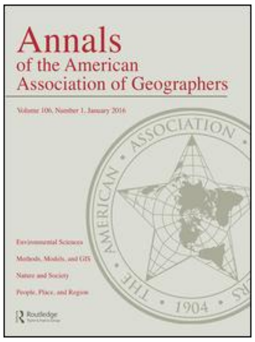

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Some Perspectives on Avalanche Climatology

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Avalanche climatology is defined as the study of the relationships between climate and snow avalanches, and it contributes in aiding avalanche hazard mitigation efforts. The field has evolved over the past six decades concerning methodology, data monitoring and field collection, and interdisciplinary linkages. Avalanche climate research directions are also expanding concerning treatment in both spatial scale and temporal timescales. This article provides an overview of the main themes of avalanche climate research in issues of scale from local to global, its expanding interdisciplinary nature, as well as its future challenges and directions. The growth of avalanche climatology includes themes such as its transformation from being mostly descriptive to innovative statistical methods and modeling techniques, new challenges in microscale efforts that include depth hoar aspects and increased field studies, expanding synoptic climatology applications on studying avalanche variations, efforts to reconstruct past avalanches and relate them to climatic change, and research on potential avalanche responses to recent twentieth-century and future global warming. Some suggestions on future avalanche climatology research directions include the expansion of data networks and studies that include lesser developed countries, stronger linkages of avalanche climate studies with GIScience and remote sensing applications, more innovative linkages of avalanches with climate and societal applications, and increased emphases on modeling and process-oriented approaches. *Key Words: avalanche climatology, microclimatology, snow science, spatial scale, synoptic climatology.*

雪崩气候学定义为气候和雪崩之间的关係之研究，并对于增进雪崩灾害减轻的努力做出贡献。该领域中的方法论、数据监控、田野搜集和跨领域连结，在过去六十年来已有所进展。雪崩气候研究的方向，在处理空间尺度和暂时的时间尺度上亦有所扩张。本文提供了雪崩气候研究在从地方到全球尺度，其扩张中的跨领域本质，及其未来的挑战和方向等重大议题之概要。雪崩气候学的成长，包含了诸如从多半为描述性到创造性的统计方法和模式化技术之变革，包含雪中白霜面和增加的田野研究之微观尺度努力的挑战，扩张的天气气候学在研究雪崩变异性方面的应用，重建过往雪崩并将其连结至气候变迁的努力，以及对于晚近二十世纪和未来全球暖化的潜在雪崩回应之研究等主题。对于未来雪崩气候学研究方向的若干建议，包含扩大数据网络与含纳第三世界国家的研究，雪崩气候研究和 GIS 科学与遥测应用之间更为强大的连结，雪崩与气候和社会应用之间更为创新的连结，以及更为强调模式化和以过程为导向的方法。*关键词：雪崩气候学，微气候学，雪科学，空间尺度，天气气候学。*

La climatología de avalancha se define como el estudio de las relaciones entre el clima y las avalanchas de nieve, y contribuye en los esfuerzos de mitigación por los riesgos de aludes. Esta especialidad ha evolucionado durante las pasadas seis décadas en lo que se refiere a metodología, monitoreo y recolección de datos de campo, y vínculos interdisciplinarios. Las direcciones de la investigación sobre clima de avalancha también se están ampliando en lo que concierne al tratamiento del problema a escalas espacial y temporal. Este artículo suministra una visión de conjunto de los temas principales de investigación sobre clima de avalancha en aspectos relacionados con la variación de escala de lo local a lo global, su naturaleza interdisciplinaria en expansión, lo mismo que sus retos y direcciones futuras. El crecimiento de la climatología de avalancha incluye temas como su transformación de ser principalmente descriptiva al uso de métodos estadísticos innovadores y técnicas de modelado, nuevos desafíos en los esfuerzos a microescala que incluyen aspectos de escarcha de profundidad y más estudios de campo, expandiendo las aplicaciones de climatología sinóptica al estudio de variaciones de las avalanchas, esfuerzos para reconstruir avalanchas pasadas para relacionarlas con cambio climático, e investigación sobre avalanchas potenciales en respuesta al reciente calentamiento global del siglo XX y hacia el futuro. Algunas sugerencias sobre direcciones futuras de investigación en la climatología de avalancha incluyen la expansión de redes de datos y estudios que incluyan a los países menos desarrollados, vínculos más fuertes de los estudios de clima de avalancha con la ciencia de los SIG y aplicaciones de percepción remota, vínculos más innovadores de los estudios de avalanchas con aplicaciones climáticas y sociales, y un mayor énfasis en el diseño de modelos y en enfoques orientados a proceso. *Palabras clave: climatología de avalancha, microclimatología, ciencia de la nieve, escala espacial, climatología sinóptica.*

