4

Snow and avalanches

SVEN FUCHS, MARGRETH KEILER AND SERGEY SOKRATOV

4.1 Introduction

4.1.1 Snow cover

After seasonally frozen ground, seasonal snow cover has the second largest extent of any component of the cryosphere, with a mean annual area of approximately 26 million km^2, most of it located in the Northern Hemisphere [1]. In many mountain ranges snow and ice are key components of the hydrological cycle with the duration and depth of the seasonal snow cover being key climatic factors of the alpine ecosystem [2]. In mountain regions snow cover plays an important role as an economic factor (e.g. tourism, hydro-power, agriculture, etc.; [3]). Also, snow cover is a determinant of potential snow avalanches and other hazards in mountain areas [4,5].

Spatial and temporal variability of snow cover and snow depth are strongly related to regional and local precipitation patterns and temperature regimes, both parameters interacting with the terrain [6]. Changing snowpack affects subsurface temperatures and permafrost distribution, accumulation as well as ablation of glaciers and vegetation growth in the high-mountain area. The generation of runoff in the high mountains is primarily determined by snowmelt and thus by spring temperature [7], and during summer also by ice melt of the glaciated areas. For the society, especially in arid mountain regions such as the Southwestern United States or Central Asia, freshwaters from high-mountain areas are the most important perennial water resource [8]. On the other hand, a fast and early-season onset of snowmelt may lead to snowmelt-generated floods in the mountains and the lowland [9].

In a very broad and long-term perspective, snow cover is also influencing the climate through albedo. Considering the multiple interactions of snow with other

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phenomena of high-mountain areas, and their local and regional effects, it is essential to obtain a better understanding of the current and future snow cover dynamic in space and time [10]. Yet, measured and observed data regarding snow (solid precipitation, snow water equivalent, snow cover duration, snow depth) in high-mountain areas are limited. Ground-based observations of different snow parameters such as snow depth are very sparse, thus the analysis of satellite snow cover data is considered as an efficient alternative assessment method [11].

4.1.2 Snow avalanche hazard and risk

An avalanche is defined as the sudden release of snow masses and ice on slopes, and may contain a certain portion of rocks, soil and vegetation; the dislocation on the trajectory is more than 50 m downhill. Due to the speed of the moving mass, snow avalanches can be distinguished from creeping and gliding movements of snow. A number of classifications of snow avalanches exists, developed in different countries and based on different classification principles. De Quervain *et al.* [12] suggested a scheme to classify avalanches according to their release type, the shape of the trajectory and the type of movement, which is still used by the majority of scientists and practitioners in the field (Table 4.1). The evolution of the snowpack from the start of accumulation of solid precipitation until the snow cover melt is crucial regarding the release of snow avalanches. The conditions that lead

Table 4.1 *International snow avalanche classification [12].*

Zone	Criterion	Characteristic and denomination	
Origin	Manner of starting	From a point ***Loose snow avalanche***	From a line ***Slab avalanche***
	Position of failure layer	Within the snowpack ***Surface-layer avalanche***	On the ground ***Full-depth avalanche***
	Liquid water in snow	Absent ***Dry-snow avalanche***	Present ***Wet-snow avalanche***
Transition	Form of path	Open slope ***Unconfined avalanche***	Gully or channel ***Channelled avalanche***
	Form of movement	Snowdust cloud ***Powder-snow avalanche***	Flowing along ground ***Flowing snow avalanche***
Deposition	Surface roughness of deposit	Coarse ***Coarse deposit***	Fine ***Fine deposit***
	Liquid water in deposit	Absent ***Dry deposit***	Present ***Wet deposit***
	Contamination of deposit	No apparent contamination ***Clean deposit***	Rock debris, soil, branches, trees ***Contaminated deposit***

to the release of avalanches, and also a possible increase in avalanche hazard, are often quite widespread, but the prediction of individual avalanches is extremely difficult due to the high spatial variability and transient/dynamic nature of the snowpack [13]. As a result, however, whole valleys may be endangered by snow avalanches during a winter season.

