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ATMOSPHERIC CIRCULATION PATTERNS ASSOCIATED WITH HEAVY SNOWFALL EVENTS, BRIDGER BOWL, MONTANA, U.S.A.

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ABSTRACT Predicting heavy mountain snowfall, which is critical for avalanche hazard forecasting, is difficult due to complex interactions between rugged topography and atmospheric circulation. In this study the relationship between atmospheric circulation patterns and extreme snowfall events is examined at Bridger Bowl, Montana, U.S.A. which has a 26-year winter record of daily snowfall. Five hundred millibar composite and anomaly maps were constructed for days of heavy snowfall (greater than 32.8 cm). These maps show that during and prior to heavy snowfall, Bridger Bowl is located beneath the back side of a upper-level trough, with predominant winds and storms coming from the northwest. This atmospheric circulation pattern differs from those for other high-elevation sites in the North American interior due to the surrounding regional topography. High mountain ranges to the southwest and west often block incoming moisture, while relatively lower topography to the northwest allows Pacific moisture to reach Bridger Bowl. The results of this study can be used to complement operational forecasting models for predicting heavy snowfall at Bridger Bowl, thereby facilitating snow avalanche forecasting in the region.

RÉSUMÉ *Configurations de la circulation atmosphérique associées aux grosses chutes de neige à Bridger Bowl dans le Montana, Etats-Unis.* La prédiction des grosses chutes de neige en montagne, indispensable pour la prédiction des dangers d'avalanche, est difficile du fait des interactions complexes entre la topographie accidentée et la circulation atmosphérique. Cette étude examine la relation entre les configurations de la circulation atmosphérique et les chutes de neige extrêmes à Bridger Bowl au Montana, Etats-Unis, là où un registre des chutes de neige quotidiennes a été tenu au cours des 26 dernières années. Des cartes d'anomalies et des cartes combinées à l'échelle 500 millibars ont été compilées pour les jours de grosses chutes de neige (supérieures à 32,8 cm). Ces cartes indiquent qu'avant et pendant les grosses chutes de neige, Bridger Bowl est situé au-dessous de l'arrière d'un creux barométrique en altitude, avec des tempêtes et des vents proéminents en provenance du nord-ouest. Cette configuration de la circulation atmosphérique diffère de celles d'autres sites à haute altitude de l'intérieur de l'Amérique du Nord, à cause de la topographie régionale environnante. Les chaînes de hautes montagnes du sud-ouest et de l'ouest bloquent souvent l'arrivée d'humidité, alors que la topographie relativement basse du nord-ouest permet à l'humidité en provenance du Pacifique d'atteindre Bridger Bowl. Les résultats de cette étude peuvent être utilisés en tant que supplément aux modèles opérationnels de prédiction des grosses chutes de neige à Bridger Bowl, facilitant ainsi la prédiction des avalanches de neige dans la région.

ZUSAMMENFASSUNG *Atmosphärisches Strömungsverhalten bei starkem Schneefall im Bridger Bowl Gebiet, Montana, U.S.A.* Starke Schneefälle im Gebirge führen zu erhöhter Lawinengefahr, deren Vorhersage durch komplexe Wechselwirkungen zwischen der zerklüfteten Topografie und der atmosphärischen Zirkulation, erschwert wird. Diese Arbeit untersucht für das Bridger Bowl Gebiet in Montana, U.S.A., die Beziehungen zwischen Luftströmungen und starkem Schneefall anhand täglicher Aufzeichnungen, für die eine 26-jährige Datenbasis zur Verfügung steht. Für hohe Tages-Schneefallwerte (mehr als 32,8 cm) wurden barographische Karten der Mittelwerte und Tendenzen bei 500 mb erstellt; und es zeigte sich, daß während starkem Schneefalls–und kurz davor–das Bridger Bowl Gebiet auf der Rückseite einer hochgelagerten Tiefdruckzone lag und die vorherrschenden Winde aus nordwestlicher Richtung kamen. Die lokale Topografie hat einen entscheidenden Einfluß auf das atmosphärische Strömungsverhalten; und diese unterscheidet sich in starkem Maße von anderen Gebirgsregionen in Nordamerika. Hohe Gebirgszüge im Süden und Westen blockieren den Zufluß feuchter Luft, die, von den niedrigen Gipfelhöhen der Randberge begünstigt, aus Nordwesten vom Pazifik her in das Bridger Bowl Gebiet einströmt. Ergebnisse dieser Arbeit können bestehende Schneefall-Vorhersagen für das Bridger Bowl Gebiet ergänzen und Warnungen über Lawinengefahren zuverlässiger machen.