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Avalanches are a dangerous natural hazard in mountainous regions worldwide, killing hundreds of people annually. Avalanche victims in less developed countries tend to be killed by large avalanches descending into villages or onto roads. Exact fatality numbers are hard to ascertain in these areas, but fatalities from well-documented avalanche cycles in these countries occasionally number in the hundreds. Although less frequent, such avalanche deaths also occur in developed countries such as in the European Alps, occasionally involving accidents with many dozens of deaths. Zoning efforts over most developed areas ensure that such incidents are relatively rare. Some areas, though, like Juneau, Alaska, still have high population densities living in avalanche-prone areas and are threatened by nearby large avalanche paths.

Avalanche victims in developed countries are primarily people recreating on skis, snowboards, snowmobiles, and snowshoes, and they typically trigger the avalanches that kill them. Europe and Canada have about fifty and fifteen victims annually, respectively. Twenty-five to thirty people are killed in avalanches annually in the United States, a number that has stayed consistent since the early 2000s (Figure 1). Dangerous avalanche conditions routinely close highways, causing sizable economic impacts. For example, an avalanche closure of Little Cottonwood Canyon near Salt Lake City, Utah, affected approximately 10,000 automobiles per day in the early 1990s (Blattenberger and Fowles 1995; Figure 2), and the number of affected automobiles and associated economic costs are much higher today.

Climate acts as a background condition that characterizes snowpack conditions that can cause different types of avalanching, and seasonal-to-daily weather conditions are the primary drivers for large avalanche cycles. The application of climate and weather data as a first trigger for understanding snow avalanche activity has been routinely conducted by scientists dating back to the earlier twentieth century (Seligman 1936) and was coined *avalanche climatology* initially by R. L. Armstrong and Armstrong (1987) and popularized by Mock and Kay (1992). Avalanche climatology deals with a range of timescales from daily to decadal. In recent decades, climatologists have studied climatic processes related to various environmental responses in more detail, linking information from various space scales to gain a more holistic knowledge of climate system components. This article describes the historical developments of avalanche climatology in recent decades, emphasizing issues of spatial scale from local to regional, growing interdisciplinary aspects, and some suggestions for future directions.

Avalanche Climatology at Local and Microscales

Prior to the mid-1900s, research involving weather as an important control on avalanche activity was mostly locally applied with a forecast emphasis. This research was basically descriptive, supplemented by some field observations. As longer and more numerous mountain weather and avalanche records became available in the 1970s for many mountain settings around the world (Beniston, Diaz, and Bradley 1997), statistical quantification became more common. These methods initially focused on basic bivariate analyses to identify important weather variables associated with avalanching at certain locations, like heavy precipitation and wind speed (Perla 1970). The statistical techniques employed for local avalanche forecasting eventually evolved to more multivariate and later more nonparametric approaches (e.g., Föhn et al. 1977; Davis et al. 1999; McCollister et al. 2003; Hendrikx, Murphy, and Onslow 2014). Supplemental nonstatistical approaches on avalanche forecasting, using increased understanding of snowpack processes gathered from field data, continued as demonstrated by Fitzharris (1976) for Mt. Cook in New Zealand and Conway and Raymond (1993) for the Pacific Northwest of the United States. Despite advances in statistical techniques, avalanche forecasting today continues to rely largely on conventional techniques (LaChapelle 1980), although methods of remote data collection and data sharing (Stethem et al. 2003) have expanded dramatically in the past thirty-five years. Climatologically, coastal locations might rely more heavily on weather data for avalanche forecasting, whereas intermountain and continental zones require careful analysis of existing snow structure (LaChapelle 1966, 1980). Ultimately, conventional avalanche forecasting requires the consideration of all factors, regardless of the climate zone.