Different mechanisms of snow avalanche formation correspond to different volumes, repeatability and dynamic characteristics of the events [4]. Loose snow avalanches are released from a more or less definable point in a relatively cohesionless surface layer of either dry or wet snow. Slab avalanches, in contrast, involve the release of a cohesive slab over an extended plane of weakness. Typically, natural slab avalanche activity is highest soon after snowstorms because of the additional load of the deposited snow [13]. The existence of a weak layer below a cohesive slab layer is a prerequisite for the development of dry snow slab avalanches. This weak layer is either buried surface hoar or a result of the metamorphism in the snowpack; during this metamorphism the properties of the snowpack are changing. Crystals formed by kinetic grain growth such as surface hoar or depth hoar [14], together with changes in response to temperature and variability in water vapour gradients, can also be accompanied by formation of solid and icy layers on top of the snowpack. Such surfaces restrict the connection of new-fallen snow with the older snow below the solid layer, and often forms the horizon at which the snow masses start to move downhill. Slab thickness is usually less than 1 m, typically about 0.5 m, but can reach several metres in the case of large, disastrous avalanches [15]. In general, snow avalanches start from terrain that favours snow accumulation and is steeper than about 30–45°. On terrain of less than about 15° snow avalanches start to decelerate and finally stop. Differently to the causes of snow avalanches release, the mechanism of avalanche movement and corresponding distances and forces are rather well described and can be modelled (e.g. [16]).

Avalanche flow velocities vary between 50 and 200 km/h for large dry snow avalanches, whereas wet avalanches are considerably denser and slower (20–100 km/h, [4]). If the avalanche path is steep, dry snow avalanches may generate a powder cloud. Depending on the type of avalanche the moved amount of snow is variable, but in combination with the high velocities the induced damage may vary significantly. In general, slab avalanches and dry snow avalanches with a powder cloud are most disastrous.

Besides natural triggering by overloading or internal weakening of the snow-pack, snow slab avalanches can also be triggered artificially – unlike most other rapid mass movements – through localised, rapid, near-surface loading by, for example, people (usually unintentionally) or by explosives (intentionally) used as part of avalanche control programmes or industrial activities [17]. The industrial development, especially in previously non-exploited regions, is often associated with the increasing degree of hazard occurrence, including snow avalanches [18]. In addition, the artificial change in the vegetation and slope morphology, for example by mining activity [19,20] or during a new ski resort construction [21], can change the position of avalanche-endangered areas at a modified territory or change the run-out distances at the existing avalanche tracks [22]. Occasionally, snow avalanches have been triggered by large earthquakes [23]. In general, naturally released avalanches mainly threaten residents and infrastructure, whereas human-triggered avalanches are the main threat to recreationists.

The threat of avalanches on the anthroposphere can be quantified by the concept of risk. It has been introduced in disaster management since experiences from past years suggested that elements at risk and vulnerability should be increasingly considered within the framework of hazard management in order to reduce losses (e.g. [24]). Starting with the 1990s as the United Nations International Decade for Natural Disaster Reduction, the primary focus was shifted from hazards and their physical consequences to the processes involved in the physical and socio-economic dimensions of risk and a wider understanding, assessment and management of natural hazards. This highlighted the integration of approaches to risk reduction into a broader context between sciences and humanities [25].

Taking the perspective of the sciences, the risk concept is given by a quantifying function of the probability of occurrence of a hazard scenario (p_{Si}) and the related consequences on objects exposed. The consequences can be further quantified by the elements at risk and their extent of damage, and specified by the individual value of elements j at risk (A_{Oj}), the related vulnerability in dependence on scenario i ($v_{Oj,\,Si}$) and the probability of exposure ($p_{Oj,\,Si}$) of elements j exposed to scenario i (Eq. 4.1).

$$R_{i,j} = f(p_{Si}, A_{Oj}, v_{Oj,Si}, p_{Oj,Si}) \tag{4.1}$$

If snow avalanche risk is considered by the potential loss to an exposed system, resulting from the convolution of hazard and consequences at a certain site and during a certain period of time, it becomes obvious that dynamics in risk has different sources. These will be discussed in the following sections separately. The main challenge of risk assessment is rooted in the system dynamics driven by both geophysical and social forces, stressing the need for an integrative risk-management approach based on a multidisciplinary concept that takes into account different theories, methods and conceptualisations, including environmental and socio-economic change.

Embedded in the overall concept of risk management, mitigating snow avalanches is pillared by technical mitigation, land use regulations, risk transfer, organisational measures and information. Conventional mitigation concepts – which influence both the magnitude and the frequency of avalanches – mainly consider technical structures within the catchment, along the channel system or track and in the run-out area. Throughout many mountain regions, conventional mitigation of snow avalanche hazards can be traced back to the late nineteenth century [26]. According to the approach of disposition management (reducing the probability of occurrence of avalanches) and event management (interfering with the transport process of the hazard itself), a wide range of technical measures is applicable. These measures were supplemented by efforts to afforest high altitudes. Conventional technical measures against avalanche hazards, such as deflection and retention walls, as well as snow rakes in the avalanche starting zones, are not only very costly in construction, but, because of a limited lifetime and therefore an increasing complexity of maintenance, the feasibility of technical structures is restricted due to a scarceness of financial resources provided. Since conventional technical measures neither guarantee reliability nor complete safety, a residual risk of damage remains, which may be reduced by local structural protection [27]. Experiences from past decades suggested that the reduction of exposure should be increasingly considered within the framework of avalanche hazard risk reduction by land use regulations [28,29], risk transfer and organisational measures [15] and information [26].

