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TACKLING RISKS THROUGH THE SUSTAINABLE DEVELOPMENT GOALS

Towards a holistic paradigm for long-term snow avalanche risk assessment and mitigation

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Abstract In mountain territories, snow avalanches are a prevalent threat. Long-term risk management involves defining meaningful compromises between protection and overall sustainability of communities and their environment. Methods able to (i) consider all sources of losses, (ii) account for the high uncertainty levels that affect all components of the risk and (iii) cope for marked non-stationarities should be employed. Yet, on the basis of a literature review and an analysis of relations to Sustainable Development Goals (SDGs), it is established that snow avalanche risk assessment and mitigation remain dominated by approaches that can be summed up as deterministic, hazard oriented, stationary and not holistic enough. A more comprehensive paradigm relying on formal statistical modelling is then proposed and first ideas to put it to work are formulated. Application to different mountain environments and broader risk problems is discussed.

Keywords Environmental risks · Mountains · Socio-environmental changes · Statistical modelling · Sustainable development goals · Systemic approach

INTRODUCTION

In many mountain environments of the world, snow avalanches are a recurrent danger in winter (e.g. Vera-Valero et al. 2016 for the Andes; Ballesteros-Cánovas et al. 2018 for the Himalayas; Peitzsch et al. 2021 for the USA.) resulting in direct (casualties, damages to buildings, infrastructures, forests) and indirect (e.g. road closures that isolates high valleys from the rest of the world) losses. For example, extreme winters like 1999 can still claim a hundred lives in Europe, with damage caused by avalanches during that period close to 1 billion Euros (Ammann and Bebi 2000). More recently, an avalanche destroyed an Italian hotel, killing 29 people (Braun et al. 2020) and, during the same 2017–2018 winter, considerable road disturbances and damages to defence structures were reported in the European Alps (Stoffel and Corona 2018; Bühler et al. 2019). No countermeasures can be taken after the avalanche initiation because the time before the damageable impact is generally less than one minute. To reduce death tolls and costs for settlements and critical infrastructures, land-use planning is, therefore, the most efficient way to mitigate snow avalanche risk on long time scales.[1] This includes (i) the definition of land-use maps that prevent installation of new settlements at places where hazard levels are too high and (ii) the construction of defence structures whose choice and design must take into account their effectiveness as well as construction and maintenance costs, aesthetical considerations and consequences for ecosystems[2] (Fig. 1). Both (i) and (ii) highlight that finding the right compromise between protection and overall sustainability of the community and its environment is the true challenge raised by long-term snow avalanche risk management. An example of the difficulty in finding an adequate balance is the Taconnaz avalanche path located in the iconic and highly touristic valley of Chamonix (Fig. 2). Despite recurrent avalanche activity, including large

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[1] We focus here on long-term avalanche risk, in contrast to short-term risk that mostly threatens recreational activities (e.g. back-country and cross-country skiing) and is routinely mitigated by operational forecasting conditional to snow and weather conditions (e.g. Morin et al., 2020).

[2] Notably green (nature based) and/or grey ("classical" engineering involving, e.g. reinforced concrete) defence structures.

