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The Major Snow Avalanche Cycle of February 1986 in the Western United States

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Abstract. Snow avalanches are a significant hazard in mountainous environments around the world. This paper investigates the major February 1986 avalanche cycle that occurred in the western United States, and broadly analyzes the avalanche, snowpack, and weather conditions at twenty sites. These analyses suggest that the avalanche cycle resulted from the interaction of a relatively 'normal' snowpack with an exceptional storm event, which was particularly noteworthy for the amount of precipitation it produced. Composited 500-hPa anomaly maps show the event resulted from an uncommonly persistent blocking pattern that resulted in a strong zonal flow and copious moisture being funneled over the western United States. Understanding severe and widespread avalanche cycles may improve our long-term forecasting of these events, and help mitigate the resulting avalanche activity.

Key words: avalanches, snow avalanches, avalanche forecasting, avalanche climatology.

1. Introduction

Snow avalanches are a significant, life-threatening natural hazard in western North America, killing more people in the United States on an average annual basis than earthquakes or other landslide hazards (Voight *et al.*, 1990). Further, each winter avalanches destroy property, and disrupt transportation networks and recreational facilities (Armstrong and Williams, 1992; McClung and Schaerer, 1993). Though isolated extreme avalanche events occur in mountain ranges every few years (Mears, 1992), widespread avalanche cycles in which many avalanche paths produce large avalanches over a broad spatial area are more rare. The focus of this paper is one such widespread avalanche cycle that occurred in the western United States in February 1986, resulting in closed interstate highways, numerous damaged structures, and several deaths.

Avalanches result from the interaction of terrain, weather, and the existing snowpack (Fredston and Fesler, 1994). Slopes steeper than about 25 degrees without dense tree cover (less than about 1000 trees/hectare) comprise the necessary terrain for avalanche initiation (McClung and Schaerer, 1993). Weather events, typically large snowstorms, rain, or strong winds that blow snow onto leeward slopes, provide the added weight to trigger avalanches. The role of the existing snowpack in avalanche release is the most complex of the three factors. Weaknesses in the basal layers of the snowpack may exist which may cause the entire snowpack to fail with only a small amount of added weight. Further, surficial snowpack layers such as surface hoar or near-surface faceted crystals can create conditions whereby new snowfall does not effectively bond to the existing snowpack (Jamieson and Johnston, 1998; Davis *et al.*, 1998; Birkeland, 1998). The interaction of the new snow loading, the existing snowpack structure, and the amount of snow in the track and runout zones available for entrainment determines the potential size of the avalanches. Thus, large avalanches occur due to some unique combination of weather and snowpack conditions (Mears, 1992).

The western United States is delineated into three primary avalanche climate zones: the coastal, intermountain, and continental zones (Figure 1). The existence of these three zones was first recognized by Roch (1949), later described in detail by LaChapelle (1966), and has since been confirmed in a number of studies (Armstrong and Armstrong, 1987; Mock and Kay, 1992; Mock, 1995, 1996a). In essence, the coastal zone of the Pacific mountain ranges is characterized by abundant snowfall and relatively high temperatures, which result in a relatively strong snowpack structure. Consequently, most avalanches in coastal areas result from large snowfalls. Lower temperatures and relatively low snowfall, resulting in a weaker snowpack, characterize the continental zone of the Colorado Rockies. Avalanches in this zone often result from relatively small storms which overload buried weaknesses in the snowpack. The intermountain zone of Montana, Wyoming, Idaho and Utah is intermediate between the two, and may have either continental or coastal characteristics depending on the particular winter.

Most previous work looking at broad patterns of avalanche activity has investigated the weather conditions responsible for the cycles. Such research has focused on the general weather conditions associated with avalanching in Norway (Fitzharris and Bakkehøi, 1986), Iceland (Björnsson, 1980), the European Alps (Calondar, 1986), Switzerland (Hächler, 1987), the western Himalaya (Rangachary and Bandyopadhyay, 1987), Turkey (Gürer *et al.*, 1995), and New Zealand (Fitzharris, 1976; McNulty and Fitzharris, 1980), but none of these studies examined a broad range of avalanche sites to examine the spatial extent and severity of the avalanche cycles. Likewise, research in Canada has quantitatively investigated the severity of major avalanche winters and their climatology since the early twentieth century (Fitzharris, 1981, 1987), but this work has focused solely on the extensive Rogers Pass data.

While a few isolated large avalanches can cause considerable localized damage, a widespread cycle of large avalanches has the potential to create problems over an entire region. One such avalanche cycle occurred in the European Alps during the 1998–99 winter. A thin snowpack in the early season contributed to the development of weak depth hoar and faceted crystals in Austria. February brought snowfalls exceeding 3 m, and widespread destruction followed in Austria (Höller, 1999), France, and Switzerland. The winter was the deadliest for persons caught in

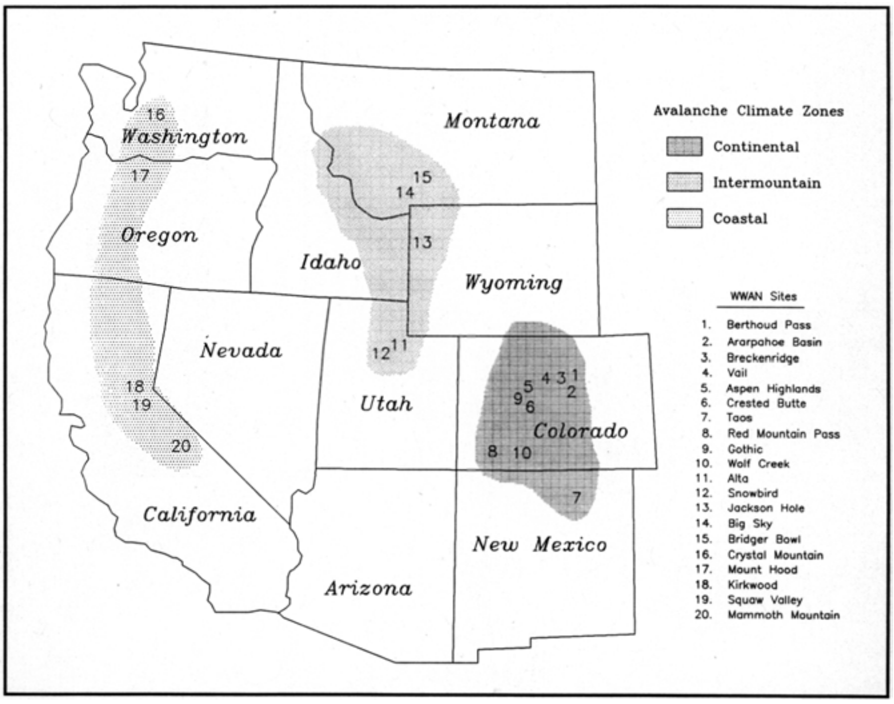


Figure 1. Map of Westwide Avalanche Network (WWAN) sites used in this study, and the general boundaries for continental, intermountain, and coastal snow avalanche climates.

