Climate Factors Associated With Major Avalanche Events on the Wasatch Plateau, Utah

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Abstract

Dendro-ecological methods were used to construct avalanche chronologies for 16 paths on the Wasatch Plateau, Utah. Major avalanche years between 1928-1996 were distinguished from others using weighted avalanche and path indices. Since the 1900's, avalanche chronologies and historic documents indicate that large widespread avalanches events occurred during winters of 1932, 1936, 1938, 1944, 1952, 1957, 1965, 1974, 1977, 1978, 1983, 1986, 1989 and 1992. A binary classification tree analyses (CART) used climate data from the area to predict the occurrence of major avalanches during the period of study. The CART model provided a good probability for predicting non-avalanche, or minor years (0.67). The correct classification of major avalanches was only fair (0.53). The lack of high quality climate data and the absence of snow pack information may have prohibited obtaining a higher classification probability for major avalanches. The model, however, may help substantiate explanations of avalanche formation and initiation in the intermountain region, or serve to generate alternative hypotheses for predicting major avalanche events. Avalanche professionals and land managers might use this information to augment conventional strategies for protection, forecasting, land use planning and management. This information also has broad ecological implications increasing our understanding of major avalanches as important disturbances of intermountain alpine and subalpine ecosystems.

Keywords: snow avalanches, intermountain climate, tree-ring analyses, disturbance ecology

1. Introduction

Snow avalanches commonly occur in mountains of the intermountain region. The complexity of interactions between topography, weather, and the existing snowpack structure makes understanding avalanche occurrence difficult, particularly in intermountain locations because winters often embody characteristics of both maritime and continental climates (Roch 1949, LaChapelle 1966, Armstrong and Armstrong 1987, Mock and Birkeland 2000).

Investigations of factors contributing to major avalanches in the intermountain region have often been limited in scope. Studies have either examined one event that occurred during an exceptional season, or several events that occurred in one locality (Mock and Kay 1992, Birkeland and Mock 2001). Many avalanche events selected for study were also triggered artificially, or occurred in paths that experienced regular avalanche control. Control measures within ski areas or transportation corridors can influence the frequency and magnitude of avalanche events in affected paths (Jenkins and Hebertson 1994, Jenkins and Hebertson 1998).

Few studies have attempted to explore factors associated with major avalanche events that occurred naturally within a certain geographic area over a relatively long temporal scale. Problems limiting this research are the lack of remote sites with long-term, contiguous weather and snow pack data and historical documentation. Various numerical techniques and computer models may be used to rectify weather records, estimate missing values or infer values for remote sites from existing weather data. A number of snow pack prediction models have been developed and used primarily for hydrologic purposes, although some do address snow pack properties and processes. In the absence of historical records, few methods provide a reliable means for deriving chronologies of naturally occurring avalanches.

Dendro-ecology is one method that has proven useful for constructing avalanche chronologies of undocumented paths (Burrows and Burrows 1976, Bryant et al. 1989, Jenkins and Hebertson 1994). Trees growing in avalanche paths

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respond to damage in several ways thus providing a record of avalanche events. Dendro-ecological methods utilize tree ring analyses along with the examination of scars, reaction-wood formation, suppressed growth and other indicators of avalanche damage to date avalanche events. The ability to date avalanche events also allows one to calculate other information for avalanche paths including avalanche frequencies, return intervals and maximum runout distances.

The purpose of our research was to construct chronologies of natural avalanche events for a number of paths on the Wasatch Plateau in south-central Utah utilizing dendro-ecological methods. These avalanche chronologies were then used to date the occurrence of major avalanche events across the Plateau during the period of record. We next examined associations between the occurrence of major avalanches events and historic climate data for the area including temperature, precipitation, snowfall and hydrologic variables.

2. Methods

2.1. Dendro-ecological Analyses

The study area encompassed the southern portion of Wasatch Plateau. Using topographic maps and aerial photographs over 50 avalanche paths within the study area were identified. Of these, 16 paths were selected for sampling based on their accessibility and the apparent absence of other disturbances (landslides, rock avalanches, fire, timber harvesting). The expected maximum extent of avalanche runout was delimited on topographic maps and aerial photographs for each sample path. Increment cores and scar samples were removed from conifers greater than 13 cm diameter at breast height (1.37 m) growing within the flanks and runout zones of each path. An increment core, or disk was also removed from the base of new vertical stems to determine their age. Trees exhibiting evidence of damage or stress induced by agents other than snow avalanches were not sampled.