The formation of snow is influenced by many meteorological variables that are changing constantly in time and space (Nakaya 1954; Libbrecht 2005). Each storm is unique in its temperature, humidity, wind speed, turbulence, and other factors; thus, each snowfall deposits a unique layer. Once on the ground, these layers further differentiate due to rapid snow

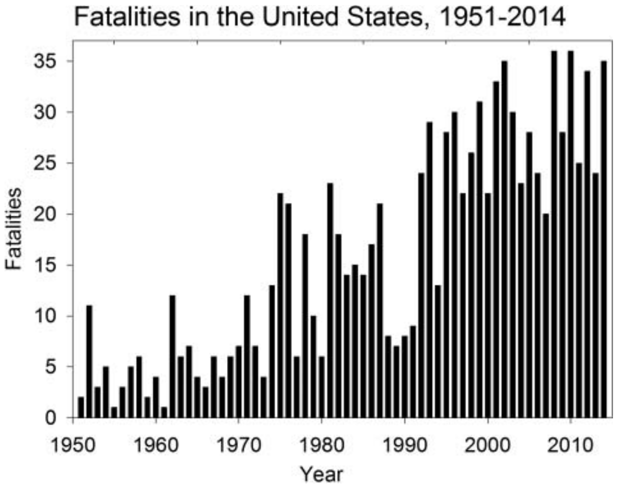

Figure 1. Avalanche fatalities of the United States from 1951 to 2014.

metamorphism (Fierz et al. 2009), and the nature of these layers ultimately determines the avalanche danger. When snow falls in mountainous terrain, micrometeorological processes significantly influence both the snow surface and the subsurface snow. This emphasizes the importance of addressing different spatial scales when studying avalanche climatology. Limited work has been completed to address the micrometeorological influences on avalanche activity, due to the challenging nature of researching constantly changing snow packs. The research that has been done is also geographically limited to British Columbia (Colbeck, Jamieson, and Crowe 2008; Bellaire and Jamieson 2013; Horton, Bellaire, and Jamieson 2014), Davos, Switzerland (Stossel et al. 2010; Reuter et al. 2015), and northern Wyoming and western Montana (Birkeland 2001; Kozak et al. 2003; Slaughter et al. 2009) and not necessarily representative of all avalanche-prone areas.

One of the most important formations on top of the snow surface from an avalanche perspective is that of surface hoar (Figure 3). The winter equivalent of dew, surface hoar is feathery or solid crystals that grow upward with formation typically taking place overnight during clear, calm, and relatively humid conditions (Colbeck 1988). Once buried by subsequent snowfall, surface hoar creates a thin, dangerous, and persistent weak layer. Indeed, Jamieson and Johnston (1992) reported that surface hoar was present in 50 percent of avalanche accidents involving professionals. The difficult assessment of surface hoar instability is amplified further by its variable distribution pattern across an already inconsistent mountain terrain, in terms of both surface hoar formation and its persistence until burial (Lutz and Birkeland 2011; Helbig and van Herwijnen 2012).

Figure 2. A large avalanche descends Mount Superior in Utah's Little Cottonwood Canyon. (Color figure available online.)