structures since 1950–51, with 67 fatalities, and damage estimates for Switzerland alone exceed 700 million U.S. dollars (Bachman, 1999). Damage and death tolls would have been much higher except for extensive zoning, structural protection, evacuations, and avalanche warnings.

The western United States is more sparsely populated than the European Alps, and consequently the public exposure to avalanches is also less. However, this exposure is increasing dramatically as the western United States mountain ranges are coming under mounting development pressure. Given the increasing potential for widespread disruption, it is important to understand some of the controls on severe, widespread avalanche cycles in this area. In order to gain a better understanding of such an avalanche cycle, this paper uses the best available avalanche and climate data to explore the extensive avalanche cycle that occurred in February 1986. Our analysis examines twenty sites throughout the western United States to investigate the spatial extent and severity of the avalanche cycle, the snowpack and weather conditions that contributed to the cycle, and the atmospheric conditions associated with the series of storms that created the widespread, dangerous conditions.

2. Data and Methodology

2.1. DATA

This study utilizes avalanche and climatic data from the Westwide Avalanche Network (WWAN), which is currently the longest established high elevation climate and avalanche database in the United States. Data collection began at three sites (Berthoud Pass, Colorado, Alta, Utah, and Steven's Pass, Washington) in the 1950s. Increased coverage began in the late 1960s when the WWAN officially started (Judson, 1970), and we used twenty sites for our analyses (Figure 1). All WWAN sites are located close to avalanche paths and runout zones. Daily data on the number and size of avalanches, as well as climatic data such as maximum and minimum temperatures, total snow depth, new snowfall, snow water equivalent (SWE), and measured rainfall exist for each site. Avalanche data follow the United States recording system (Perla and Martinelli, 1978).

With the exception of Gothic, Colorado, all of the WWAN sites we used conduct avalanche control work, and they all record both natural avalanches occurring in and around the area as well as controlled avalanches. Typically, avalanche workers use explosives to release avalanches during times of high danger so the public is not caught in any slides. The number of triggered avalanches is far greater than the number of naturally occurring slides. Though such avalanche control work is clearly necessary for safety, it also affects the WWAN data since the number, size, and timing of avalanches depends to a certain extent on the intensity of the control work conducted. Despite this limitation, the WWAN data are still a powerful tool to examine the severity and extent of a widespread avalanche cycle.

Atmospheric circulation data consist of gridded 500-hPa heights (in geopotential meters) provided by the National Center for Atmospheric Research, and cover the period from January 1946 to January 1994. The 500-hPa level lies above the elevation of the highest peaks in the western United States, thereby limiting influences of the planetary boundary layer. Many avalanche professionals favor the use of these maps for their mountain weather forecasts (Birkeland and Mock, 1996). The circulation data cover the region from the western Pacific to the eastern Atlantic so that large-scale atmospheric circulation features such as longwave ridges and troughs can be adequately described (i.e., Mock, 1995). The data consist of an interpolated octagonal grid of observations at 0Z and 12Z (Mass, 1993).

2.2. METHODOLOGY

We chose to analyze the February, 1986 avalanche cycle for several reasons: (1) anecdotal evidence from numerous avalanche workers indicate this was a major and widespread avalanche cycle, (2) the storm cycle that produced the avalanche cycle has been described as "the storm of the century" (Williams, 1986), dropping 2.5 to 4.0 m of snow over a 10 day period from the California's Sierra Nevada Range to Colorado's Rocky Mountains (Mears, 1992), (3) data from the Sierra Nevada

Range in California show this avalanche cycle produced exceptionally long running avalanches that uprooted trees up to 300 years old (Frutiger, 1990) and destroyed thousands of hectares of mature timber (Wilson, 1986), implying the avalanches had an exceptionally long recurrence interval, and (4) dendrochronological studies of avalanche paths in Colorado (Rayback, 1998) and Montana (Butler, 1989; Birkeland, 1996) indicate that the 1986 cycle caused significant forest damage in these locations as well, demonstrating the widespread nature of the avalanche cycle.

We needed to simplify the WWAN avalanche data to analyze the daily data at numerous sites. WWAN avalanche data consist of records of the size of each individual avalanche on each path for a given day. Size is recorded on the 1 to 5 United States scale, where a 1 is a small sluff and a 5 is the maximum sized avalanche for a given path (McClung and Schaerer, 1993). To better analyze the severity of the daily avalanche hazard at a site, we constructed an avalanche hazard index by squaring the recorded size of the individual avalanches and summing them up for each day. We squared the avalanche size because some conditions lead to a large number of small avalanches that are often relatively harmless, while larger avalanches are more likely to damage facilities and are more indicative widespread instabilities in the snowpack in the surrounding backcountry. This index worked well for identifying avalanche extremes at several WWAN sites over time and space in previous research (Birkeland *et al.*, in press; Mock and Birkeland, 2000).

We quantified the spatial extent and relative severity of the February 1986 avalanches by summing up the avalanche hazard index at each site for the month, and comparing that month to all the other months (from December to March), and to all the other Februarys of record. Index values greater than the 75th percentile (upper interquartile range) indicated that February 1986 was a particularly active avalanche month for each location. To better understand the nature of the February 1986 avalanche cycle, we attempted to reconstruct both the existing snowpack and the subsequent storm event that triggered the avalanche activity. Information on the existing snowpack came from written accounts, and an analysis of daily time series of important avalanche climate variables from several sites (Mock *et al.*, 2000). Storm data were analyzed by comparing long-term climate averages for several sites with the WWAN data for February 1986.