INTRODUCTION

Mountain snowfall forecasting, an important prerequisite for snow avalanche forecasting, is difficult due to complex interactions between large-scale atmospheric circulation and topography (Armstrong and Williams, 1992). Mountainous areas in western North America are prime examples of these difficulties, exhibiting spatially heterogeneous climatic responses to patterns of atmospheric circulation (Mock, 1996). Therefore, analyses of relationships between regional atmospheric circulation patterns (the synoptic scale) and surface climate have to focus on individual locations within certain areas (Mock, 1995). Some studies have provided useful information on patterns of atmospheric circulation that cause heavy snowfall for specific locations in the western United States (e.g., Mahoney and Brown, 1992), but such research is limited for high-elevation sites since few locations have data re-

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cords longer than 15 years (Barry, 1992). However, more long-term climatic records from high elevations are now becoming available through the Westwide Avalanche Network, a network administered by the U.S. Forest Service that collects snow and avalanche data from approximately 60 sites in the western United States. Some synoptic climatic studies utilizing Westwide Avalanche Network data have been conducted at the monthly timescale (Mock and Kay, 1992; Mock, 1995), but to date none has been conducted at the daily timescale which is critical for short-term avalanche hazard applications.

This paper presents a case study that examines synoptic circulation patterns associated with heavy daily snowfall events at Bridger Bowl, Montana, U.S.A. Bridger Bowl was selected for two reasons. First, it has a nearly continuous daily winter record of snowfall since 1968, one of the longest available records for a high-elevation site in the western United States. Second, Bridger Bowl Ski Area and the nearby backcountry are susceptible to a high avalanche hazard. Bridger Bowl commonly ranks in the top five United States ski areas for avalanche activity, and recent increases in regional backcountry use have led to a sharp increase in avalanche-related incidents in the region during the last several years (Birkeland, 1991–1995; Westwide Avalanche Network, 1992–1995).

THE STUDY AREA

Bridger Bowl Ski Area is located in the Bridger Range, about 19 km northeast of Bozeman, Montana (Figure 1). The Bridger Range is an overturned anticline, consisting of a single ridge of mountains approximately 10 km wide running north–south for 40 km. Rising 1,400 m above the Gallatin Valley to the west, the highest peaks are 2,900 m above sea level. The east side of the range was lightly glaciated 20,000 to 70,000 years before present, resulting in numerous small cirques. Within three of these east-facing cirques lies Bridger Bowl (Figure 2). Data used in this study were from the Alpine study plot, located in a sheltered area at an elevation of 2,260 m. This plot was established shortly after the construction of the Alpine lift on the northern side of the ski area in 1967, and has been monitored continuously during the ski season since that time.

The Bridger Range is located in the interior northwestern United States. Mountain ranges to the west include the Tobacco Root and Pioneer Mountains in southwest Montana, and the Bitterroot Range on the Montana/Idaho border. To the southwest of the Bridger Range lie Montana's Madison Range, the Beaverhead Mountains on the Montana/Idaho border, and Idaho's Lemhi Range, Lost River Range, Pioneer Mountains, Beaverhead Mountains, and Sawtooth Range. The predominantly northwest–southeast alignment of these ranges, which all have peaks higher than 3,000 m, reduces the amount of Pacific moisture reaching the Bridger Range from the southwest and west, thereby creating a more continental climate at Bridger Bowl as compared to the areas farther west. Northwest of the Bridger Range are areas of relatively lower relief, including the northwest–southeast oriented Swan Range, Lewis and Clark Range, and Big Belt Mountains.