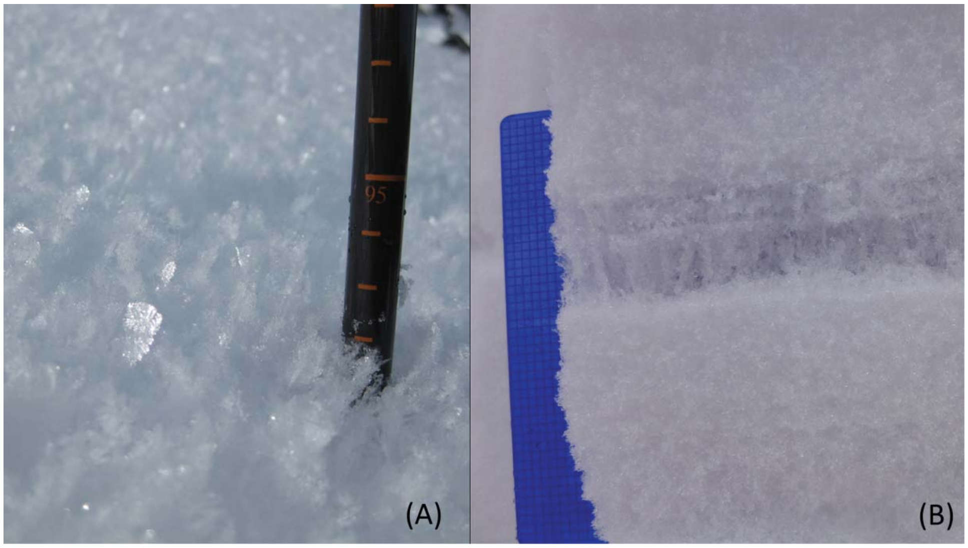

Figure 3. Surface hoar (A) is typically composed of feathery crystals (probe markings are 1 cm) and (B) creates a dangerous weak layer when buried (grid size is 2 mm). (Color figure available online.)

Spatial variations of surface hoar growth have been modeled based on terrain characteristics (Helbig and van Herwijnen 2012), weather models (Bellaire and Jamieson 2013; Horton, Bellaire, and Jamieson 2014), and laboratory experiments (Slaughter et al. 2009). Other surface hoar research includes tracking the hardness of snow layers (Kozak et al. 2003), a direct comparison between eddy flux measurements of moisture transport and surface mass changes (Stossel et al. 2010), and examining turbulence, vapor pressure, and solar radiation influences of surface hoar growth at the microlevel (Colbeck 1988). The lack of fine-scale micrometeorology measurements on the snow surface challenges our ability to track surface hoar growth and persistence over a wider spatial extent.

Regional Avalanche Climatology and Synoptic Climatology

Some research focuses on surface avalanche and weather conditions at longer regional and temporal scales. Compared to conventional climatology research, avalanche climatology studies are mostly restricted to time frames of no more than a few decades per location, given the paucity of upper elevation data near avalanche paths. Climate is generally viewed as statistical mean characteristics of weather series under steady-state conditions, and many studies use this steady-state concept. These steady-state characteristics could vary within longer timescales, however, thus placing the concept of avalanche climatology quite differently when assessing consequences of climate change on avalanche activity.

Regionalization of three main avalanche climates of the western United States, initially based on field observations, have long been recognized to exist, representing generally a west–east gradient: the coastal, intermountain, and continental (LaChapelle 1966). This zonation provides a general framework for understanding how climatic variables influence avalanche activity. The coastal zone is characterized by abundant snowfall, higher snow densities, warmer temperatures, and a higher frequency of avalanches. The continental zone is characterized by cooler temperatures, lower snowfall, lower snow densities, and extensive faceted crystal growth resulting from high temperature gradients in the snowpack. Relatively lower numbers of avalanches occur in the continental zone, but this zone has a higher avalanche hazard potential due to difficulties in predicting the behavior of buried faceted crystals (Birkeland 1998). The intermountain zone is intermediate between the other two types. R. L. Armstrong and Armstrong (1987), Fitzharris (1981), McClung and Tweedy (1993), Mock and Kay (1992), Mock (1995), Mock and Birkeland (2000), and Haegeli and McClung (2003) further documented similar climate zones over western North America. Some studies used multivariate statistics for classification (e.g., Mock 1995), whereas some had more of a qualitative–quantitative mixture such as a decision trees approach (Mock and Birkeland

2000). Hackett and Santeford (1980) mapped Alaska in a similar avalanche climate classification, based mostly on field observations. Recently, Ikeda et al. (2009) extended Mock and Birkeland's (2000) classification approach for analyzing the avalanche climate of Japan.

Operational avalanche forecasting has a long traditional synoptic meteorological component dating back to the advent of detailed daily synoptic weather maps in the mid-twentieth century. This component links daily synoptic-scale circulation patterns to big avalanche events, some of which are in governmental reports. Published studies on this approach include those by Birkeland and Mock (1996) for Bridger Bowl, Montana; Fitzharris (1981) for Rogers Pass, British Columbia; Calonder (1986) and Hächler (1987) for the Swiss Alps, which involve the application of daily Grosswetterlagen synoptic types to avalanche activity; Rangachary and Bandyopadhyay (1987) for the Himalayas; and Gürer et al. (1995) on an avalanche case study for northwest Anatolia, Turkey.

