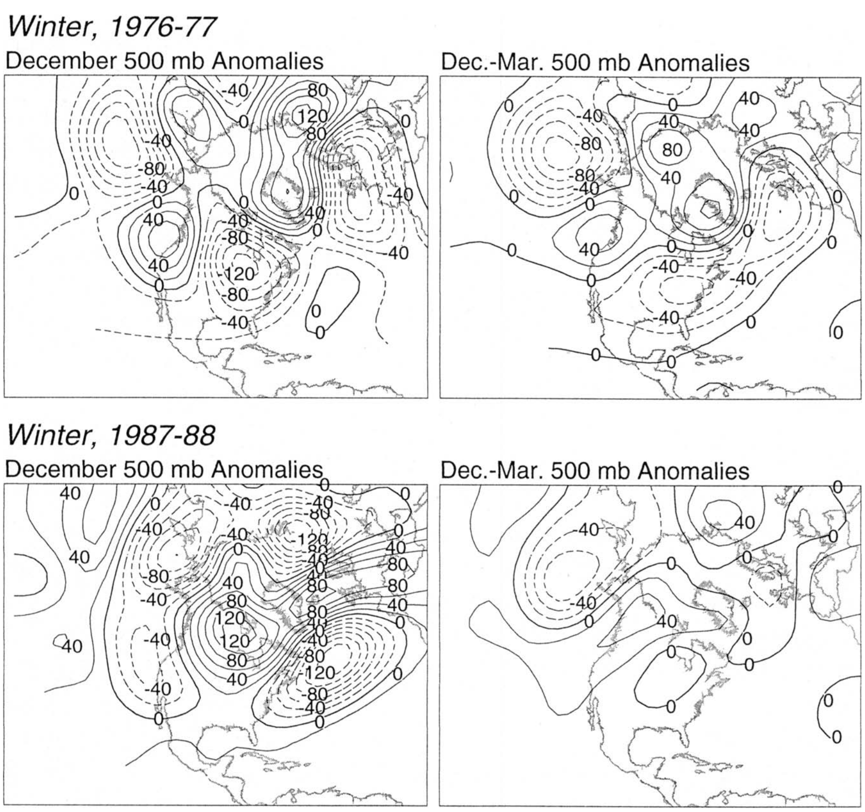

FIG. 13. The 500-mb anomalies for the continental winters of 1976/77 and 1987/88. Units are in geopotential meters.