To look at the atmospheric conditions responsible for the series of storms and subsequent avalanche activity in February 1986, we constructed 500-hPa maps and 500-hPa anomaly maps for: (1) the 1985-86 winter from December to March, (2) the month of February, and (3) the period from February 13th to the 21st, which was the period of the primary storm event.

Table I. Long-term all-month (December through March) and February values of the avalanche hazard index in comparison to values for February 1986 for twenty WWAN sites in the continental, intermountain and coastal avalanche climate zones (CO = Colorado, NM = New Mexico, UT = Utah, WY = Wyoming, MT = Montana, WA = Washington, OR = Oregon, CA = California)

Site	N (all)	Median (all)	75th percentile (all)	N (Feb.)	75th percentile (Feb.)	Feb. 1986*
Continental						
Berthoud Pass, CO	182	92.5	159.75	27	151	***175***
Arapahoe Basin, CO	125	84	170.5	22	236	***349***
Breckenridge, CO	132	85.5	188.3	26	130	59
Vail, CO	133	30	46.5	25	47	40
Aspen Highlands, CO	103	87	217	23	448	***1146***
Crested Butte, CO	97	75	164.5	23	158	***416***
Taos, NM	119	152	466	25	399	***747***
Red Mtn Pass, CO	135	162	401	26	647	**471**
Gothic, CO	126	170	351.7	20	594	***869***
Wolf Creek, CO	133	61	135	24	169	54
Intermountain						
Alta, UT	102	391	571.3	20	628	**616**
Snowbird, UT	159	400	687	27	772	**742**
Jackson Hole, WY	109	274	452.5	24	481	***537***
Big Sky, MT	105	249	439	22	578	***890***
Bridger Bowl, MT	135	253	574	27	562	536
Coastal						
Crystal Mountain, WA	136	220.5	515.8	26	575	***961***
Mount Hood, OR	107	191	316	22	362	***453***
Kirkwood, CA	105	348	694.5	20	744	***1407***
Squaw Valley, CA	132	344.5	779.8	25	1395	***1448***
Mammoth Mtn, CA	112	199	380.5	22	383	***1338***

*Bold/italics/underlined represent sites where the avalanche hazard index for February 1986 is greater than both all-month (December through March) and February 75th percentiles. Bold represents sites where February 1986 is greater than all-month 75th percentile, but less than February 75th percentile.

3. Results and Discussion

3.1. SPATIAL EXTENT AND SEVERITY OF THE FEBRUARY 1986 AVALANCHE CYCLE

The February 1986 avalanche cycle was notable not only for the severity of avalanches produced, but also for the widespread nature of the cycle. Exceptional avalanche activity occurred throughout the western U.S. (Table I). Of the ten sites in Colorado and New Mexico, only Breckenridge, Vail, and Wolf Creek, Colorado recorded avalanche indices for February 1986 that were less than their long-term 75th percentile for all months. One site (Red Mountain Pass, Colorado) exceeded its long-term 75th percentile for all months, but was less than the long-term 75th percentile for Februarys, while six sites exceeded their 75th percentile for both all months and Februarys. Notably active Colorado sites included Aspen Highlands and Crested Butte, which both had indices over 2.5 times greater than their February 75th percentiles in 1986. Observers throughout Colorado reported 750 avalanches to the Colorado Avalanche Information Center during the cycle. At Aspen Highlands one slide ran over 1000 m vertical in the biggest slide observed on that path in more than 25 years (Williams, 1986). Other large slides blocked Interstate 70 (a major traffic corridor over the Rocky Mountains), damaged buildings at several mines, and damaged a ski lift at Arapahoe Basin (Williams, 1986). Rayback (1998) found the 1986 event to be the most clearly shown in the dendrochronological record of several Colorado avalanche paths.

Farther west in the intermountain avalanche climate of Utah, Wyoming, and Montana, the avalanche cycle was also big and widespread (Table I). Of five sites, only Jackson Hole, Wyoming and Big Sky, Montana exceeded their 75th percentile for both all months and all Februarys. Alta, Utah and Snowbird, Utah exceeded their all month 75th percentile, but not their February 75th percentile. Bridger Bowl, Montana, located farther north than all of the other sites, did not exceed either 75th percentile. Despite the avalanche cycle not seeming as 'extreme' in the intermountain zone based on the WWAN data, even seasoned avalanche workers had difficulty assessing the avalanches created by this avalanche cycle. At Alta, Utah, an extremely rare event occurred when an enormous avalanche released naturally from a closed area. Instead of stopping in the usual location, the slide ran over a lake and a small ridge, covering an open ski run and burying a person who later died. At Jackson Hole an experienced ski patroller was killed when a slope that had been controlled with artillery and hand explosives avalanched as he skied onto it (Williams, 1986). One large slide at Jackson Hole triggered by explosives released about 500 m wide and ran 1000 vertical meters, destroying a mid-mountain restaurant and narrowly missing several houses as it caused 60,000 U.S. dollars in damage. Snowbasin, Utah, which is located north of Snowbird and Alta and is not part of the WWAN database, experienced several large slides including one that heavily damaged their mid-mountain ski lodge and another that buried a ski patroller, who was quickly dug out alive. Finally, a large slide destroyed a house valued at 2 million U.S. dollars at Sundance, Utah, located south of Snowbird and Alta (Meiklejohn, 1986).

Even though Bridger Bowl did not experience exceptional avalanche activity during the February 1986 avalanche cycle, some parts of Montana were clearly affected. Bridger Bowl's relative lack of avalanche activity might be due to the direction of the upper-level air flow, which was westerly, while the favored direction for heavy snowfall in this area is from the northwest (Birkeland and Mock, 1996). However, other parts of Montana were affected by the strong zonal flow that predominated during this series of storms, as shown by the data from Big Sky, and by the dendrochronological record of numerous avalanche paths in the mountains south and southeast of Bridger Bowl which indicate that numerous large avalanches occurred during 1985–86 season (Birkeland, 1996).