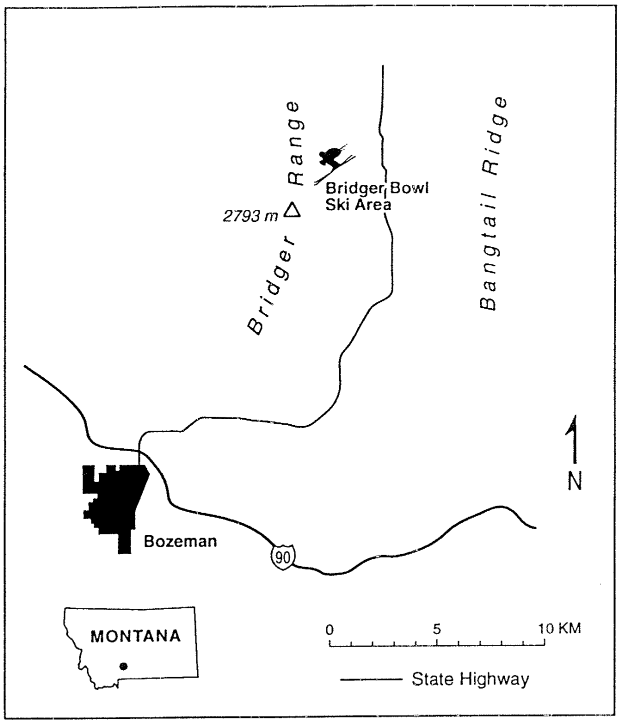

FIGURE 1. Bridger Bowl Ski Area is located on the east side of the Bridger Range, approximately 19 km northeast of Bozeman, Montana, U.S.A.

Bridger Bowl is classified as having an intermountain snow and avalanche climate (Mock, 1995), with climatic conditions and snowpack characteristics normally intermediate but ranging from those in the Pacific mountain ranges (higher temperatures, higher snowfall, higher snow density, and less faceted crystal growth) to those in the Colorado Rockies (lower temperatures, lower snowfall, lower snow density, and more faceted crystal growth). To the northwest of Bridger Bowl in northern Idaho and far northwestern Montana, the snow avalanche climate is classified as more coastal, as snowfall is generally higher due to more frequent intrusions of Pacific moisture (LaChapelle, 1966). Although still intermountain in classification, the snow avalanche climates for locations farther southward in Wyoming and Utah are characterized by higher snowfall than Bridger Bowl (Mock and Kay, 1992; Mock, 1995). Perhaps heavy snowfall events at Bridger Bowl are caused by stronger northwesterly and/or southwesterly flow, extending avalanche climate characteristics typical of other locations occasionally to Bridger Bowl.

DATA AND METHODOLOGY

The Westwide Avalanche Network snowfall data for Bridger Bowl are expressed as amounts for the 24 hours prior to observation; data were normally recorded in the morning hours. The data cover daily snowfall events from November to April during the time period from February 1968 to April 1993. Snowfall was measured from a 24-hour snow board to the nearest 1.27 cm (0.5 inch), and the board was cleared after each measurement. Daily circulation data consisted of 500-mb heights (in geopo-

FIGURE 2. Bridger Bowl Ski Area occupies several small east-facing cirques in the lightly glaciated Bridger Range. Data for this study were from the Alpine study plot, located in a sheltered area in the trees immediately to the right of the photograph.

tential meters), covering a region from the western Pacific to the eastern Atlantic. The data were provided by the National Meteorological Center (Mass, 1993) and were available for the period 1968–1989. This study used daily 500-mb data recorded at 0Z (1700h Mountain Standard Time). Data from 0Z were chosen in order to examine atmospheric circulation the evening before the snowfall data were recorded, thereby corresponding more closely to the hours when snowfall occurred. The 500-mb level is commonly used by meteorologists to study upper-level flow as it relates to surface weather. The 500-mb level also lies above the friction of the highest peaks around Bridger Bowl, eliminating complicating influences from the planetary boundary layer.

The methodology consisted of two main parts. Part one identified an abnormally high snowfall event, defined as a day with snowfall accumulation of greater than or equal to 32.8 cm (13 inches). We chose this criterion because observers at the Gallatin National Forest Avalanche Center in Bozeman have noted that snowfall accumulation meeting and exceeding this amount commonly correspond to hazardous avalanche conditions.