Increment core and scar samples were prepared and analyzed according to the basic principles described extensively in other literature (Fritts 1966, Stokes and Smiley 1968, Burrows and Burrows 1976). Each sample was examined for years of atypical growth responses including reaction-wood formation, narrow ring series and scars. Years of potential avalanche events were determined by counting the annual rings, beginning with the outermost ring, inward to rings exhibiting the initiation of atypical growth responses or scars. The age of new vertical stems was determined by counting the annual rings inward to the pith. Years determined from all samples collected from each avalanche path were graphed on a modified skeleton plot after Schroeder (1978).

To help minimize potential sources of dating error, increment cores were extracted from large, damage-free spruce, subalpine fir and limber pine growing on sensitive sites in forests adjacent to avalanche paths and used to develop a master tree-ring chronology. The purpose of the master chronology was 1) to determine if atypical growth responses observed in tree samples might be attributed to climate, and 2) to cross-date samples with false, or locally absent tree rings. Modified skeleton plots derived from tree samples were compared with the master tree-ring chronology and historical climate records. Atypical growth responses potentially resulting from confounding factors were disregarded as avalanche event responses.

Methods of cross replication were used to validate potential avalanche events for both within tree samples and samples collected from each path. Samples that did not have sufficient event replication, or were too difficult to decipher were eliminated from further analyses. Replicating avalanche events were summed between all samples collected from a path to date avalanche years.

Because few old trees survived to record earlier events the number of responses decreased backward in time making the verification of early avalanche events difficult. To reduce this problem, an index number at year t was calculated after Schroder (1978) to weigh the number of event responses in any given year according to the number of trees providing the record for that year. The formula is given as:

$$\left(\sum_{i=1}^{n} R_t\right) / \left(\sum_{i=1}^{n} A_t\right) \bullet 100 = I_t$$

where R is the event responses for year t (not more than one per year per tree per year) and A is the number of sampled trees alive in year t. Using index numbers calculated for each year a graph was produced for each path to help verify the occurrence of earlier avalanches (Schroder 1978). The modified skeleton plot (Figure 1) for North Black Mountain illustrates how the dates of avalanche events were derived using these methods.