4.2 Environmental change

4.2.1 Climate change and mountain snow cover

Information on changes of snowfall is limited and mostly restricted to Northern Hemisphere areas (North America and Eurasia), and has to be discussed on a region-by-region basis [30]. Regions with increases of snowfall are located in Canada and Northern Europe; however, a high number of areas show a decline in snowfall events. A decrease in snowfall events can be caused by a variety of reasons: (1) decrease of winter precipitation (e.g. Japan); (2) increase of temperature in winter (more precipitation as rain rather than snow); and (3) earlier onset of spring [30].

Based on analysis of satellite records, the extent of snow cover is significantly decreasing in the Northern Hemisphere during spring time [30]. This trend is confirmed by most station observations of snow, though the results depend on considered snow variables, station elevation and period of record. Correlated to the changes in snow cover duration are the trends in earlier timing in snowmelt-driven streamflows (e.g. in Northwestern America, [31]) and for the earlier spring floods in snow-dominated regions [32]. Nevertheless, the distribution of snow cover in mountains is highly influenced by both variable meteorological conditions and local topography. For two case studies in the European Alps and one in Central Asia, Dedieu *et al.* [11] indicated that elevation is the dominant topographic parameter and changes in snow cover duration can be compared to the changes in temperature and precipitation. Yet, the highest variation between the comparison of snow cover duration and the meteorological parameters are attributed to winters with a scarcity of snow. Stewart [7] concluded that the response to temperature and precipitation change has to be interpreted in the context of physical characteristics for a particular location. At low and mid elevations of mountains (near freezing temperature in winter season) a decrease of the snowpack and the snow cover duration could be observed. At elevations that remain well below freezing during winter, increasing temperatures have had little or no effect on snowpack accumulation and melt; in areas with increasing precipitation a high variable response was detected. The duration of snow cover is also variable, as illustrated in Figure 4.1 for the region of Sochi (Krasnaya Polyana) in the Russian Federation. From 1960 to 1985 the amount of days with snow cover, as well as the amount of days with 'reliable' (deposition for more than 30 days without disappearance for more than three days) snow cover, was increasing; for the last 25 years it has been decreasing.

Projected changes for snow consider mainly the decrease of snow cover extent and are related to both precipitation and temperature changes [30]. Projected

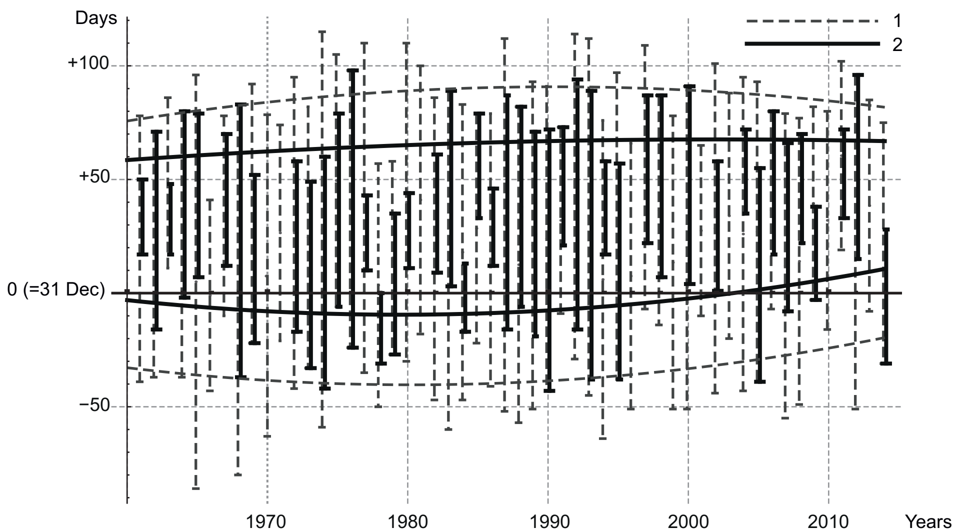

Figure 4.1 Duration of snow cover (1) and duration of 'reliable' snow cover (2) since 1960 in Sochi (Krasnaya Polyana), Russian Federation. Note: the value of 0 corresponds to December 31 in each year; negative values indicate the days before, and positive values the days after the turn of the year.