Part two examined associations between atmospheric circulation patterns and heavy snowfall. This step was conducted through the composite anomaly approach (Mock, 1995), which illustrates 500-mb height differences between averaged values of selected weather extremes and climatic normals (Mock, 1995). Interpretation of contoured composite anomalies is similar to traditional weather anomaly maps, with clockwise (anticyclonic) flow around positive centers (ridges) and counterclockwise (cyclonic) flow around negative centers (troughs). A seasonal climatological average of 500-mb heights was calculated according to a weighting based on number of abnormally heavy snowfall events by winter month (Ferber *et al.*, 1993). Composite anomaly maps were constructed for all of the days with heavy snowfall greater than or equal to 32.8 cm as well as for one day prior to the days with abnormally heavy snowfall. The latter step provided a means of understanding and forecasting the development of circulation patterns that lead up to heavy snowfall (Ferber *et al.*, 1993).

HEAVY SNOWFALL EVENTS AND ATMOSPHERIC CIRCULATION

Tabulation of the total number of heavy snowfall events equal to or greater than 32.8 cm by month indicated that such events were rare in November and April. This may simply result from infrequent data collection during those months since the ski area is commonly closed for most of November and the latter two thirds of April. Heavy snowfall events were fairly evenly distributed from December to March (Table 1). A slight January maximum is evident, perhaps indicating the importance of cold air masses and a strong 500-mb flow needed for heavy snowstorm development. Examination of annual seasonal totals (November–April) indicates no obvious trends over the 24-year period of record that might suggest systematic problems in snow measurement (Figure 3). Most heavy snowfall events occurred non-continuously; out of the total of 53 days, only five two-day consecutive snowfall events greater than 32.8 cm were detected. These five events might reflect a two-day persistence in atmospheric circulation patterns during those storms.

The 500-mb heights from the period 1968–1989 were analyzed for 44 abnormal heavy snowfall events. The 500-mb composite anomaly map of heavy snowfall events shows negative height anomalies centered in the interior Pacific Northwest and northern Great Basin and weaker negative anomalies in the North Atlantic Ocean (Figure 4A). Distinctive positive anomalies are centered in the northeastern Pacific Ocean and off the eastern United States. The anomaly pattern suggests that as the ridge normally found over the western United States breaks down, increased zonal flow results which is conducive for causing a stronger northwesterly flow than normal at Bridger Bowl.

Contours of mean 500-mb heights for the 44 heavy snowfall events also show strong ridging over the eastern Pacific Ocean as well as a trough into interior North America (Figure 4B). The trough is positioned a bit farther westward than normal, corresponding with the area of negative height anomalies and weakened ridge, thus enabling increased zonal flow and stronger than normal northwesterly flow over Bridger Bowl. The relationships

TABLE 1

Dates of daily snowfall events at Bridger Bowl, Montana with snowfall greater than or equal to 32.8 cm (13 inches) (month/day/year). Numbers in parentheses at the top of the column represent the totals listed by month

November (1)	December (12)	January (15)	February (12)	March (12)	April (1)
11/12/86	12/02/70	1/18/69	2/20/68	3/18/68	4/12/93
	12/24/70	1/20/69	2/18/70	3/27/72	
	12/26/73	1/18/70	2/26/71	3/03/74	
	12/02/77	1/19/70	2/14/72	3/14/77	
	12/16/77	1/23/74	2/07/74	3/31/81	
	12/01/78	1/26/75	2/04/79	3/28/83	
	12/16/81	1/06/76	2/08/81	3/02/85	
	12/14/82	1/25/76	2/02/82	3/28/85	
	12/01/84	1/26/78	2/19/83	3/28/88	
	12/02/84	1/16/84	2/22/84	3/13/90	
	12/10/89	1/28/85	2/27/89	3/14/90	
	12/02/91	1/29/85	2/28/89	3/11/91	
		1/11/88			
		1/09/89			
		1/28/91			

of the 500-mb contours and the location of the area receiving heavy snowfall is similar to what Younkin (1968) termed a "coming out" storm.