In the coastal areas of Washington, Oregon, and California, the effects of the February 1986 avalanche cycle are particularly apparent in the WWAN data, with all five sites analyzed exceeding both their all-winter and February 75th percentiles. Particularly notable are the sites in California's Sierra Nevada range, where snowfall totals ranged from 2 to 3.5 m, water from rain and snow exceeded 0.75 m, and winds peaked at 270 kilometers per hour (Williams, 1986). All the California WWAN sites we analyzed recorded total avalanche hazard indices exceeding 1000 for February 1986. Mammoth Mountain had perhaps the most extreme month of any of the sites, with a hazard index over four times greater than the February 75th percentile. One large slide at Mammoth reportedly released over 6 m deep at the crown face, though Frutiger (1990) estimates an average slab depth for this slide of about 2.8 m. Avalanches throughout the Sierra Nevada range destroyed thousands of hectares of mature timber (some up to 300 years old), damaged ski lifts and other buildings, and buried kilometers of highways (Wilson, 1986). Numerous slides ran farther than expected; in one case a slide ran more than 100 m past the maximum extent of the mapped runout zone (Frutiger, 1990). The damage to property could have been much worse. Wilson (1986) noted that the freezing levels and snow accumulation zones were conducive to avalanche formation in the upper elevation starting zones, and he deduced that if conditions had been lowered 200 to 300 m to the level of lower starting zones, damage "could have extended well into the more heavily populated zones".

The timing of the avalanche cycle varied between WWAN sites, but it generally encompassed the period of the series of storms, from about February 13th to the 21st (Figure 2). In Colorado, the avalanche hazard index peaked at Berthoud Pass, Arapahoe Basin, and Aspen Highlands ski areas on February 20th or 21st. This peak is later than the other sites, possibly because snowfall finally overloaded buried weak layers in the snowpack, or perhaps due to the timing of avalanche control work, which may have been delayed in some areas until the bulk of the storm event passed. Gothic, Colorado, which records only natural avalanche activity, reported a peak avalanche hazard index on February 15th. Taos, New Mexico shows a peak on the 10th, just as the storm event was beginning, and another

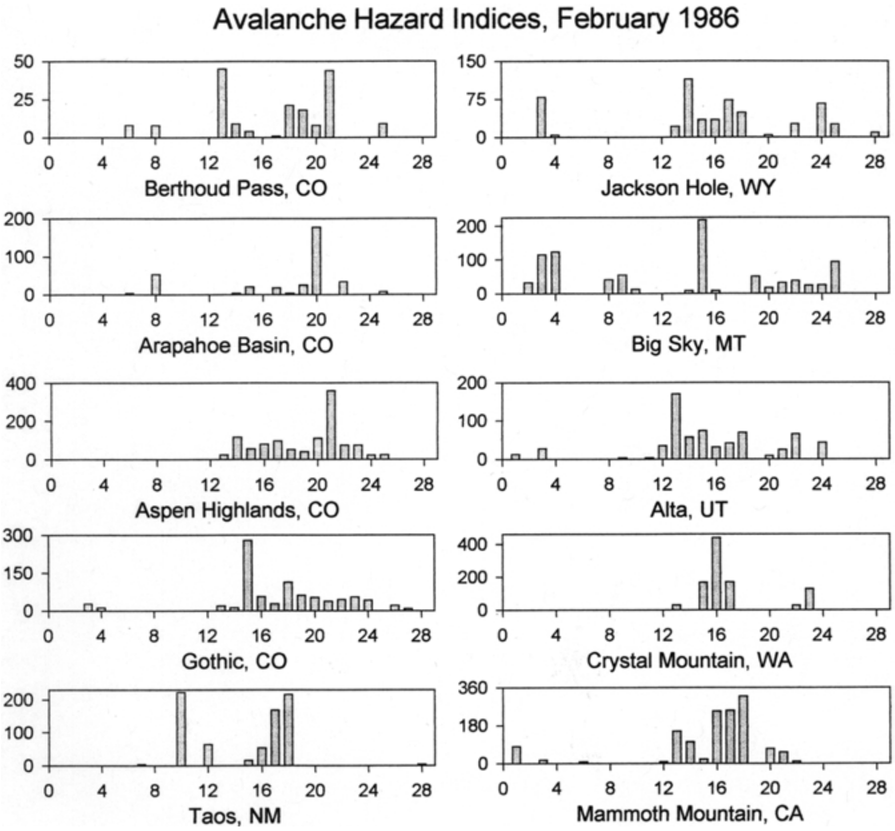


Figure 2. Avalanche hazard indices for selected WWAN sites for February 1986.

peak on the 17th and 18th. In the intermountain zone, Jackson Hole, Wyoming, Big Sky, Montana, and Alta, Utah have the most activity from about the 13th to the 18th of the month, with peak days from the 13th to the 15th. In the coastal areas of California and Washington, Crystal Mountain, Washington and Mammoth Mountain, California had peak days on the 16th and the 18th, respectively. The 18th is also when many massive natural avalanches were released in California's Sierra Nevada range (Wilson, 1986).

3.2. SNOWPACK CONDITIONS ASSOCIATED WITH THE FEBRUARY 1986 AVALANCHE CYCLE

Significant avalanche cycles may result from unusual snowpack conditions, unusual weather conditions, or both. A general analysis of the February 1986 snowpack conditions indicates relatively 'normal' conditions existed throughout the western United States prior to the avalanche cycle, inferring that the exceptional nature of the storm event was responsible for the avalanche cycle. Since snow profile information for various sites is not available, we attempted to make a broad reconstruction of snowpack conditions existing prior to the February 1986 storm cycle from climatological records and written accounts.

The 1985/86 winter started off with a large storm in November when 0.6 to 1.5 m of snow fell throughout the western United States; by the end of November, all WWAN sites had snowpacks well above normal (Williams, 1985). Conditions changed in December when a high-pressure system dominated the weather, leaving the region mostly dry. Continued dry weather with a few small storms persisted through January, with below normal snowfalls for all WWAN sites except in Alaska. An analysis of the snowpack on February 1st at the selected WWAN sites shows that nearly all the sites had a snow depth within one standard deviation of their long-term February 1st mean snow depth (Table II). The only exceptions were the two most northerly sites, Bridger Bowl, Montana and Crystal Mountain, Washington, both of which had significantly less snow than normal.