changes for the next century may be inconsistent: Scandinavia can expect an increase in snow-related floods for the next 50–80 years, but this trend might be reversed within decades by a substantial change from solid precipitation to rain, given that temperatures continue to increase [33]. Diffenbaugh *et al.* [9] evaluated the response of snow-dependent regions under global warming and stressed that extreme change in snow accumulation and melt remains a key unknown for assessing climate change impacts. Their results indicate that many snow-dependent regions of the Northern Hemisphere are likely to experience increasing stress from low-snow years within the next three decades. For mountain areas, a diverse response is expected: due to warmer temperatures in the next decades, the snow volume may respond with reduction at mid-elevation sites by 90% (1000 m) to 50% (2000 m) and at high-elevation sites by 35% in the European Alps [3,5]. Regarding the different projections of climate change, important caveats are that the general circulation models (GCMs) do not resolve the complex topography of the snow-dominated mountain regions and the shifts in liquid/solid threshold of the precipitation [5,9].

4.2.2 Effects on snow avalanches

While it seems to be evident that climate change will affect temperatures and precipitation responsible for avalanche activity (see Figure 4.2; e.g. [30,34,35]), it is not as evident that avalanche events will increase in the near future.

The number of studies focusing on the effect of future environmental change on the occurrence and magnitude of snow avalanches is limited. However, a few papers provide insight into the climatic control of snow avalanches (e.g. [36]) but do not address recent changes in avalanche activity. Changes of temperature, precipitation (amount and solid–liquid thresholds) and wind characteristics influence the structure and stratigraphy of the snowpack and consequently the release and properties of snow avalanches. In general, a classification to different snow climates (e.g. two basic types of snow climate are maritime and continental, based on dominant weather and snow characteristics; and transitional snow climate exhibiting features associated with both types) and their influence on snow avalanche activity is necessary [4,37,38]. Shifts from one snow climate to another may lead to changing avalanche activities.

Germain *et al.* [39] analysed climatic conditions that account for avalanche activity in a Canadian case study with a maritime influence and a mean annual temperature of 0 °C. Five climatic categories were identified: (1) above-average total snowfall, (2) high-frequency of snowstorms, (3) major rain events and facet–crust development, (4) sequences of freezing rain and strong winds and (5) early-season weak layers of faceted crystals and depth hoar. Categories (1) and (2)

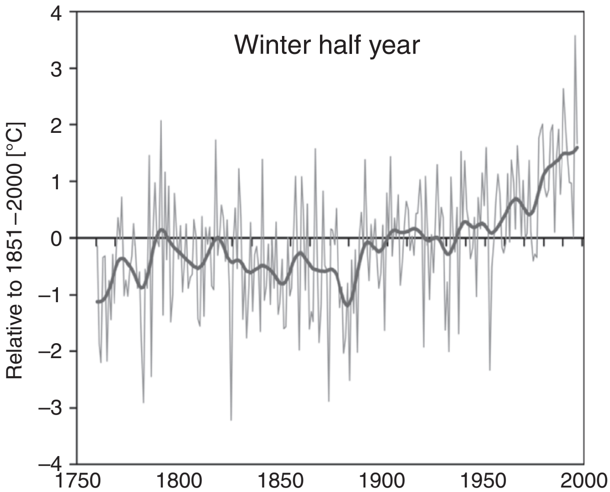

Figure 4.2 Annual mean winter temperatures in the greater Alpine area, 1760–2007. Annual means (grey bars) and 21-year low-pass filtered data (bold line) are shown as deviation from the average 1851–2000. It is shown that in the European Alps the average winter temperatures – adjusted to measurement uncertainties – increased about 2.5 °C during the last 250 years.
Data based on 32 LSS monthly series of the HISTALP database at ZAMG [35,85].

are crucial for dry snow avalanches triggered by the load of new snowfall. These categories should be considered for mountain areas with increasing snow precipitation or a high frequency of snowstorms. Categories (3) and (4) may indicate a shift in the solid–liquid precipitation thresholds, and category (5) accounts for warm periods and unfrozen ground during the first snowfall; all three influence the characteristics of the snowpack.