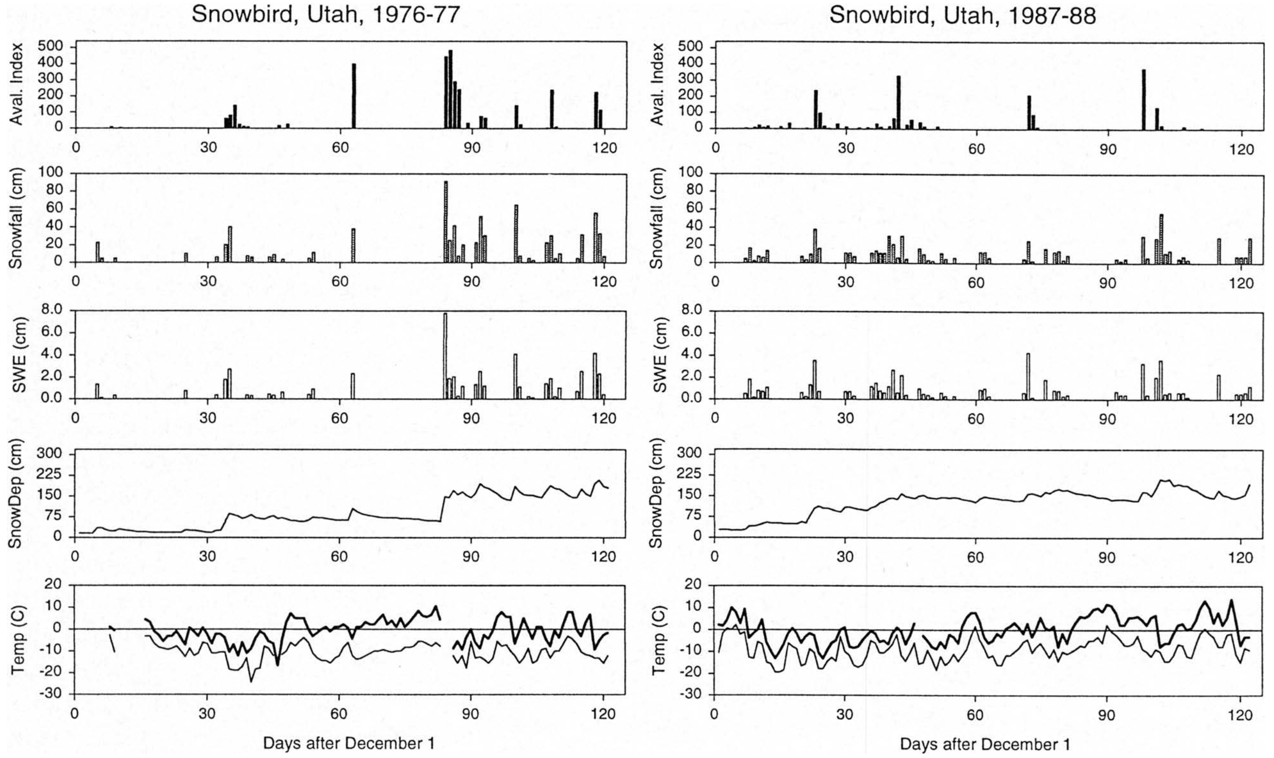

FIG. 14. Daily plots of weather and avalanche variables for Snowbird for the continental extreme winters of 1976/77 and 1987/88.

cific decadal oscillation (PDO). The PDO entered a positive phase after around 1977 (Mantua et al. 1997; McCabe and Dettinger 1999). This positive phase would generally accentuate the effects of warm ENSO events and be associated with a positive PNA pattern and ridging over much of the West—thus perhaps leading to a higher frequency of continental and coastal winters for Alta. As discussed previously, a strong positive mode of the PNA in the early winter can lead to either a weak snowpack characterized by depth hoar, or a persistently positive mode of the PNA throughout the winter may create an extremely stable snowpack through increased melt–freeze metamorphism.

6. Conclusions

Our seasonal binary snow avalanche climate classification, based on all available Westwide Avalanche Network data and well-established thresholds of snow avalanche climate characteristics, provide a useful means to examine the spatial and temporal variability of snow avalanche climates over the western United States. WWAN climatic data, independent of the data used to derive the classification, verified that the classification works extremely well, correctly classifying almost every WWAN site. Climatically, our results indicate that the spatial extent of the three major avalanche climate zones over the western United States broadly correspond to patterns suggested by LaChapelle (1966), Mock (1995), and Armstrong and Armstrong (1987). Some stations, such as Sunlight and Purgatory in southwestern Colorado, exhibit more intermountain characteristics as compared to continental. Similarly, Mount Bachelor and Mission Ridge seem more intermountain rather than coastal. These contradictions to the broadscale west–east gradient from coastal to continental indicate the importance of understanding the mediation of topographic features on synoptic-scale atmospheric circulation features (Birkeland and Mock 1996).

Generally, the spatial variability of snow avalanche climates over the western United States is relatively stable through time; most coastal and continental sites rarely exhibit intermountain characteristics. Sites in northern Utah exhibit the greatest temporal variability of avalanche climatic regimes, occasionally experiencing coastal and continental winters. Sites in southwestern Colorado exhibit the most variability within the continental zone, occasionally experiencing intermountain characteristics. However, four winters were found that exhibited strong spatial shifts in

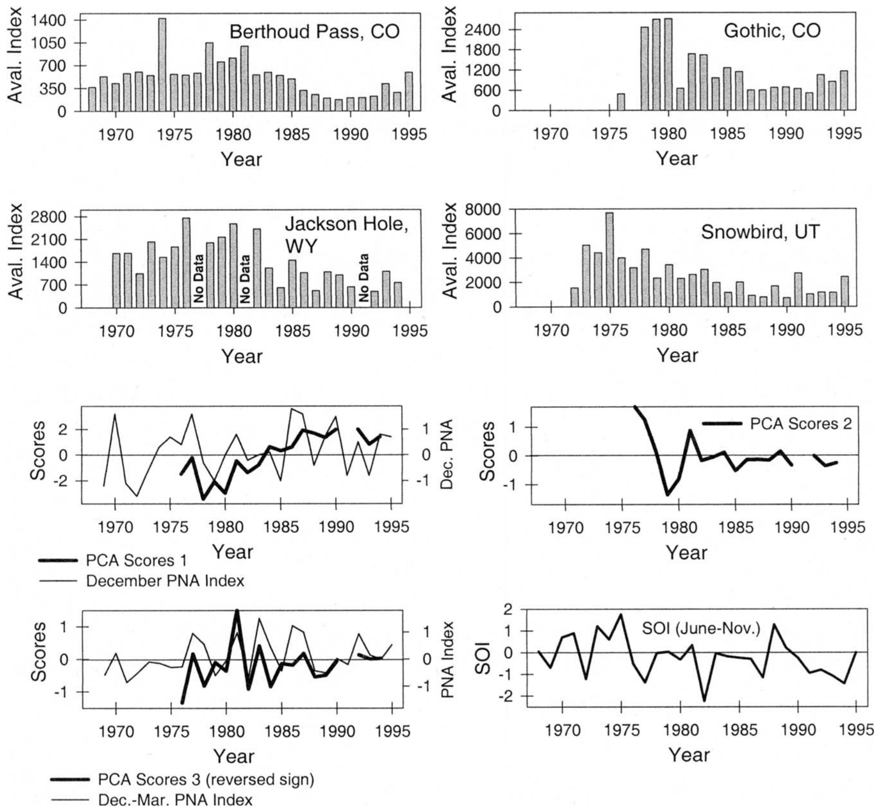

FIG. 15. Time series of seasonal avalanche hazard indices for four selected locations in the central Rocky Mountains (top four graphs), scores derived from a principal component analysis of seasonal avalanche hazard indices of the four locations, and Jun–Nov-averaged values of the SOI from 1969 to 1995. Time series of Dec and Dec–Mar values of PNA indices are also shown for comparisons with the first and third component scores.