The composite anomaly map of 500-mb heights for a day prior to heavy snowfall events at Bridger Bowl, and its comparison to the composite anomaly map of the days of heavy snowfall, provide additional information on the synoptic weather pattern for Bridger Bowl (Figure 4C). The composite anomaly map for a day prior to heavy snowfall shows positive anomalies centered in the northeast Pacific Ocean and in the eastern United States, and negative anomalies centered in the North Atlantic Ocean. These anomaly patterns relate to increased zonal flow, resulting in increased troughing in the western United States, a pattern that is clearly evident on the composite map for the days of heavy snowfall at Bridger Bowl. The pattern of mean 500-mb heights for all of the events of a day prior to heavy snowfall at Bridger Bowl (not shown) is virtually identical to that for the days of heavy snowfall, differing only by showing a weaker trough into Bridger Bowl since it is not yet strongly developed for snowstorm initiation.

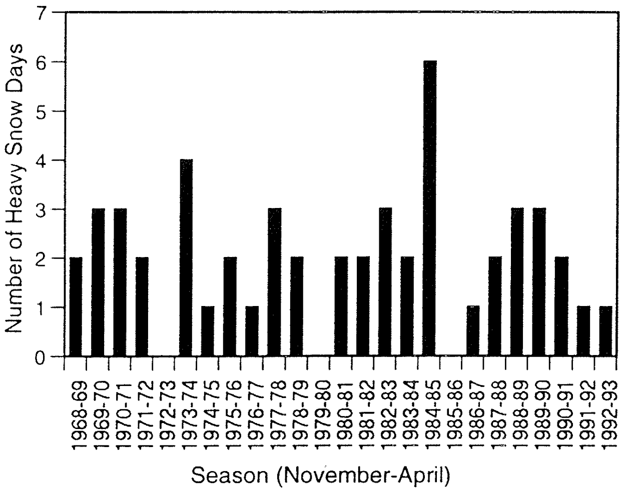

FIGURE 3. A time series of seasonal (November–April) frequencies of heavy snowfall events at Bridger Bowl equal to, or greater than, 32.8 cm (13 inches) from 1969 to 1993 shows no obvious trends that might suggest problems in snow measurement.

We constructed a difference map of 500-mb height changes by subtracting the mean heights representing the composite of a day prior to heavy snowfall from the mean heights representing the composite of the day of heavy snowfall. This procedure allowed the examination of disturbances (shortwaves) moving eastward along the main jetstream at the 500-mb level as heavy snowstorms developed at Bridger Bowl. Although the detection of shortwaves is also conducted using 700-mb heights, we used 500-mb heights because the Bridger Range lies near the 700-mb level (elevations up to 2,900 m), and because six years of experience by forecasters at the Gallatin National Forest Avalanche Center has shown that the detection of shortwaves at the 700-mb level is difficult for this area. Shortwaves, related to surface frontal activity as well as upper-level disturbances, are important features for snowstorm development, particularly for the "coming out" pattern as discussed by Younkin (1968).

The difference map between the two composite anomaly maps of snowfall for Bridger Bowl shows a large area of negative anomalies over the western United States, illustrating the rapid deepening of 500-mb heights (Figure 4D). It also shows some smaller areas of positive and negative anomalies in the North Pacific Ocean. These anomalies represent the movement of shortwaves towards the east along the jetstream as a result of their smaller sizes. The pattern of the difference map suggests that as the trough in the western United States intensifies, a shortwave moving from the Pacific along the back side of