Based on snow depths and the timing of snowfall, we can make conjectures about the snowpack structure existing on or around February 1st, 1986. Deep early snowfalls inhibit the formation of weak layers of depth hoar, which form in response to temperature gradients within the snowpack (McClung and Schaerer, 1993). However, clear weather and a lack of December and January snowfall probably adversely affected the snowpack. Weak layers most likely formed in areas with thinner snowpacks and lower temperatures, such as the continental climate in Colorado. A time series graph of data from Gothic, Colorado demonstrates the nature of the 1985/86 winter at a continental site (Figure 3). Though snowfall started out deep on December 1st (about 1 m), prolonged cold, clear weather followed through much of December and January. With temperature gradients exceeding 10 degrees C/m for much of this time, weak faceted snow probably formed near the ground (McClung and Schaerer, 1993). Further, clear periods may have formed weak layers of near-surface faceted crystals (Birkeland, 1998). Thus, a typical continental snowpack, with significant basal and near-surface weaknesses, apparently existed in the continental avalanche climate zone before the large February 1986 storm event and resultant avalanches.

Farther west in the intermountain zone the snowpack started out fairly deep. Perusal of daily data from our selected intermountain sites shows that high temperatures kept temperature gradients generally below the 10° C/m threshold, thereby inhibiting the formation of basal depth hoar. However, weak surface layers likely formed during clear weather periods of December and January. The existence of such weak layers of near-surface faceted crystals is common in the intermountain snow climate, and would contribute to what avalanche workers would consider fairly ‘normal’ snowpack conditions for this region (Birkeland, 1998).

Unlike areas farther inland, the coastal regions of Washington, Oregon, and California probably had stronger snowpacks. Most of these areas started with deep snowpacks, and the higher temperatures recorded at all sites prevented the widespread formation of weak snow. An examination of daily data from Squaw Valley, California confirms that, though the snowpack was fairly thin at this site

Table II. Comparison of long-term records of February 1st snow depth with snow depth on February 1st, 1986 for selected WWAN sites. N represents the number of observations

Site	N	Feb. 1st avg. snow depth (cm)	Std. dev. (cm)	Feb. 1st, 1986 snow depth (cm)
Continental				
Berthoud Pass, CO	41	122.5	26.9	121.9
Arapahoe Basin, CO	19	123.9	24.4	147.3
Breckenridge, CO	23	131.2	36.2	132.1
Vail, CO	28	153.8	34.7	137.2
Aspen Highlands, CO	16	110.3	26.2	104.1
Crested Butte, CO	27	109.8	32	101.6
Taos, NM	27	146.5	49.6	101.6
Gothic, CO	20	119	41.7	119.4
Wolf Creek, CO	19	211.6	61.3	198.1
Intermountain				
Alta, UT	53	201.3	60.8	147.3
Snowbird, UT	25	191.6	45	165.1
Jackson Hole, WY	27	193	53.9	213.4
Big Sky, MT	18	116.3	20.5	119.4
Bridger Bowl, MT	28	160.3	39.9	***91.4***
Coastal				
Crystal Mountain, WA	25	141.4	62.5	***61***
Mt Hood, OR	22	235.8	101	203.2
Squaw Valley, CA	25	153	123.9	61
Mammoth Mtn, CA	26	169.5	95.7	200.7

Bold/italics represent sites where the snow depth on February 1st, 1986 differs by more than one standard deviation from the long term February 1st average snow depth.

(less than 1 m) for much of the season, warm temperatures inhibited the formation of significant weak layers (Figure 4). This analysis is backed up by Wilson (1986), who characterized the February 1986 snowpack as a generally strong, ‘normal’ Sierra snowpack.

Given the available data and written reports, it appears that relatively ‘normal’ snowpack conditions existed throughout the western United States prior to the February 1986 avalanche cycle. Such ‘normal’ conditions include a relatively weak snowpack with fragile layers of basal depth hoar in the continental areas of Colorado and New Mexico, and a strong snowpack with few major weaknesses in the coastal areas of Washington, Oregon, and California. The intermountain zone of Montana, Wyoming, and Utah probably had intermediate conditions with some