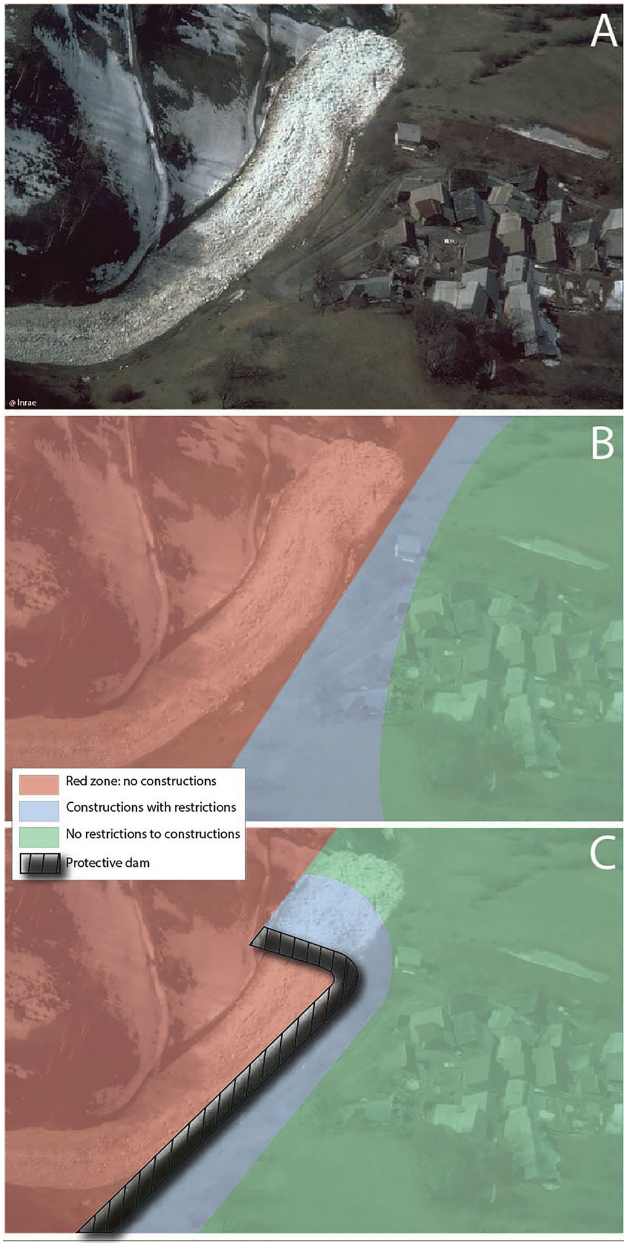

Fig. 1 Land-use planning in avalanche-prone terrain: a compromise between safety and overall sustainability. **A** Avalanche deposit in the immediate vicinity of a village of the French Alps; **B** Schematic representation of a land-use planning map; **C** Same land-use planning map modified after the construction of a defence structure (protective dam). In **B–C** red zones mean no possible constructions, blue zones indicate constructions possible with restrictions only (thicker walls, no windows on the wall facing the avalanche, etc.) and no restrictions apply in green areas

events, due to the very high real estate pressure, dwelling houses cover now almost completely the natural runout area. The latter is protected by a huge protective system that was extremely difficult and costly to design and build (Naaim et al. 2010) and that severely alters the local landscape (the frontal dam is $\sim$ 25 m. high).[3]

Mountain environments are now changing faster than ever (Altaweel et al. 2015; Hock et al. 2019). For instance, changes in mountain climate conditions have been drastic, with overall warming that has had stringent consequences on the cryosphere: shrinkage of glaciers, permafrost and snow cover, but increase in extreme snowfall at high elevations where temperatures are still cold enough (O'Gorman 2014; Beniston et al. 2018; Le Roux et al. 2021). These changes have modified the frequency, magnitude and flow type of snow avalanches in many mountain ranges as well as their preferred location and timing within the season (e.g. Eckert et al. 2013; Ballesteros-Cánovas et al. 2018; Giacona et al. 2021; Peitzsch et al. 2021). In addition, simultaneous changes in land use and society and their interactions make snow avalanche risk highly non-stationary in all its components: hazard, vulnerability and exposure (García-Hernández et al. 2017; Mainieri et al. 2020; Zgheib et al. 2020), and interactions between the bio-physical and societal spheres make risk change patterns especially complex (e.g. Giacona et al. 2018). For example, mountain forest ecosystems (location of forest stands, species composition, etc.) are modified by gradually changing climate conditions, changes in logging and agro-pastoral pressure and increasing frequencies of disturbances, such as insect outbreaks or wildfires, which affects their protective effect downslope (e.g. Bebi et al. 2009; Takeuchi et al. 2011), and such complex patterns should be accounted for to elaborate efficient risk management strategies. In the illustrative Taconnaz area, over 120 years, changes have been exacerbated, modifying the different drivers of avalanche risk completely. Glaciers have strongly retreated, whereas pastures have been replaced by forests, modifying the terrain characteristics and, hence, avalanche release and propagation conditions (terrain smoothness, protective effect of forests, etc.). Notably, location and size of seracs have changed on Taconnaz glacier (Vincent et al. 2015), affecting avalanche frequency, volume, ice content, and, hence, damage potential. In parallel, dwellings and critical infrastructures (a transnational highway, a railway, power lines, etc.) have been built all over the "flat" terrain, and different defence