In the European Alps the long-term natural avalanche activity seems to be constant [40,41], although it is pointed out that the variability of events makes an exact statement difficult. Baggi and Schweizer [42] investigated the occurrence of dry and wet snow avalanches in a small study area in Switzerland over a period of 20 years. The results indicate that loose snow avalanches occurred when air temperature was high and/or after a (liquid) precipitation period. Slab avalanche occurrence was primarily related to warm air temperatures and snowpack properties. Regarding a transitional snow climate, they concluded that wet snow avalanches are also often related to rain events (overloading), but wet slab instability strongly depends on snowpack properties in relation to warming of the snowpack (weakening) and meltwater production (infiltration and storage). Changing climate conditions will supposedly affect the wet snow avalanche activity as far as time and elevation of occurrence are concerned [42]. According to modelling results for the Aspen Mountains, wet snow avalanches will likely occur 2–19 days earlier in the season compared to historical records [43]. Eckert *et al.* [36] focused on changing annual avalanche run-out and correlated it to climate variability using an advanced statistical framework. The results indicate no change in the mean avalanche run-out altitude during the last 60 years in the French Alps, despite the increase in temperature (Figure 4.2). Corresponding to the high variability of snow depth and snow cover in mountain areas, possible effects on snow avalanche activity will cover a wide range, from decreasing or increasing occurrence to a shift from dry snow avalanches to wet snow avalanches.

4.3 Socio-economic change

4.3.1 Drivers of socio-economic change

Socio-economic change in mountains includes land use changes, such as deforestation and urban development in mountain regions, but also population growth, migration and the associated changes such as the development of traffic infrastructure and tourism facilities. Starting in the 1990s, these issues were increasingly addressed on the scientific but also political level [44] – the United Nations International Decade for Natural Disaster Reduction or the implementation of Agenda 21 at the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro are prominent examples. Agenda 21 acknowledges the importance of mountain regions and promotes generating and strengthening knowledge about the ecology and sustainable development of mountain ecosystems and providing the public with knowledge concerning mountain-related global change issues, including natural hazard risk management. The importance of mountains in the global ecosystem, as well as their provision of livelihood for considerable parts of the world population, has been further expressed by the UN declaration of the year 2002 as the International Year of the Mountains.

Population density and land use are direct drivers for socio-economic change in mountain regions. Apart from the overall population number, it is also the population distribution and composition, such as the level of urbanisation and household size, as well as the increasing effects of counterurbanisation [45,46] which defines the level of exposure to mountain hazards [47]. If population density is taken as a proxy for the intensity of human activities in mountain areas, considerable parts of the high-mountain areas are potentially at risk (Table 4.2).

Therefore, a sustainable use of mountain areas must include the analysis, assessment and management of socio-economic change due to the relative scarceness of living space. Taking countries in the European Alps as an example, only 38.7% of the territory is suitable for land development purposes in the Republic of Austria, while in the western part of the country (Federal State of Tyrol) it is only

Table 4.2 *Mountain area, population number and density for selected mountain areas [47].*

Article I.	Mountain area (1000s of km^2)	Population in the mountains (millions)	Population density in mountains (persons/km^2)
Svalbard	48	0.001	0.02
Japan	185	15	81
Ethiopia	471	35.2	77
Tajikistan	131	2.9	22
Ecuador	108	5.3	49
Austria	55	3.3	60
British Columbia	750	0.5	0.7

11.9%. In Switzerland, 26% of the territory is classified as non-productive and approximately 68% of the territory is classified as an area for agriculture and forestry; as a result only around 7% is suitable for the development of settlements and infrastructure. In the Russian Federation, approximately 10% of the Russian territory with an average population density of 8.3 persons per km^2 is prone to mountain hazards. The historical shift of a traditionally agricultural society to a service industry- and leisure-oriented society is reflected by an increasing pressure on alpine areas for human settlement, industry and recreation. Accordingly, a conflict between human requirements and naturally determined conditions such as steep terrain leads to an increasing concentration of tangible assets and population in certain regions, in particular with respect to agglomerations along the larger valley bottoms (e.g. [48]).

One of the major industries in the mountain regions is winter tourism [49]. It is crucial for the local economies, and for many mountain-region communities it is unfavourably affected by climate change [50]. Climate change increasingly threatens winter tourism, starting with lower mountain ranges and extending towards high-mountain areas [51]. In particular, communities below 2500 m asl will be affected from this regionally differing trend [49]. Apart from abandonment in low-mountain regions, the adaptation technique involves artificial snow production. The latter affects the whole ecosystem, hydrological and biological cycles, and often has negative impacts on anything other than skiing-related businesses [52], such as an increased demand for water and a higher energy consumption [53].

An increased population density in mountain areas is accompanied by a development of infrastructure, such as sanitation and power lines, but also traffic infrastructure. As a result, an increasing amount of network infrastructure is exposed to snow avalanches [54–59].