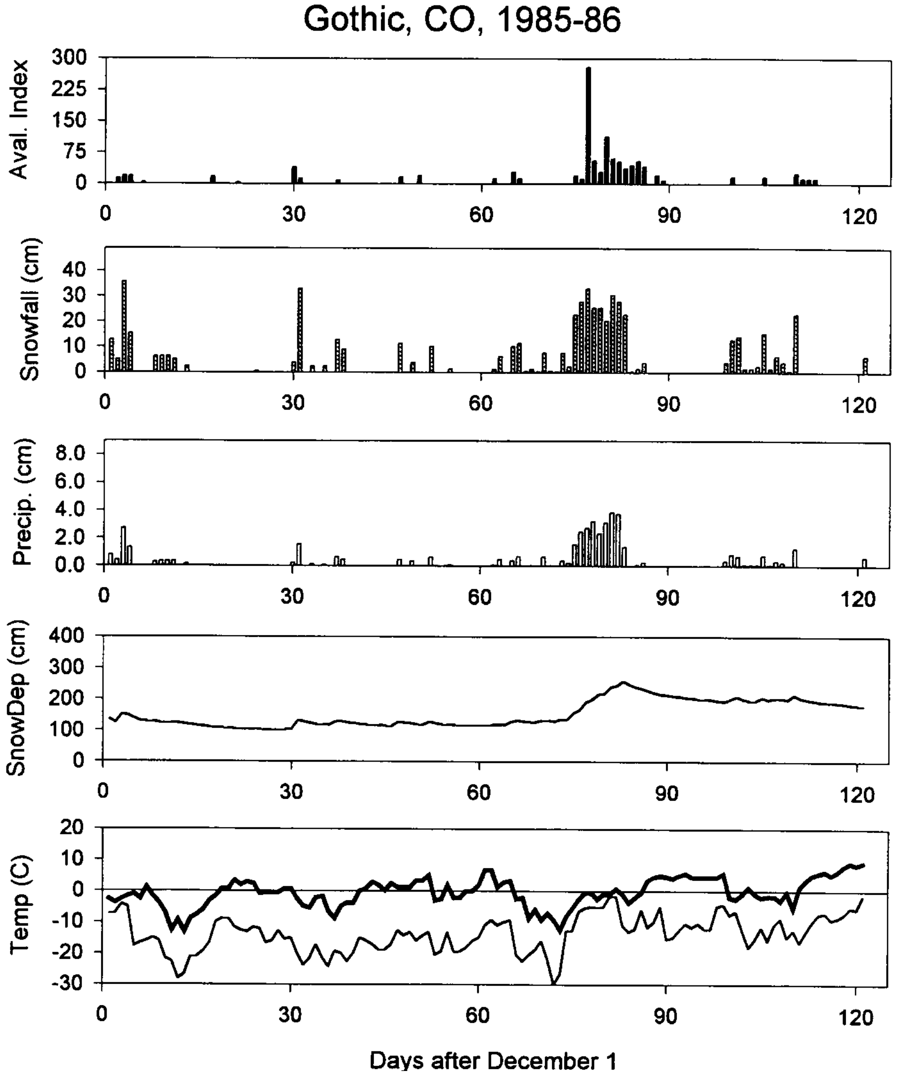


Figure 3. Time series plot of avalanche and climate data for Gothic, Colorado for the 1985/86 winter. The bars on the precipitation graph indicate snow water equivalent.

weak layers throughout the snowpack. Thus, the widespread avalanche cycle of February 1986 likely resulted predominantly from an exceptional weather event rather than exceptional snowpack conditions.

3.3. WEATHER CONDITIONS ASSOCIATED WITH THE FEBRUARY 1986 AVALANCHE CYCLE

To look at the weather conditions associated with the avalanche cycle, we analyzed climate data from our WWAN sites, comparing February 1986 with the long-term

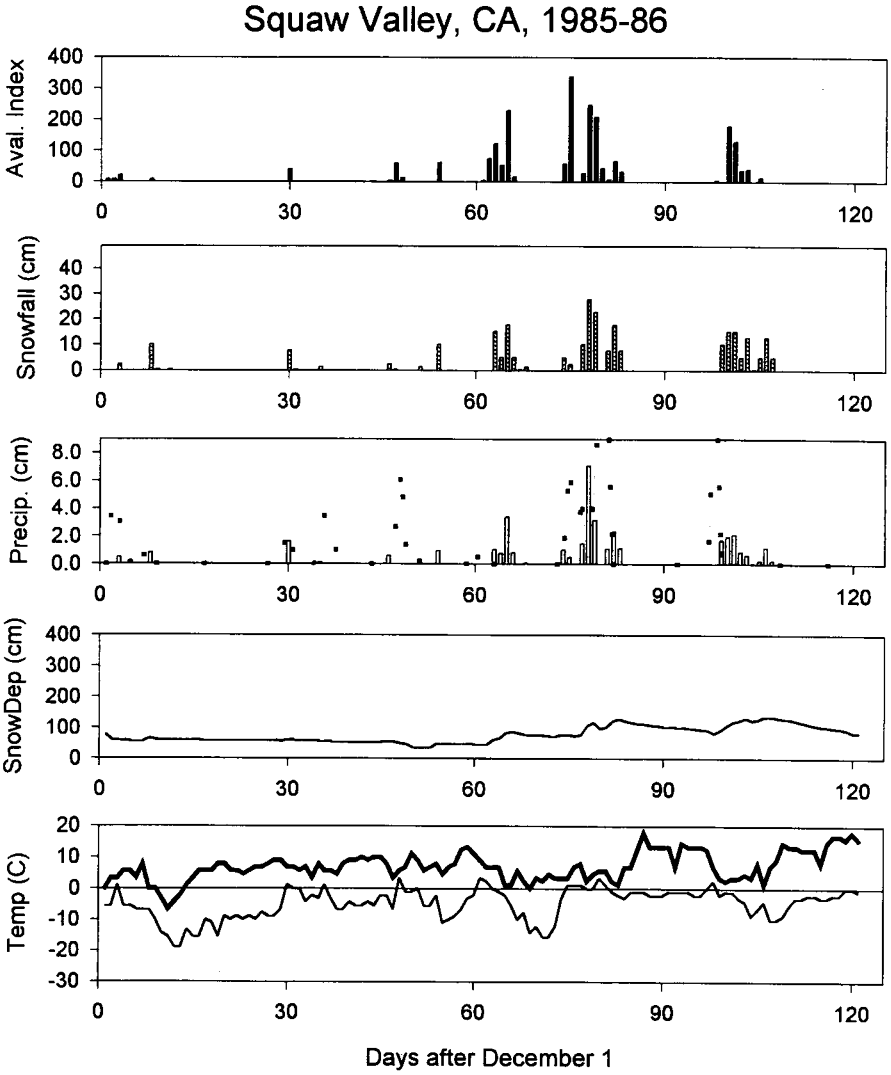


Figure 4. Time series plot of avalanche and climate data for Squaw Valley, California for the 1985/86 winter. The dots on the precipitation graph indicate rain, while the bars indicate snow water equivalent.

February averages (Figure 5; Table III). Fourteen of seventeen sites recorded higher than average temperatures in February 1986, as shown by positive temperature departures. High temperatures are due to the warm westerly and southwesterly flow.

Snowfall more clearly deviated from average conditions. With the exception of Crystal Mountain, Washington, all sites recorded above normal snowfall, with some sites recording exceptional amounts (Figure 5; Table III). In the continental zone, Breckenridge recorded 217% of long-term average February snowfall, while

Table III. Long-term February averages and data for February 1986 for average air temperature, snowfall, and precipitation