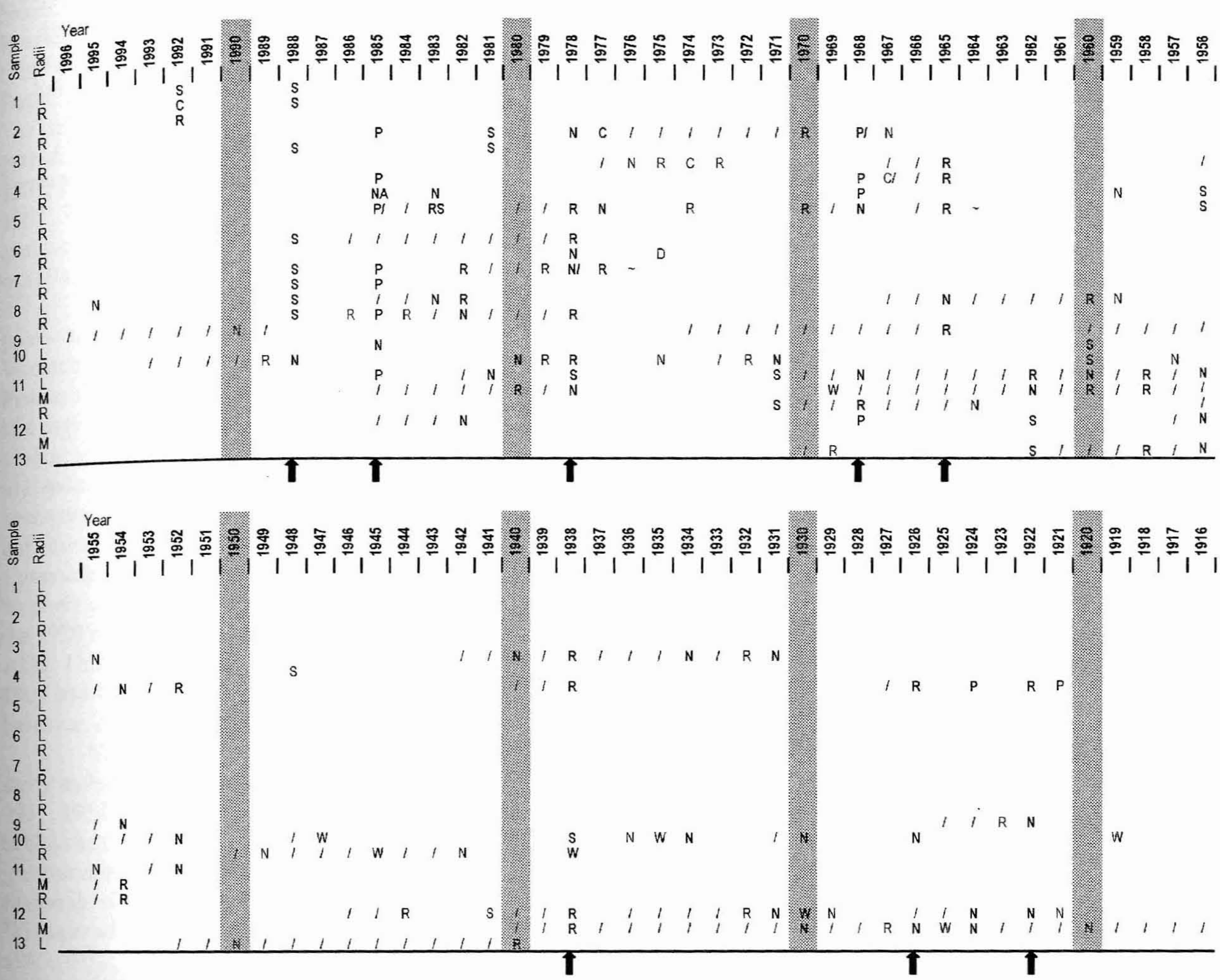

Figure 1. The modified skeleton plot constructed for the North Black Mountain avalanche path. The arrows indicate avalanche years. R=reaction wood; S=scar; N=narrow ring; C=corrasion; W=wide; D=dark ring; P=rupture; A=locally absent ring; / = continued response.

2.2. Distinguishing Major Avalanche Events

The distinction between major avalanche events and cycles and those of less magnitude was based upon two assumptions. First, extensive tree damage caused by major avalanches would result in a proportionately greater number of event responses recorded in each path during a given year. Second, major avalanche cycles would most likely affect a larger number of paths across the Plateau. Weighted index values similar to those above were calculated for each year from the total number of event responses recorded in all paths and for the total number of paths affected in a given year. A graph of avalanche and path indices for each year is given in Figure 2. These indices were then used to rank the magnitude of avalanche events that occurred during the period of record. The avalanche rankings for each year are given in Table 1.

2.3. Climate Data

Historic weather data from Manti, Utah were used for climate analyses. Variables selected for analyses included mean precipitation, snowfall and temperature for the months of October through May, from 1928–1996. These data were also used to derive seasonal values for temperature, precipitation and snowfall for the same period of record. Fall included the months of October and November, winter, the months of December, January, and February and spring, the months of March, April and May. Mean precipitation and snowfall values for each season were summed, while mean temperature values were averaged. Snowmelt reflected by stream discharge data (United States Geological Survey) measured in cubic meters per second was used to provide a surrogate for snow water content during the period of record. These data might also provide some insight into relative annual snow depths and seasonal freeze-thaw cycles. Mean values for the months of October through May, from 1928–1996 were selected to correspond with the Manti climate data. Since snowmelt might occur through early summer, mean monthly values for June and July and total spring discharge were also analyzed. Although wind loading and slab formation often contribute to the initiation of avalanches, historic records for wind speed and direction were unavailable for analyses. A classification and regression tree analyses (CART) (Brieman et al. 1984, Steinberg and Colla 1997) was used to predict the occurrence of major avalanche events from climate data.