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[3] The proposed paradigm for long-term snow avalanche risk assessment and mitigation aims at being independent of local peculiarities. Hence, the Taconnaz exemplary case is only introduced to illustrate the specificities of long-term snow avalanche risk management, to show how important this risk can be for mountain communities and how quickly and strongly it can change through time. "Variability in the risk, its drivers and management practices" section discusses spatial variability in avalanche risk, its drivers and management and to which extent the developed approach applies to different contexts.

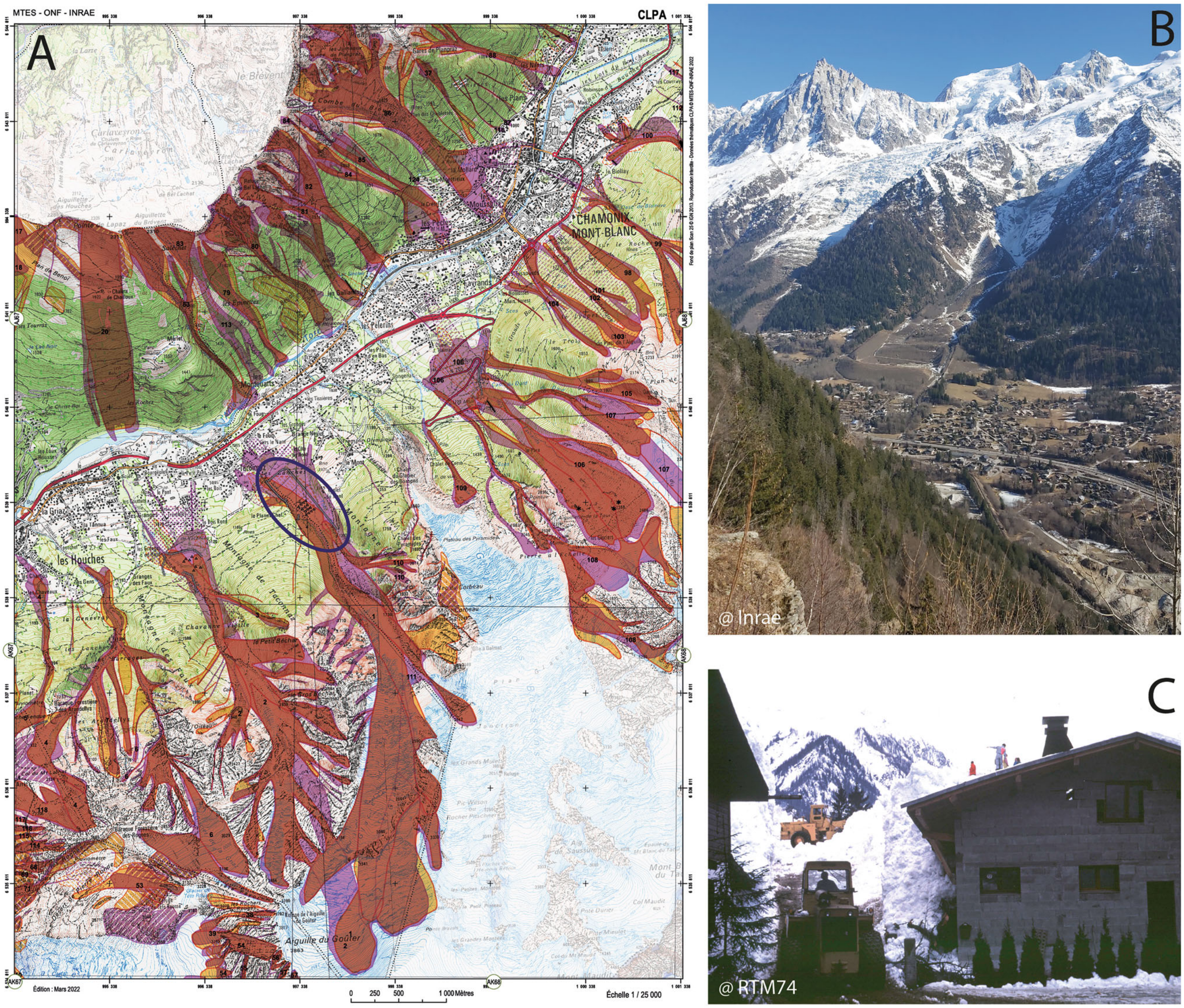

Fig. 2 Avalanche risk in the Chamonix Valley, French Alps, in the vicinity of Taconnaz avalanche path. **A** Official French avalanche cadastre "CLPA" (March 2022 edition, full legend at https://www.avalanches.fr/static/1public/epaclpa/CLPA_feuilles_carte/CLPA_legende_carte.pdf), with black ellipse highlighting the massive Taconnaz protective system (deflective mounds and several dams); **B** the Taconnaz avalanche path and its protective system in March 2022 (photo credit @Inrae). The path extends from the highest summits of the Mont Blanc range to the valley bottom (Les Houches village); **C** Avalanche deposit on dwelling houses in Taconnaz, 20 March 1988 (photo credit @RTM74)

structures have been built to contain the risk increase[4] (Fig. 3).

At the global scale, to face the current situation of environmental emergency, multiple and increasingly restrictive action frameworks have been adopted, e.g. the United Nations Paris Agreement on climate (United Nations 2015), the United Nations' action for Disaster Risk Reduction (DRR), known as "Sendai framework" (United Nations Office for Disaster Risk Reduction 2015), etc. Most of them use the risk concept more or less explicitly (IPCC 2014, 2020). Whereas the different initiatives initially focused on specific domains, such as biodiversity (IPBES 2019) or climate change (IPCC 2021), it has been progressively acknowledged that the interconnected nature of environmental and societal issues makes a broader perspective mandatory. The different frameworks therefore progressively converged, now promoting all more or less the same systemic, inter-sectorial and interdisciplinary approach of sustainability (UNDRR 2019a; Pörtner et al. 2021). These dynamics culminated with the adoption in 2015 by all 193 member states of the UN of the 2030 Agenda for Sustainable Development (United Nations General Assembly 2015). The 2030 Agenda includes 17 Sustainable Development Goals (SDGs), specified by 169

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[4] The Taconnaz protective system per se, and other defence structures in surrounding paths.