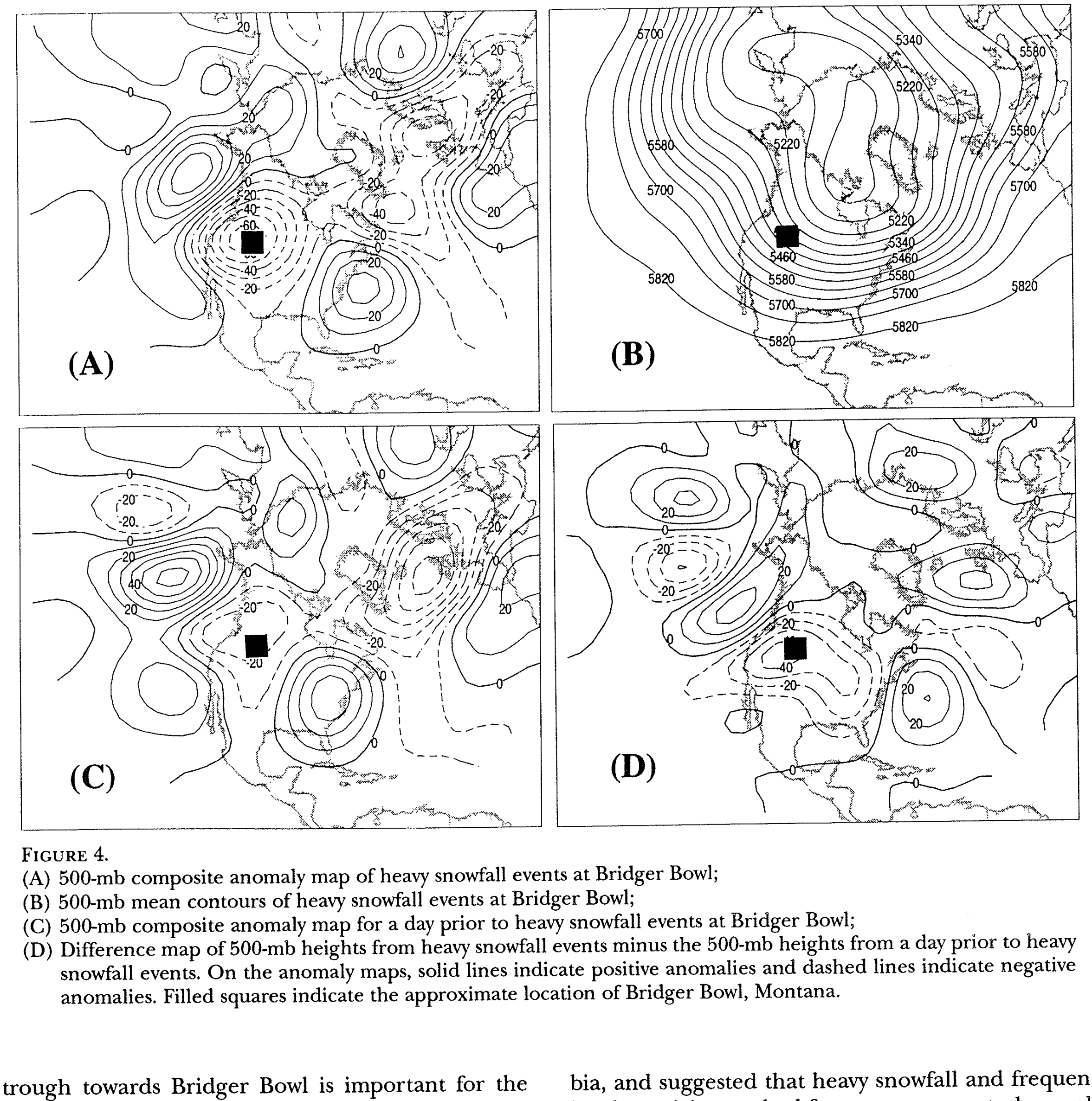

FIGURE 4.
(A) 500-mb composite anomaly map of heavy snowfall events at Bridger Bowl;
(B) 500-mb mean contours of heavy snowfall events at Bridger Bowl;
(C) 500-mb composite anomaly map for a day prior to heavy snowfall events at Bridger Bowl;
(D) Difference map of 500-mb heights from heavy snowfall events minus the 500-mb heights from a day prior to heavy snowfall events. On the anomaly maps, solid lines indicate positive anomalies and dashed lines indicate negative anomalies. Filled squares indicate the approximate location of Bridger Bowl, Montana.

the trough towards Bridger Bowl is important for the development of heavy snowfall, consistent with Younkin's (1968) "coming out" pattern. Five-hundred-millibar height changes are also evident in the Atlantic Ocean, but these changes are too small to indicate any important contribution towards snowstorm development at Bridger Bowl. However, as illustrated in both composite anomaly maps during and prior to snowfall at Bridger Bowl, the presence of large negative anomalies in the North Atlantic is usually associated with the buildup of heavy snowfall.