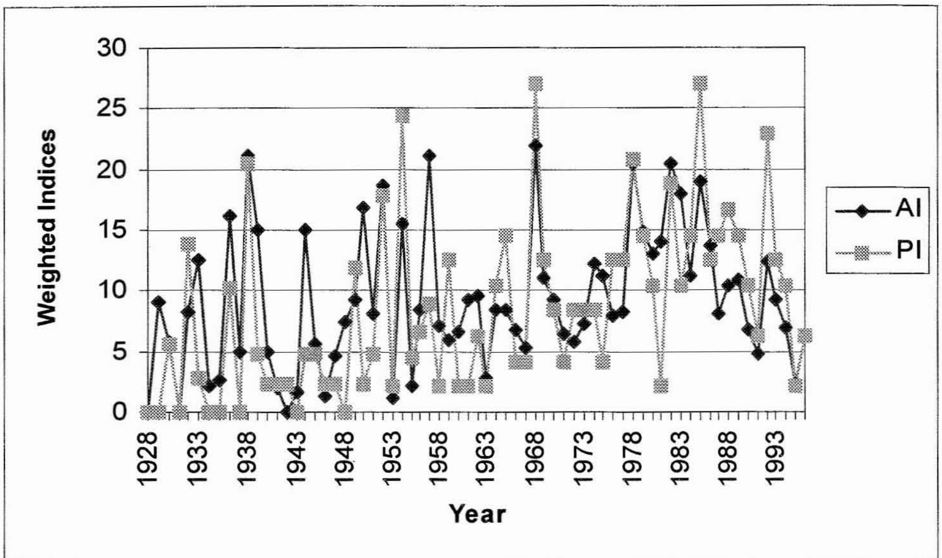

Figure 2. A graph of avalanche and path indices for years between 1928 and 1996.

Table 1. Avalanche ranks for years from 1928 – 1996.

Rank	Year	Rank	Year	Rank	Year	Rank	Year	Rank	Year	Rank	Year	Rank	Year
1	1968	11	1983	21	1932	31	1959	41	1972	51	1958	61	1941
2	1985	12	1988	22	1993	32	1970	42	1951	52	1929	62	1946
3	1938	13	1936	23	1949	33	1994	43	1996	53	1960	63	1953
4	1978	14	1986	24	1977	34	1990	44	1930	54	1948	64	1935
5	1954	15	1984	25	1974	35	1981	45	1961	55	1940	65	1942
6	1982	16	1989	26	1976	36	1962	46	1991	56	1947	66	1934
7	1952	17	1969	27	1939	37	1973	47	1966	57	1955	67	1943
8	1992	18	1980	28	1944	38	1975	48	1971	58	1937	68	1931
9	1957	19	1965	29	1950	39	1933	49	1945	59	1963	69	1928
10	1979	20	1987	30	1964	40	1956	50	1967	60	1995		

3. Results

3.1. Dates of Major Avalanche Years

Increment cores, scars and other samples were collected from 297 trees in the 16 avalanche paths on the Wasatch Plateau. Reaction wood formation, narrow rings, scars and other event responses were evident in over 90 % of the trees sampled. The earliest event response was dated to 1861 providing an avalanche chronology of 135 years for the Plateau. Early dates lacked sufficient cross replication precluding them from further analyses in this study. Many dates, however, coincided with early avalanches dated from chronologies constructed for paths in northern Utah (Jenkins and Hebertson 1994, Jenkins and Hebertson, *unpublished reports*) and historic documents (Kalatowski 1988). These chronologies included No Name in Snowbasin, Nordic Knob in Park City, Little Pine East, Ben Hame, Culp's West Hellgate, East Hellgate all in Little Cottonwood Canyon, Grey's Cliff in American Fork Canyon and Bridal Veil Falls in Provo Canyon. The earliest avalanches on the Wasatch Plateau potentially occurred during the winters of 1870, 1871, 1875, 1883, 1885, 1893, 1898, 1901, 1906 and 1907[1]. Several chronologies indicated that avalanches were particularly widespread across Utah in 1898, 1906 and 1907.