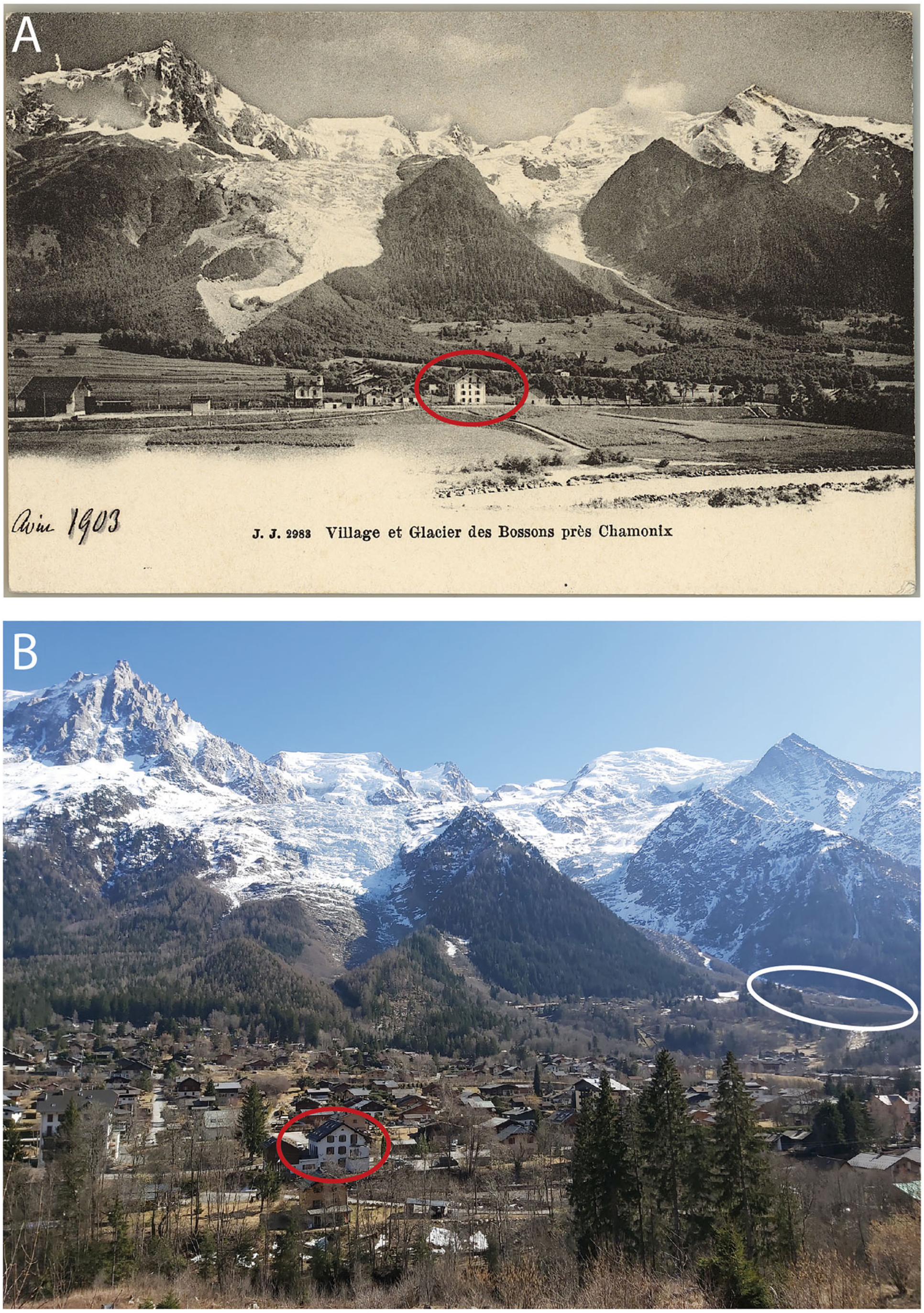

Fig. 3 Diachronic evolution of the Chamonix Valley, French Alps, in the vicinity of Taconnaz avalanche path. **A** Landscape in 1903 (photo credit @ETH-Bibliotek Zurich); **B** same area in March 2022 (photo credit @Inrae). In **A**–**B**, the red ellipse highlights the same dwelling house. In **C**, the white ellipse locates the Taconnaz protective system (Fig. 2B)

individual targets as well as indicators to evaluate progress towards SDGs. The latter are mostly ratios allowing monitoring trends over time at the international and national levels (e.g. Kleiber and Vey 2017; United Nations 2020). Thanks to its holistic perspective that accounts for the complexity of socio-environmental systems, the 2030 Agenda is designed as a comprehensive framework capable of guiding the world on a virtuous path. Many SDGs relate to risks in a broad sense, with, e.g. explicit mapping between SDG targets and the goals of the Sendai framework (UNDRR 2019b).