Site	Average temperature (deg C)		Total snowfall (cm)		Precipitation (cm)	
	Feb. 86	Departure from avg.	Long-term avg.	Feb. 86 (% of avg.)	Long-term avg.	Feb. 86 (% of avg.)
Continental						
Berthoud Pass, CO	−9.3	0.6	116	213 (184%)	8.0	17.1 (213%)
Breckenridge, CO	−8.5	0.6	109	237 (217%)	7.9	19.6 (248%)
Vail, CO	−8.7	0.6	143	196 (137%)	8.9	13.4 (151%)
Aspen Highlands, CO	−5.7	1.1	105	191 (182%)	8.1	15.8 (195%)
Crested Butte, CO	−6.0	1.8	100	158 (158%)	7.2	17.1 (238%)
Taos, NM	−5.9	1.2	97	113 (116%)	6.0	6.0 (100%)
Gothic, CO	−7.4	2.4	162	290 (179%)	11.4	28.0 (246%)
Wolf Creek, CO	−6.9	0.5	167	261 (156%)	13.9	25.5 (183
Intermountain						
Alta, UT	−4.6	1.3	210	286 (136%)	19.1	34.2 (179%)
Snowbird, UT	−3.1	1.5	196	208 (106%)	16.1	21.8 (135%)
Jackson Hole, WY	−9.4	−0.9	149	326 (219%)	12.0	36.8 (307%)
Big Sky, MT	−7.0	0.4	105	154 (147%)	8.3	14.2 (171%)
Bridger Bowl, MT	−5.7	−0.1	120	163 (136%)	7.6	13.5 (178%)
Coastal						
Crystal Mountain, WA	−2.6	−0.6	114	110 (96%)	16.8	18.6 (110%)
Mt Hood, OR	−1.7	0.1	200	341 (171%)	29.9	N/A
Squaw Valley, CA	1.0	1.0	135	146 (108%)	21.2	N/A
Mammoth Mtn, CA	−4.1	−0.3	156	383 (246%)	19.4	73.6 (380%)

N/A indicates that data are not available.

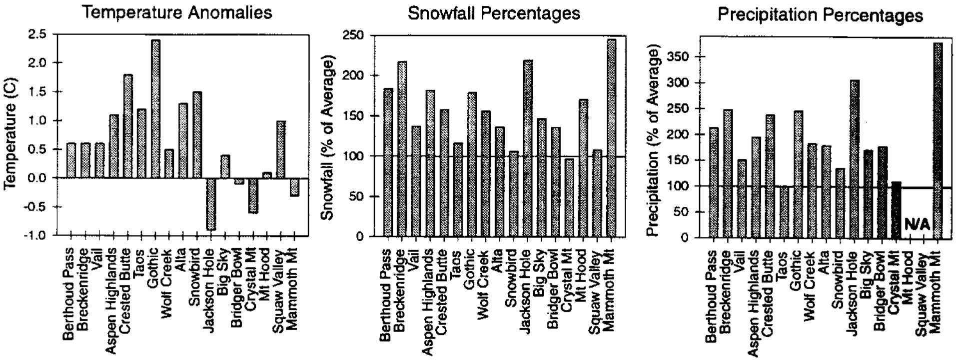


Figure 5. Temperature anomalies (departures from average), snowfall percentages, and precipitation percentages for selected WWAN sites for February 1986. Data clearly show that February 1986 had higher temperatures, more snowfall, and much more precipitation than normal.

Berthoud Pass, Aspen Highlands, and Gothic, Colorado, all reported around 180% of normal. Gothic had the most snowfall in the continental zone, with 290 cm. In the intermountain zone Jackson Hole, Wyoming received 326 cm of snowfall, which is 219% of normal. Jackson Hole is perfectly positioned to receive snowfall from storms with a strong zonal flow since it is located at the head of the Snake River Plain, a topographic feature that funnels moisture far inland (Mock, 1996b; Birkeland *et al.*, in press). Zonal and southwesterly flows also favor snowfall at Big Sky, Montana, which received 147% of normal snowfall. In the coastal avalanche climate zone, Mammoth Mountain recorded the most snowfall with 383 cm, which is 246% of normal. Interestingly, Crystal Mountain and Squaw Valley reported near or below normal snowfall. This is due to the warmth of the storms, resulting in copious rain at some locations. The time series plot for Squaw Valley clearly shows the rain, represented by dots on the precipitation graph (Figure 4).

While snowfall is an important variable used for avalanche prediction, the amount of precipitation, which is the sum of the snow water equivalent (melted snowfall) and rainfall, is even more critical since it indicates the amount of weight being added to the snowpack. Snowfall from the February 1986 storm event was noteworthy, but the real significance of this event is the tremendous amount of precipitation recorded throughout the western United States. In the continental zone, all sites except Taos, New Mexico recorded more than 150% of normal precipitation, with Berthoud Pass, Breckenridge, Crested Butte, and Gothic, Colorado all receiving more than 200% of normal (Figure 5, Table III). Except for Snowbird, Utah, all our intermountain sites reported more than 170% of normal precipitation. Jackson Hole reported an extraordinary 36.8 cm of precipitation, 307% of normal. In the coastal zone, Crystal Mountain, Washington was just above normal. Mammoth Mountain, California recorded more than twice the amount of any of our other WWAN sites, with an amazing 73.6 cm, over 380% of normal.

The February 1986 storm event was exceptional because of its duration and intensity. The amount of precipitation is particularly noteworthy, and is why this event resulted in such widespread avalanche activity. The storms were spatially extensive, strongly affecting all of our sites except for the most northwestern (Crystal Mountain, Washington) and southeastern (Taos, New Mexico) sites. California's Sierra Nevada Range, Wyoming's Jackson Hole, and many of the Colorado mountains were particularly hard hit. Not surprisingly, these areas are also some of the places that reported the largest and most widespread avalanche activity (Table I).