Unlike previous booms in mining, cattle or energy, the development wave in land use changes is driven by growth in the secondary and tertiary economies such as services, recreation and information businesses, instead of commodity production. The result is sprawling land use conversion, mostly from agricultural to residential, in even the most rural areas. Such changes have been investigated for mountain areas world-wide, but not explicitly and solely directed towards the exposure to snow avalanches [60–64].

Closely related to these challenges are the continuous spatio-temporal changes of landscape processes and of society that are subject to dynamical but also interactive changes [65]. Moreover, research questions relating to these changes on the interlinkage between individual landscape processes (e.g. coupled and multi-hazards, [66]) as well as between landscape systems and human systems, have not been sufficiently studied so far.

4.3.2 Effects on snow avalanche risk

Socio-economic change is a major driver for the dynamics of avalanche risk since the concept of risk is rooted in the connected system dynamics driven by both geophysical and social forces. The social system (and therefore land use), elements at risk exposed and vulnerability are hence not constant over time and space [29,67,68]. Socio-economic change is also an important part of avalanche risk management in order to plan and implement tailored management solutions and adaptation strategies [27].

For the European Alps, a statistically significant trend with regard to an increase in the annual cost of snow avalanche loss could not be proven. While the large avalanche events in 1951, 1954, 1968, 1975 and 1984 can clearly be traced, a data set for the Swiss Alps had not shown any trend [69]. Due to the construction of mitigation measures, the number of devastating avalanches [70], as well as the corresponding losses, has declined over the last 50 years in Switzerland [71]. Within the period 1946–1992, 295 individuals were buried inside buildings, 135 of which (46%) died and 56 (19%) were injured. A detailed study within the canton of Grisons in the eastern part of Switzerland concluded that there was a reduction of annual damage costs between 1950 and 2000, in particular with respect to the years with above-average avalanche activity. The total sum of avalanche losses due to direct building damage in eastern Switzerland amounted to €63.3 million. This is 40% of the sum paid by the mandatory building insurer for natural hazards losses in the canton, but avalanches make up only 15% of the number of all incidents. This means an average loss of €1.25 million per year, compared with €1.77 million per year for losses due to other natural hazards, such as debris flows, rockfall events and floods. Damage resulting from avalanches amounted to an average of €17 500 per event, while losses caused by other types of natural hazard processes cost an average of €6000 per event.

In the Eastern European Alps, information related to destructive snow avalanches is rather sparse. Between 1967 and 1992 a total of 5135 avalanches had been reported [72], 4032 of which caused damage to settlements and infrastructure. The data did not show any trend; however, large events were reported from 1969, 1974, 1980, 1981 and 1983 during the period under investigation. An analysis of destructive avalanches between 1950 and 2008 from the written reports, which were compiled in the course of the implementation of hazard maps by the Austrian Torrent and Avalanche Control Service, shows a decreasing trend related to the overall number [73].

4.3.2.1 Temporal dynamics of socio-economic changes

The temporal variability of exposure has an important influence on the assessment of avalanche risk since socio-economic developments in the human-made environment have led to an asset concentration and a shift in urban and suburban population in many mountain regions. Long-term changes are related to a significant increase in numbers and values of buildings endangered by snow avalanches [59,74–78]. Short-term fluctuations in exposure supplemented the underlying long-term trend, in particular with respect to temporary variations of migrating or commuting citizens in settlements and of vehicles on the infrastructure network [28,55,79], as well as with respect to different management strategies [80]. By implementing a quantifying fluctuation model it was shown that strong variations could be observed for mountain resorts during the winter season as well as throughout the day [59,79].

If the exposure on traffic corridors is considered, short-term variability becomes obvious [59]: the number of persons or the freight traffic potentially affected by snow avalanches is subject to high fluctuations on different temporary scales. As a consequence, risk (resulting from the daily traffic during the period of investigation, the mean number of passengers and the mean value of good being transported, the speed of the vehicles crossing the endangered sections of the traffic corridor, etc.; [54,56,81]) is variable with a high temporal resolution.