All in all, snow avalanche long-term risk (i) primarily belongs to the disaster risk category, which the Sendai framework (United Nations Office for Disaster Risk

Reduction 2015) aims at reducing with a systemic approach (UNDRR 2019a). However, snow avalanche long-term risk also encompasses other potential sources of losses that relate to broader sustainability issues; (ii) biodiversity and/or aesthetic losses through excessive building of "grey" defence structures (e.g. dams). Such constructions impact ecosystems, but also mountain communities that may suffer from lowered touristic income because of the degradation of their environment and (iii) more widely, losses resulting from excessive land-use restrictions or building of too large protection structures. Such non-optimal (too costly) solutions may hamper the development, leading to non-sustainable trajectories on the long range. Assessing and mitigating all these risks involve promoting integrative land-use planning methods accounting for the different factors at play and their complex non-stationarities. To this aim, this prospective paper bridges SDG/DRR literature with knowledge and practices of the snow avalanche community and formal risk modelling. After setting the scene, "Current state of long-term snow avalanche long-term risk assessment and mitigation" section establishes on the basis of a broad literature review and an analysis of its relation to SDGs that avalanche risk mitigation and related research remain dominated by approaches arguably not holistic enough to define compromises between all aspects of long-term snow avalanche assessment and mitigation within a sustainability perspective. "Towards a more holistic paradigm" section then (i) formulates a paradigm more able to fulfil this need, (ii) develops first ideas to put it at work by integrating knowledge and data sources within a formal framework based on statistical modelling and decision theory and (iii) discusses its applicability and relevance for various spatio-temporal scales and mountain environments. "Discussion, conclusion and outlooks" section sums-up main outcomes of the work and opens perspectives for wider mountain risk problems.

CURRENT STATE OF LONG-TERM SNOW AVALANCHE LONG-TERM RISK ASSESSMENT AND MITIGATION

Background on snow avalanche long-term risk and its management

System at risk

The relevant system to analyse long-term snow avalanche risk is a mountain community (from a few buildings to a whole region) and its environment, but the exact nature of this system varies slightly according to the considered type of losses. For instance, the disaster risk concerns mostly human populations (to a lesser extent, forest and wildlife), whereas the risk for life on land due to excessive grey protection is for ecosystems. Relevant spatial scales range from the local mountain slope to the "regional" scale, with strong interactions between small-scale processes (e.g. how temperature and land cover controls avalanche activity) and large-scale changes in climate and social practices ("Bridging scales" section). However, contrary to other disaster risks, such as those related to tsunamis or floods on large rivers, the impact of a catastrophic avalanche event has limited spatial extent.[5] Long-term snow avalanche risk is generally addressed at temporal scales of 30–300 years, which correspond to usual references in land-use planning (e.g. Salm et al. 1990; Eckert et al. 2018).

Risk components and their drivers

Snow avalanche hazard is determined by local topographical constraints (slope, elevation) and climate conditions that together control avalanche activity (Schweizer et al. 2003). Forest management policies as well as defence structures modulate hazard levels, either by preventing avalanche initiation or by modifying the magnitude (runout distance, impact pressure, volume, etc.) of released events. Exposure of settlements downslope is determined by land use and people behaviours, which more widely relates to social practices and individual and institutional risk perception, experience and management. Vulnerability of buildings and people inside is strongly determined by technological choices (e.g. reinforced walls and masonry versus concrete.). Spatial variability in snow avalanche long-term risk amongst countries, mountain ranges and even seasons and elevations is very high ("Variability in the risk, its drivers and management practices" section), as function of the variability of its hazard, vulnerability and exposure components and their underlying drivers (topography, climate, social practices, etc.).

Experience and narration of the risk

Risk to settlements and infrastructures primarily affects permanent and temporary (e.g. tourists) local populations. Experiences of the risk include crises due to avalanche disasters, recovery/reconstruction phases and business-as-usual phases during which conflicts between protection and development may arise. These experiences lead to oral and written testimonies related, e.g. to past disasters or successive land-use planning decisions. Such documentary

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[5] During severe winter storms, so-called avalanche cycles can yet have a regional impact through a large number of avalanches occurring the same days (e.g. Eckert et al., 2010a; Bühler et al., 2019).

sources may be analysed to grasp the evolution through time of the risk and of its different components (Giacona et al. 2017a) as well changes in risk perception and management. Risk is also experienced by wildlife and forests. Notably, trees keep memory of avalanche impacts in their rings, which allows reconstructing time series of past events (e.g. Schläppy et al. 2014).