During the period from 1910 to 1920, potential avalanche activity was relatively high on the Wasatch Plateau. Several samples from the Wasatch Plateau recorded event responses in 1911, the 1912 that may coincide with large and widespread avalanches reported in northern Utah. The 1916 avalanche was verified by an account from a historic newspaper clipping (The Park Record, volume unknown) and is also evident in four northern Utah chronologies. The years with relatively large numbers of event responses through the first half of the 1920's were 1924 followed by 1921, 1922, and 1926. Only one other chronology substantiated the 1924 and 1926 dates. Several chronologies, however, dated avalanches in 1921 and 1922.

Major avalanche years during the period of study included 1992, 1985, 1982, 1979, 1978, 1968, 1957, 1954, 1952, 1944 and 1938 as determined by avalanche ranks (Table 1). The year of 1968 had the greatest number of verified event responses relative to sample size followed by 1957 and 1982. Widespread avalanching was most evident in 1968, 1985, 1954, 1957 and 1992. Of the above years, avalanches in 1938, 1944, 1952, 1978, 1992 were considerably substantiated by the northern Utah chronologies and historic documents. Other years on the Wasatch Plateau with a relatively high avalanche rank were 1983, 1988, 1936, 1986, 1984, 1989, 1969, 1980, 1965 and 1987. Seven avalanche chronologies, in addition to Utah Department of Transportation records substantiated the 1965 avalanche event. The 1986 avalanche was dated in three chronologies and also widely documented (BRAIC, *unpublished report*, Birkeland and Mock 2001).

3.2. Associations Between Major Avalanche Years and Climate

Classification and regression tree analyses used to examine associations between major avalanche events and climate variables produced the classification tree given in Figure 3. The best CART model used November snowfall, June discharge and January snowfall to optimize the splitting of avalanches events. The values at which CART split each variable were 7 cm, 8 m^3/s and 36 cm for November snowfall, June discharge and January snowfall, respectively. Cross validation classification probabilities (Table 2) indicated that model had a good probability (0.67) of correctly classifying non-avalanche, or minor avalanche years. The probability of correctly classifying major avalanches, however, was only 0.53.

4. Discussion and conclusions

4.1. Predicting Non-avalanche and Minor Avalanche Years

Both the model variables and splitting values CART used for partitioning were considered reasonable, particularly for predicting non-avalanche and minor avalanche years. These years would likely result from generally low seasonal precipitation, or snowfall. The lack of November snowfall might also infer the development of a generally dry seasonal pattern. When compared with seasonal data, 65% of years with either below average snowfall, or precipitation had < 7 cm of mean November snowfall. The splitting values of June discharge (< 8 m^3/s), and its primary surrogate, mean May discharge (6.3 m^3/s) also suggest below average snow packs during these years possibly resulting from drier-than-normal winters.

Unlike the other model variables the splitting value of mean January snow (36 cm) was relatively high. Mean January snowfall data, however, was skewed toward higher values resulting from several exceptional years. Examination of the seasonal climate data revealed that 81% of years with < 36 cm of mean January snowfall occurred during years with below average snowfall or precipitation. This might suggest that mid-winter storms produced insufficient quantities of snowfall, or precipitation to initiate sizable avalanches during non-avalanche and minor avalanche years. November snowfall alone, however, was not sufficient for predicting all non-avalanche or minor avalanche years.

4.2. Predicting Major Avalanche Years

The CART model was only fair (0.53) at correctly classifying major avalanches on the Wasatch Plateau. The lack of high quality climate data and the absence of snowpack information may have prohibited obtaining a

[1] For clarity of discussion, all dates comprise months from fall of the prior year through spring of the given year.