DISCUSSION AND CONCLUSIONS

Our results indicate that the synoptic situation that creates snowfall over Bridger Bowl differs from previously reported research. Several other studies have been conducted on the synoptic climatology of high-elevation snowfall of the interior mountain ranges in western North America, although none of these studies dealt with the daily timescale, thereby making absolute comparisons difficult. Fitzharris (1981) examined circulation maps and snow and avalanche data for Rogers Pass, British Columbia, and suggested that heavy snowfall and frequent avalanche activity resulted from a strong westerly zonal flow in the jetstream, accompanied with frequent storms. Butler (1986) analyzed historical snow and avalanche records at Glacier National Park, Montana, and implied a similar synoptic pattern that caused heavy snowfall. To the south at Alta, Utah, Mock and Kay (1992) showed that negative circulation anomalies in the eastern Pacific Ocean create stronger southwesterly flow that injects increased moisture and brings increased snowfall into the area on a monthly timescale. Strong southwesterly to westerly flow also generally causes higher snowfall for the Colorado Rockies (Barry, 1973; Armstrong and Williams, 1981; Mock, 1995). While these studies do not examine the daily timescale used in this study, none of them implies a synoptic pattern similar to the pattern described here for Bridger Bowl.

Why does abnormally heavy snowfall occur at Bridger Bowl under strong northwesterly flow as opposed to southwesterly, westerly, or perhaps easterly? The reasons may be explained primarily by the alignment of mountain ranges and topography surrounding Bridger Bowl. When southwesterly flow predominates over the region, the high mountain ranges that are located southwest of Bridger Bowl, and are aligned perpendicular to the southwest flow, tend to shield the Bridger Range from much of the moisture (Mitchell, 1976). Also, much of the moisture coming from the southwest tends to be channeled away through the low-elevation pathway of the Snake River Plain towards Yellowstone National Park, Wyoming (Bryson and Hare, 1974; Despain, 1987; Mock, 1996). The mountains to the west of Bridger Bowl act in similar fashion, although they are not as formidable a barrier as the mountain ranges to the southwest. Some of the leeward slopes of the mountain ranges in Montana receive occasional heavy snowfall from prevalent easterly winds (Boatman and Reinking, 1984), especially the east face of the Absoroka Mountains near Red Lodge. However, Bridger Bowl is generally too far west and too high to be affected by these upslope effects. Normally, the relatively lower relief to the northwest of Bridger Bowl is still sufficient to shield southwestern Montana from injections of moisture from the Pacific. However, during periods of strong northwesterly flow at the 500-mb level, moisture traveling through the low-elevation gaps of the Cordilleran Route in British Columbia and the Columbia River Gorge may be accelerated as it passes to the north around the high mountain ranges of central Idaho southeastward towards Bridger Bowl (Bryson and Hare, 1974; Mock, 1996). As the moisture mixes with cold unstable air associated with the 500 mb trough over Bridger Bowl, heavy snowfall results.

The unique synoptic situation of heavy snowfall occurring at Bridger Bowl, with strong northwesterly flow at the back side of a trough along with a shortwave moving through, illustrates a challenge for mountain weather and avalanche forecasters. Since rugged topography is critical for creating this unique synoptic situation, operational prediction models generated by the National Meteorological Center cannot accurately forecast heavy snowfall due to limitations in the models' spatial resolution. The models, however, can simulate large-scale 500-mb ridges and troughs fairly well, and these simulations can be used with 500-mb composite anomaly maps (those representing conditions for a day prior to heavy snowfall) for snowfall forecasting in the case of Bridger Bowl. Prediction of heavy snowfall can then be applied directly to snow avalanche forecasting problems since the relationship between heavy snowfall and increased avalanche activity has long been recognized (Atwater and Koziol, 1952). Since Younkin (1968) described a weather pattern conducive to heavy snowfall similar to that for Bridger Bowl as one of the main patterns that occurs in the western United States, the application of using composite anomaly maps of atmospheric circulation for other long-term Westwide Avalanche Network sites may provide more detailed information on where such atmospheric circulation patterns occur. Using this information with increasingly available radar data and automated data networks will aid in understanding how complex interactions between atmospheric circulation and topography cause heavy snowfall in mountainous areas of western North America.

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