If exposure of settlements is considered, the long-term variability becomes evident: Based on a model to quantify the long-term evolution of the built environment, Fuchs and Keiler [68] reported a significant increase in the number and value of elements at risk exposed for many alpine regions, while other regions show an opposing trend [71]. In many rural and urban settlements of the European Alps the total number of buildings exposed to snow avalanches had almost tripled since the 1950s, and the total value increased by a factor of almost four. The proportional increase in the number of buildings was significantly lower than the proportional increase in the value of buildings. Buildings inside hazard-prone areas showed a lower average value than buildings outside those areas [82]. A major part of this increase was found within the category of residential buildings: in 1950, the proportion of residential buildings was less than 15% of the total amount of endangered buildings. By 2000 this ratio had changed to almost 50%. The number of endangered persons has increased substantially since 1950. The increase in residential population was about 60%, while the increase in temporal population and tourists was a factor of ten [29,83].

To conclude, both long-term and short-term temporal changes of exposure contribute considerably to the risk level, and should therefore be included in operational risk analyses. The vast majority of avalanche fatalities in the Western world nowadays, however, are recreationists exploring the uncontrolled backcountry, making their own decisions. The societal impact of avalanches in Europe and North America has transitioned from an issue affecting settlements and infrastructure (often named involuntary exposure) to more of a recreational issue (voluntary exposure).

4.3.2.2 Spatial dynamics of socio-economic changes

The analysis of spatial dynamics of societal changes is equally crucial for risk assessment, and provides an important factor for tailored mitigation concepts. Spatial dynamics influence settlement patterns; risk management, including its analytical tools and policy recommendations, is inherently geospatial in nature, affecting the location, type and density of development [84]. The concept of space refers to the location of exposure, including distribution and regional patterns.

Until now, there were only a few approaches targeting at a small-scale spatial analysis of exposure in mountain regions; therefore, such information was only accessible through a time-consuming, and therefore costly, detailed on-site analysis [67,71,79]. With respect to the exposure to snow avalanches, a recent study has shown considerable spatial variation throughout mountain communities in the eastern European Alps [73]. Around 2.45 million buildings exist in Austria, 123 040 of which are exposed (for the definition of exposure, see [26,73]) to mountain hazards (torrents: 113 876; snow avalanches: 9164). Subtracting those buildings which are exposed to both torrents and snow avalanches (= corrected sum), approximately 120 400 buildings remain (around 5% of the building stock), with an overall value of €67.25 billion (torrents: €61.14 billion; snow avalanches: €6.11 billion). In sum, around 430 000 people are exposed in these buildings (torrents: 399 253; snow avalanches: 30 158). Taking an overall population of 8.44 million this equals around 5% of the residents.

The results were further analysed according to the construction period, and it was shown that the increase in the building density is significantly higher in potentially endangered areas than outside these areas (Figure 4.3), which in turn requires adaptation and risk mitigation.

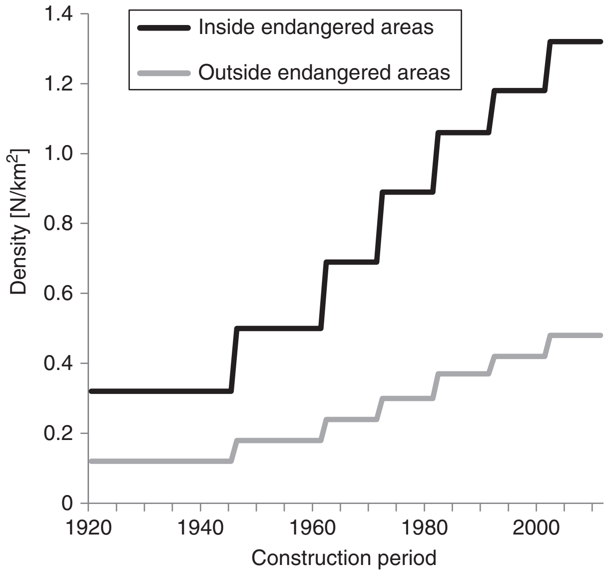

Figure 4.3 Analysis of exposure for buildings in Austria according to the density. After [82]

If queried spatially on a municipal level, considerable differences become evident throughout the country (Figure 4.4). To give an example, in the Federal State of Salzburg around 17% and in Tyrol 15% of all buildings are exposed to torrents and snow avalanches, whereas in Vienna, Burgenland and Lower Austria this value is considerably lower – which is not only a result of different socio-economic development, but also related to the drivers of socio-economic change. In the Federal State of Salzburg, moreover, the number of communities with a clearly above-average exposure is evident.

Identifying and analysing socio-economic dynamics is still a challenge in avalanche risk management, even if it is undoubted that these (1) influence the level of risk a society is exposed to on different temporal and spatial scales; and (2) provide the fundamentals for a sustainable and tailored management concept.