avalanche climatic conditions over much of the interior West: the coastal winters of 1985/86 and 1991/92, and the continental winters of 1976/77 and 1987/88. Further detailed analyses of daily weather and avalanche activity for Snowbird and Alta UDOT for these extreme winters indicate that a continental winter is conducive to a different avalanche regime than a coastal winter. However, short-term daily weather fluctuations are still very important and can dominate over the general climate effect. Both the type of predominate avalanche climate and daily weather information are crucial to assess in order to forecast destructive avalanche cycles. The winters of 1976/77 and 1985/86 are well-known avalanche winter extremes to the snow avalanche community (Mock and Kay 1992). These are rare events, and accurately forecasting them would prove invaluable for long-term avalanche hazard planning and assessment, such as for the 2002 Winter Olympics. To date, ecological and terrain factors are commonly incorporated in long-term avalanche hazard planning, but with exceptions, the potential role of extreme climatic events has received little attention (e.g., Mears 1984; Schneebeli et al. 1997).

To properly incorporate climatic aspects in avalanche hazard assessment, we need improvements in two areas. First, our understanding of the spatial variability of snow avalanche climate can still be much improved by incorporating SNOTEL, snow course, perhaps additional COOP, and remotely sensed data. Such an understanding would prove invaluable in analyzing avalanche climatic conditions in increasingly popular backcountry skiing areas such as northern Utah and southwest Montana. Enough temporal overlap exists between these data sources with WWAN data to translate these climatic data into "avalanche terms," such as the binary snow avalanche classification conducted in our study. More financial support is also needed for the WWAN to continue data collection and analysis. For some locations there are snow course and long climate records that extend back as far as the early twentieth century (e.g., Cayan 1996), and they can provide a longer record of avalanche climate variability (Laternser and Pfister 1997).

Second, we need a more comprehensive understanding of the relationships between avalanche responses in mountainous areas and the climatic patterns that occur at larger spatial scales. Avalanche forecasters routinely and successfully use daily model forecasts in avalanche hazard prediction (Williams 1992). Our current ability to provide long-range avalanche forecasting is still in the infancy stage, but some promising and potential relationships exist between avalanche activity and the Pacific–North American teleconnection pattern, the Pacific decadal oscillation, and ENSO. Some promising aspects of winter extratropical forecasting in the United States (Barnston et al. 1994; 1999) also indicate the potential to apply such information to long-range avalanche forecasting. Collaborations between operational forecasters, uni-

TABLE 4. Snow avalanche classifications for Alta UDOT and Snowbird for 1973–98: cnt = continental, imt = intermountain, cst = coastal. Bold entries emphasize coastal and continental conditions.

Year	Alta UDOT	Snowbird
1973	imt	imt
1974	imt	imt
1975	**cst**	**cst**
1976	imt	imt
1977	**cnt**	**cnt**
1978	imt	imt
1979	**cnt**	**cnt**
1980	**cst**	imt
1981	**cst**	**cst**
1982	**cst**	imt
1983	**cst**	imt
1984	**cst**	imt
1985	imt	imt
1986	**cst**	**cst**
1987	imt	imt
1988	**cnt**	**cnt**
1989	imt	imt
1990	imt	imt
1991	imt	imt
1992	**cst**	**cst**
1993	imt	imt
1994	imt	imt
1995	**cst**	imt
1996	**cst**	**cst**
1997	**cst**	imt
1998	imt	imt

TABLE 5. Snow avalanche classifications for Alta UDOT for 1946–72: cnt = continental, imt = intermountain, cst = coastal, and "—" indicates that the data are incomplete for that winter. Bold entries emphasize coastal and continental conditions.

Year	Alta UDOT
1946	imt
1947	**cst**
1948	imt
1949	imt
1950	imt
1951	imt
1952	**cst**
1953	imt
1954	imt
1955	**cnt**
1956	**cst**
1957	imt
1958	imt
1959	imt
1960	imt
1961	imt
1962	**cst**
1963	imt
1964	imt
1965	**cst**
1966	imt
1967	imt
1968	**cnt**
1969	imt
1970	—
1971	imt
1972	imt

versity researchers, and field workers will provide new opportunities in meeting the big challenges of fostering our understanding of the avalanche climatology of the western United States.

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