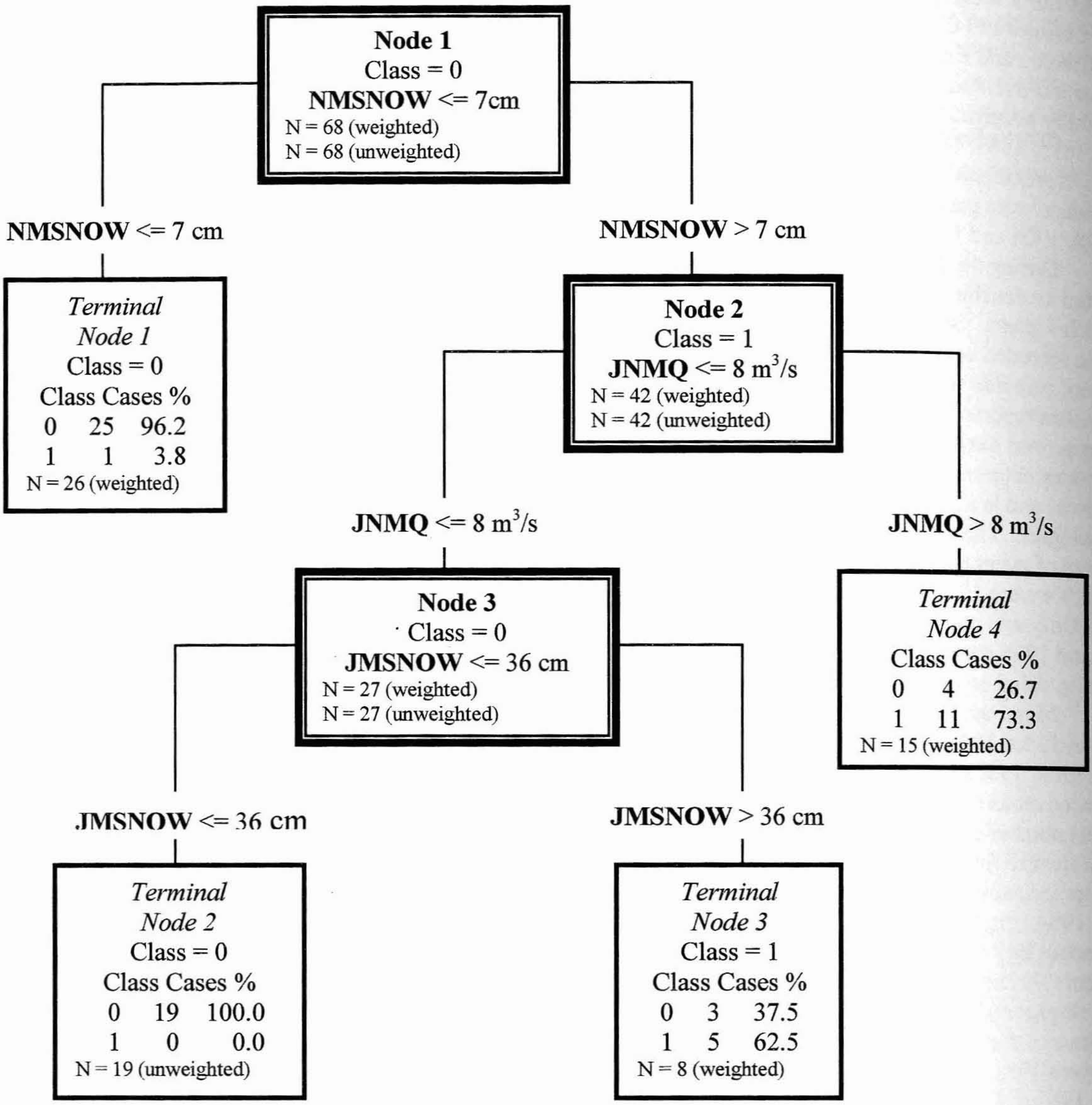

Figure 3. The CART model showing the climate variables and associated splitting values selected to optimize the partitioning of avalanches events. NMSNOW = mean November snow; JNMQ = mean June discharge; JMSNOW = mean January snow.

Table 2. Cross validation classification probability table.

	Predicted Class		
Actual Class	0	1	Actual Total
0	0.667	0.333	1.000
1	0.471	0.529	1.000

higher classification probability for major avalanches. This result, however, may also indicate that a variety of climate patterns contribute to the formation and initiation of major avalanches in the intermountain region. In onescenario, major avalanches have been attributed to the development of unstable snow structures characteristic of continental-like climate conditions that evolve under the dominance of a ridge pattern (Armstrong and Armstrong 1987). The continental climate scenario on the Wasatch Plateau was best characterized by major avalanche years of 1932, 1954, 1974, 1988, 1989, 1992 and possibly 1936. During these years, early season snow accumulation was evident with 76% of major avalanche years having mean November snowfalls > 7 cm. Fifty two percent of these same years, however, had < 8 m^3/s of mean June discharge suggesting little subsequent snowfall and relatively low seasonal snow covers.