An avalanche climate provides an idea of the avalanche problems faced in a certain area. The concept of avalanche climate is especially important during exceptional years or when climate changes. As discussed in Mock and Birkeland (2000), an area in a coastal avalanche climate might occasionally have a year with a continental avalanche climate (drier and colder than normal) and during that year they would anticipate having avalanche problems characteristic of more continental locations such as full-depth avalanches failing on depth hoar. Most avalanche and synoptic climate studies conducted to date are based on using avalanche extremes to study synoptic patterns (surface-to-circulation approach), although Mock and Birkeland (2000) and Birkeland and Mock (2001), in a few examples, used a circulation-to-surface approach to map surface avalanche climate variations for selected years. Fitzharris and Bakkehøi (1986) mapped synoptic patterns and used circulation indexes to explain major avalanche winters in Norway, and Fitzharris (1987) employed a similar approach to study major avalanche winters at Rogers Pass, British Columbia. Mock and Kay (1992) and Mock (1995, 1996) defined avalanche extremes at the surface using multivariate statistical methods on surface avalanche and weather data to then employ synoptic composite anomaly maps linked to avalanche extremes for areas in the western United States and southern Alaska. Birkeland, Mock, and Shinker (2001) expanded on this type of approach for the intermountain west but based surface avalanche extremes from a daily avalanche index based largely on size and compositing NCEP-Reanalysis data products for studying synoptic patterns. Hansen and Underwood (2012) demonstrated a comprehensive synoptic approach as related to large avalanches at Mt. Shasta, California, using synoptic composites, soundings, and trajectory models.

Some papers have addressed possible linkages between teleconnections and avalanche activity. Keylock (2003) illustrated that positive phases in the North Atlantic Oscillation can lead to increased storms and major avalanche events in Iceland, but this association is not always consistent. McClung (2013) and Dixon et al. (1999) suggested linkages between La Niña and El Niño with avalanche activity in parts of northwestern North America, with La Niña causing more snow and avalanches. McClung's (2013) results, however, are marginally statistically significant via *t* tests and failed to closely address different strengths and character of individual El Niño Southern Oscillation (ENSO) events, as well as weekly to daily weather variations within individual ENSO winters. Reardon et al. (2008) suggested possible Pacific Decadal Oscillation (PDO) signals from avalanche data at longer timescales, with linkages with decadal climate and avalanches that remain weak.

More Interdisciplinary Aspects

Proxy data, as commonly used in paleoclimatology, have similarly been used for reconstructing avalanche activity prior to modern records. Historical documents have been used to compile avalanche histories, although the subjectivity and sporadic availability of historical data through time have made reliable continuous reconstructions difficult to relate with climate. B. R. Armstrong (1977) used historical data to compile a continuous time series of avalanche fatalities for Ouray County, Colorado, back to the late nineteenth century and made broad inferences on an active avalanche period around the 1880s that was potentially linked to climate change. Butler (1986) used newspapers from Glacier National Park, Montana, to reconstruct avalanche events and attributed them to large-scale atmospheric circulation patterns. The most comprehensive historical avalanche reconstructions come from Europe, which has longer written histories. Laternser and Pfister (1997) demonstrated that severe avalanche winters can be reconstructed from documentary data extending back 500 years. They also attributed many of these extremes to synoptic patterns that similarly appear in the more recent modern record. Hétu, Fortin, and Brown (2015) analyzed a mixture of documentary and meteorological data as well as maps and photographs to compile an avalanche history of the Québec City region dating back to the early 1800s. They attributed increased avalanche activity at the end of the nineteenth century to increased snowfall, but land use and reforestation also played important roles variably with time.