4.4 Conclusions

Due to the effects of climate change, snow avalanche hazards are a dynamic risk component in high mountains. Climate change affects the global temperature and precipitation patterns – the two primary driving factors for the development of the seasonal snowpack and avalanche hazard – but very little is currently known about the effect of climate change on avalanche hazard. Given the increasing knowledge of local-scale changes in temperature and precipitation – being either observed or

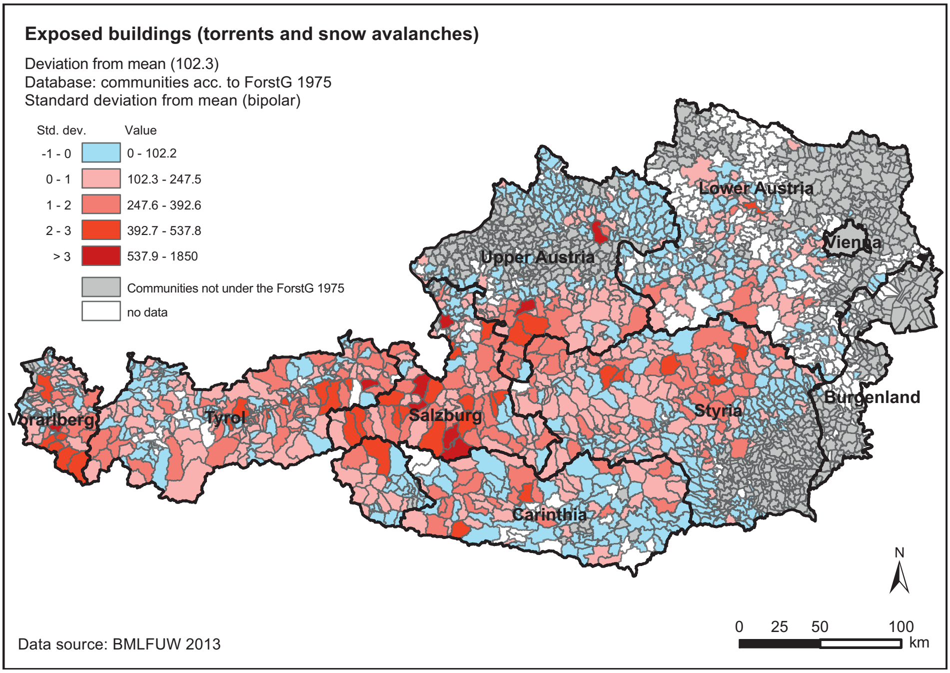

Figure 4.4 Number of exposed buildings, shown as the deviation from the mean (102.3 buildings per municipality).
After [82]

the result of modelling – the understanding of these dynamics is growing. So far, however, studies on changing avalanche frequencies and magnitudes are focusing on individual case studies in high-mountain areas, and remain therefore fragmentary for an area-wide regional hazard analysis. So far, no significant long-term trends in natural avalanche activity have been identified.

Despite the significant increase in population density and exposure of infrastructure and settlements to avalanche hazards over the last 50 years, which have been observed in many mountain regions, there are only a few studies available on the local-scale dynamics of elements at risk, which makes a regional-scale or even national risk assessment challenging. Major losses in high-mountain regions were repeatedly associated with such an increase in land use and economic activities; in contrast, a decrease in annual cost of snow avalanche loss has been reported. Currently, the vast majority of avalanche fatalities are recreationists voluntarily exposing themselves to avalanche hazards.

The concept of risk is increasingly used to track these challenges with respect to economically efficient and societally desirable management options, such as technical mitigation, spatial planning or evacuation. In practice, however, risk assessment and subsequent risk management are regularly undertaken by taking a static viewpoint, while losses are the predictable result of interactions among three major dynamic systems: (1) the specific physical environment of high mountains, which includes snow cover and snow avalanches; (2) the social and demographic characteristics of the communities that experience them; and (3) the elements at risk such as buildings, infrastructure and other components of the built environment.

Focusing on climate and global change in high-mountain areas, risk management strategies have to acknowledge the underlying dynamics in order to be prepared for adaptation and mitigation. Long-term changes are superimposed by short-term fluctuations, and both have to be considered when evaluating risk resulting from mountain hazards. Moreover, the uncertainties of global change underlying the hazard scenarios, but also the lack of knowledge with respect to socio-economic changes, have to be communicated to the stakeholders and the general public; the activities of the Intergovernmental Panel on Climate Change (IPCC) on the global scale, but also of other international organisations such as the UN/ISDR or the World Bank, focusing more on regional adaptation are indispensable. Moreover, stakeholders and the administration in charge on the local level should be aware of the drivers beyond these dynamics, and include them in their local management strategies.

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