Major avalanches also occurred during winters characterized by generally heavy seasonal snowfall and cold temperatures. Forty eight percent of major avalanche years on the Wasatch Plateau had June discharge values > 8 m^3/s in addition to above average November snowfall. Mean January snowfall values also exceeded 36 cm during these years. The occurrence of major avalanches is more often related to intense storm events. Loading from new snow may cause slabs to fail on buried surface hoar, or near-surface faceted layers. Other factors that may cause failures include rain, wind loading and intense solar input. This scenario was best characterized by the winters of 1952, 1965, 1969, 1978, 1979, 1980,1982, 1983, 1984, 1985, 1986 and 1993.

Not all heavy snowfall years on the Wasatch plateau, however, produced major avalanches or wide spread avalanche activity. The years of 1941, 1947 and 1973 for example, all had mean June discharge exceeding 8 m^3/s combined with high seasonal snowfall values. This suggests that during some years, the right combination factors including deep snow packs and warm snow pack temperatures might have allowed for the development of stable structure.

4.3. The Implications of Major Avalanche Events

Major avalanches have great human, as well as ecological significance in the intermountain region. As the number of people living and recreating in avalanche-prone terrain rises, the probability of damage to property, structures and transportation corridors continues to increase. More importantly the annual number of avalanche fatalities has nearly doubled during the past decade. Infrequent, large avalanches also play an important role in the disturbance regimes of alpine and subalpine forests. Avalanches damage can predispose injured trees to insects and disease (Jenkins et al. 1998). Avalanche paths create natural firebreaks. Woody avalanche debris increases fuel loads and provides habitat for sensitive and endangered wildlife species. Debris deposited in streams can also adversely impact fisheries.

It has also been speculated that potential relationships exist between major avalanches and El Niño-Southern Oscillation (ENSO) events (Fox 1973). Mock and Birkeland (2000) were unable to find evidence substantiating proposed relationships. They suggested that predicting potential avalanche responses necessitates better understanding of the magnitude of seasonal climate anomalies, the intra-seasonal variability of synoptic-scale circulation and surface climatic responses and potential snow pack processes. Interestingly, 64 % of ENSO events between 1931 and 1996 were coincident, or occurred one year prior to several major avalanche years on the Wasatch Plateau. These years included 1931, 1952, 1958, 1964, 1973, 1977, 1983, 1986 and 1992. Although beyond the scope of this research, this observation might warrant further investigation.

4.4. Conclusions

With the addition of the Wasatch Plateau chronology, the range of dated avalanche events now encompasses several sites from the Wasatch Front to central Utah. Since the 1900's, avalanche chronologies and historic documents indicate that large widespread avalanches events occurred during winters of 1932, 1936, 1938, 1944, 1952, 1957, 1965, 1974, 1977, 1978, 1983, 1986, 1989, 1992. Possible years include 1948, 1946, 1954, 1961,1962, 1988 and 1996. Classification and regression tree analyses provided good accuracy for predicting non-avalanche, or minor avalanche years. The selected climate variables and associated splitting values indicated that these years likely resulted from a generally low seasonal precipitation, or snowfall. The correct classification of major avalanches was only fair. Lack of high quality climate data and the absence of snow pack information may have prohibited obtaining a higher classification probability for major avalanches. The results allude to the complex interaction of factors that contribute to major avalanche events. Examination of seasonal climate data revealed that major avalanches occurred when either continental, or maritime-like conditions prevailed. The model, however, may help substantiate explanations of avalanche formation and initiation in the intermountain region, or serve to generate alternative hypotheses for predicting major avalanche events. Avalanche professionals and land managers might use this information to augment conventional strategies for protection, forecasting, land use planning and management. This information also has broad ecological implications increasing our understanding of major avalanches as important disturbances of intermountain alpine and subalpine ecosystems.

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