Some research has reconstructed avalanche activity from tree rings sampled in avalanche paths and cross-dated, assuming that suppressed tree growth immediately following avalanche occurrence can be reliably assessed (e.g., Muntán et al. 2009). These potential avalanche responses can be clarified through comparisons with tree-ring records outside avalanche paths. Viewpoints on how these tree ring reconstructions of avalanches specifically relate to climate varies among different environments, as tree-ring response is limited to within the avalanche path and also relates largely to additional nonclimatic factors. For example, Rayback's (1998) tree-ring study on avalanches for the Colorado Front Range indicated avalanche magnitude in relation to climate is limited mostly to large avalanche extremes, such as the severe avalanche winter of 1985–1986. Hebertson and Jenkins (2003) described similar results through their tree-ring reconstruction from south-central Utah. Historical data have also been used for verifying tree-ring avalanche reconstructions, as demonstrated by Carrara (1979) for Ophir, Colorado, and Butler (1986) for northwest Montana. Corona et al. (2012) provided a tree-ring reconstruction of avalanches from the French Alps back to 1338 AD and attributed some linkages of avalanche activity with annual-to-decadal temperature variability through the Little Ice Age. Schläppy et al. (2016) further studied the French Alps record via logistic regression approaches, demonstrating that their tree rings can reveal some climate signals.

Few studies have addressed snow avalanche variations related to recent climatic changes at regional to hemispheric scales, including forcing mechanisms such as prominent large-scale cycles and those related to potential global warming. Fitzharris (1981), building on previous work by Touhinsky (1966), synthesized long-term avalanche records dating back to the early twentieth century spread out in the Northern Hemisphere. He found no clear linkages of avalanche activity with solar cycles. Glazovskaya (1998) suggested linkages of climatic change governing spatial patterns of avalanche variability to the global scale, urging the need to incorporate variables of snowfall, snow days, and snow depth, but ideas were generalized.

Schneebeli, Laternser, and Ammann (1997) addressed varying long-term avalanche data quality for Switzerland as hampering efforts to detect signals related to recent large-scale warming trends. Eckert, Baya, and Deschatres (2010), later expanded by Eckert et al. (2010), applied a hierarchical modeling framework to study the spatiotemporal variability of avalanche occurrences in the northern French Alps and found no clear relation to climate trends but did find a decreasing trend probably related to avalanche runout for recent decades. Castebrunet, Eckert, and Giraud (2012) used a more detailed northern French Alps data set from 1958 to 2009 and a time-explicit model to specify climate signals. They found that avalanches at low frequencies were weakly related to temperature increases. They also found a second avalanche signal that relates to decadal variations of cold and snowier conditions. Lazar and Williams (2008) provided a local example for Aspen Mountain, Colorado, applying general circulation and regional model output to snowmelt runoff and snow quality models in forecasting wet avalanche activity. They suggested that by 2030, wet avalanches at higher elevations will occur from two to nineteen days earlier than today's climate and sixteen to twenty-seven days earlier at lower and middle elevations. Castebrunet et al. (2014) expanded on their previous work on the French Alps, conducting statistical downscaling techniques to predict avalanche activity for the 2020 to 2050 and 2070 to 2100 periods. They imply a general decrease of 20 to 30 percent of avalanche activity as well as interannual variability in the future but an increase of wet snow avalanches at higher altitudes in midwinter.

Conclusions

Several important developments on avalanche climatology are apparent (Figure 4). Due to increased data collection, technology, and data sharing, there has been increased sophistication in research concerning statistics and other methods. An increase in field and local studies concerning snow science is apparent, and this is being supplemented with more studies at larger spatial scales. Avalanche climate and related research is only prominent at a small number of academic and research centers; it also largely involves the