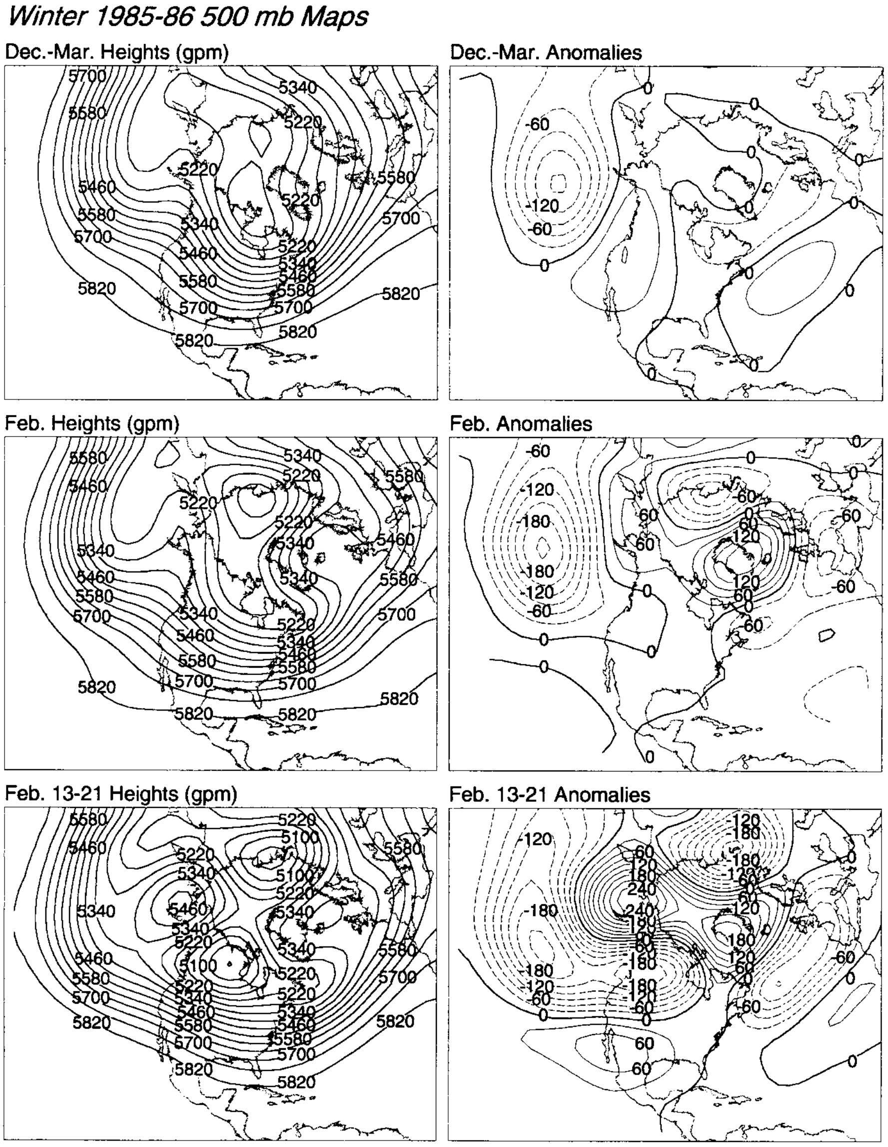
3.4. ATMOSPHERIC PATTERNS AND ANOMALIES ASSOCIATED WITH THE FEBRUARY 1986 AVALANCHE CYCLE

Since the exceptional nature of the February 1986 avalanche cycle resulted from the interaction of a relatively 'normal' snowpack with an extraordinary series of storms, we analyzed the atmospheric conditions associated with the event. Our analysis focuses on 500-hPa heights, and anomalies from our 1946–1994 dataset, for the winter (December to March), for February, and for the stormiest period from February 13th to the 21st, 1986.

The most distinctive feature of the December, 1985 to March, 1986 500-hPa height patterns is increased zonal flow, as reflected by negative anomalies over the North Pacific (Figure 6) (Arkin and Janowiak, 1987). On anomaly maps, areas with negative anomalies have increased counterclockwise flow, while areas with positive anomalies have increased clockwise flow. Thus, interpreting the anomaly map suggests increased westerly to southwesterly flow into the western United States (e.g., Klein and Bloom, 1986), and this pattern also corresponds to increased snowfall over much of the region (Mock and Kay, 1992; McCabe and Legates, 1995; Cayan, 1996). A weak zone of positive anomalies is located over the west coast, corresponding with relatively higher than normal temperatures.

The 500-hPa height pattern for February, 1986 also indicates primarily zonal flow over much of the United States as well as negative height anomalies in the North Pacific (Figure 6). The negative anomalies for February are much stronger than for the entire winter, indicating that this was a key month characterized by persistent southward displacement of the polar jetstream and increased storminess over much of the western United States.

The 500-hPa height pattern for February 13th to the 21st, 1986 shows patterns similar to the other maps, but it differs somewhat by indicating a blocking pattern over the East Pacific (high over low block) (Figure 6). Strong positive 500-hPa height anomalies are evident near Alaska, and these anomalies along with the negative anomalies in the North Pacific reflect the persistence of the blocking pattern. Interpretation of this blocking pattern implies increased southward displacement of the polar jetstream along the southern edge of the block, with increased southwesterly flow into the western United States. A separate but weaker branch of the jetstream was split to the north towards Alaska and north of the western United



Dec.-Mar. Heights (gpm)

Dec.-Mar. Anomalies

Feb. Heights (gpm)

Feb. Anomalies

Feb. 13-21 Heights (gpm)

Feb. 13-21 Anomalies

Figure 6. Composited 500-hPa maps and 500-hPa anomalies for the winter (December, 1985 through March 1986), February 1986, and February 13th to the 21st, 1986.

States. Negative anomalies over the far western United States reflect the influence of persistent shortwaves (mid-latitude cyclones) traversing through the region from the southwest, enhanced by their location in an area of general upper-level divergence. A long southwesterly fetch extending towards Hawaii, known by local forecasters as the "pineapple connection", was important for creating widespread copious precipitation over a large area. Precipitation and streamflow over the far western United States was abnormally heavy, generally in the upper tenth percentile with respect to long-term records of at least thirty years or more (e.g., Arkin and Janowiak, 1987; Roos, 1996).

4. Summary and Conclusions

Extraordinary avalanche events result from unusual snowpacks, unusual storm events, or both. The February 1986 snowpack was fairly ‘normal’ throughout the western United States. Thus, the February 1986 avalanche cycle resulted from an exceptionally intense, long-duration series of storms that dropped significant precipitation over a broad area. Avalanche activity was notable throughout the region, and resulted in considerable damage to buildings and forests, disruption of recreational facilities and transportation corridors, and several fatalities. Damage and death tolls during a similar event in the future might be much higher since the mountain ranges of the western United States are coming under increasing development pressure, thereby increasing the human exposure to avalanches.

The February 1986 avalanche cycle is currently unique in its destructiveness and widespread spatial extent in the high elevation avalanche and climate records of the western United States. Unfortunately, our 30-year data record is short; a longer temporal perspective might indicate whether such events are becoming more frequent. Potential avalanche responses to climatic change from global warming, for example, may be catastrophic if prolonged cold spells are followed by strong, wet storms and warm air masses (Föhn, 1992; Fitzharris *et al.*, 1996). Only the buildup of climate and avalanche databases, augmented by accurate weather and avalanche forecasting models, will enable detailed prediction of such extreme events in the future.

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