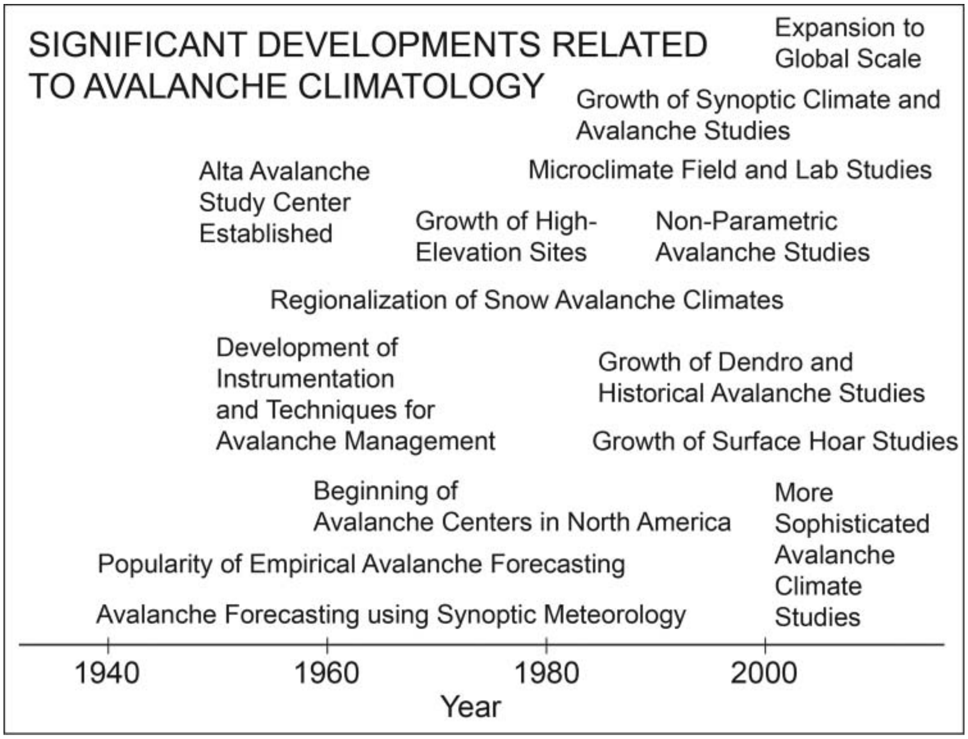

Figure 4. Timeline of important events related to avalanche climatology from 1940 to present.

applied community of avalanche practitioners such as avalanche forecasters, ski patrollers, and guides.

Several avenues exist for expanding future research involving climatology and avalanches. First, avalanche climate research to date has rarely been largely involved in GIScience applications, particularly considering climate variability. Most GIScience studies on avalanches use digital elevation models, vegetation, and basic snowfall parameters for mapping avalanche hazard zones. Some studies, particularly those from Switzerland, clearly demonstrate GIScience potential for incorporating more of a climate component (e.g., Schweizer, Mitterer, and Stoffel 2009), and this might be more important in future developments to link dynamical modeling of avalanches with climate variability and perhaps climate model output. Remote sensing might eventually become a major tool in avalanche climatology. Such applications have been useful in detecting avalanche occurrence (Eckerstorfer et al. 2016) and for surface hoar, which might relate to triggering of weak slab avalanches (Bühler, Meier, and Ginzler 2015).

Furthermore, future directions involve more research studying avalanches and climates that also includes lesser developed countries with a high avalanche hazard. Continued improvement of high-elevation networks of climate and avalanche data, including field aspects and automated data networks, is imperative. These data sets can be used to improve and verify the continued use of statistical and dynamical modeling perspectives. Longer temporal avalanche climate perspectives can be expanded for prior to the mid-twentieth century, combining paleoenvironmental and historical research with newer developments from the twentieth century reanalysis project and modeling. Another interesting area for future avalanche climate research would be to integrate climate and avalanches with society. Podolskiy et al. (2014) provided an excellent example on integrating avalanche fatalities of the Sakhalin and Kuril Islands for the last century with changing land use, politics, and climate.

Avalanche climatological research has become increasingly complex, similar to many other fields of applied climatology. Future successful avalanche research should not be based solely in climate and weather determinism approaches. Avalanche climatology is an important theme for studying future mountain environments and climatic change, and this work will continue to involve scholars ranging from atmospheric scientists to geographers to snow scientists. Given the complexities on linking climate, weather, and avalanche processes at different temporal and spatial scales, successful future research must emphasize more process-oriented and modeling approaches as opposed to being engrained in basic empiricism. Supplementing process-oriented approaches with statistical techniques and mixed-method quantitative and qualitative approaches is still vital, but geographers involved in avalanche climatology should possess substantial training spanning from meteorology to snow science to successfully tackle future challenging process-oriented approaches.

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