Risk management

Snow avalanche long-term risk management practices and policies vary amongst countries/regions as function of the local characteristics of the risk (magnitude, trends, etc., “Variability in the risk, its drivers and management practices” section) and their perception by national/local authorities and impacted populations. These perceptions themselves depend on a large number of factors, including wealth and overall development level as well as past experiences. Notably, in many countries (e.g. Jóhannesson and Jónsson 1996; Ammann and Bebi 2000; Eckert et al. 2018), major avalanche winters with destructions of settlements and numerous casualties drove important changes of land-use management policies, generally in the direction of more strict rules, and, hence, lower residual disaster risk. This reaction to the crisis can be seen as part of the resilience of the community to the catastrophic event. Hence, it can be observed with a historical perspective that occurrence of catastrophic avalanches is often “necessary” to initiate evolutions of risk management policies, as, without them, accounting for the existing disaster risk goes after other everyday preoccupations or is simply neglected (Giacona et al. 2017b). Most of the time, land-use planning is managed at the scale of the municipality (or of a group of municipalities) under the responsibility of local authorities, but with reference to national (sometimes regional) guidelines that define land-use plans. Many actors contribute to the elaboration of these plans: private or public experts, state and regional technical services, etc. These plans locate safe and unsafe zones, restrictions to constructions and sometimes identify forests that have a protective effect (Fig. 4). If exposure appears as too high, construction of defence structures can be engaged. Preventive evacuations and/or road closures can also be decided in critical weather situations, and locations where this should be undertaken may be specified in land-use plans. All in all, long-term snow avalanche disaster risk seems to be well and clearly identified, with a possible efficient management in countries/regions where it is considered as serious enough by concerned parties.[6] However, in practice, the picture should be nuanced. Indeed, land-use decisions often result from the addition of various norms (e.g. standardized reference levels for reference hazards—“Current approaches for snow avalanche risk mitigation” section—, but also norms related, e.g. to landscape or biodiversity conservation) rather than from a holistic analysis of the different aspects of long-term avalanche risk. Local considerations also often influence decisions in a questionable way, e.g. citizen associations can ask for very high protection levels, or, alternatively, promote a massive development of infrastructures. For example, excessive building of grey defence structures that cause biodiversity and/or aesthetic losses (such as, arguably, in the Taconnaz case) may result from too conservative political choices that answer the demand of very high protection levels. As a consequence, in practice, the different type of losses related to long-term snow avalanche risk are arguably not necessarily accounted for in a crystal clear and coherent manner, which makes the retained options potentially far from optimal.

Quantitative bibliometric analysis

To understand (i) which disciplines and fields shape the current state of the art of long-term snow avalanche risk and (ii) what is the associated research dynamics, we quantitatively analysed the related scientific literature published between 2000 and 2021 using bibliometric requests performed under the Scopus documentary database. First, all articles related to “snow avalanches” (in title, abstract and/or keywords) were extracted. In a second time, additional filters were used in order to restrict the search to article explicitly referring to (i) “snow avalanche risk” and (ii) “snow avalanche risk” and, either, “building” or “settlement” or “house” or “dwelling” or “zoning” or “land use”. The latter search focuses on the long-term risk problem, which is the core of our analysis. Eventually, all search results were sorted according to their publication year and to the scientific field(s)/discipline(s) to which they were attached.[7]

Results indicate that about ~ 2000 articles regarding snow avalanches were published in referenced journals over the 2000-2021 time period, namely a little less than 100 per year in mean. Annual counts were slightly lower over the 2000–2007 period (40–80 articles/year), peaked in 2008 (258 articles) and stabilized since then around ~ 100 articles/year. Restriction to articles that explicitly target snow avalanche risk returned 628 articles (32% of the total of snow avalanche articles), and restriction to articles that explicitly target long-term snow avalanche risk returned

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[6] This is different from risks that are not identified/understood enough (such as emerging risks) and for which efficient management strategies are much harder to define.

[7] According to Scopus classification. The same article can relate to several fields/disciplines.

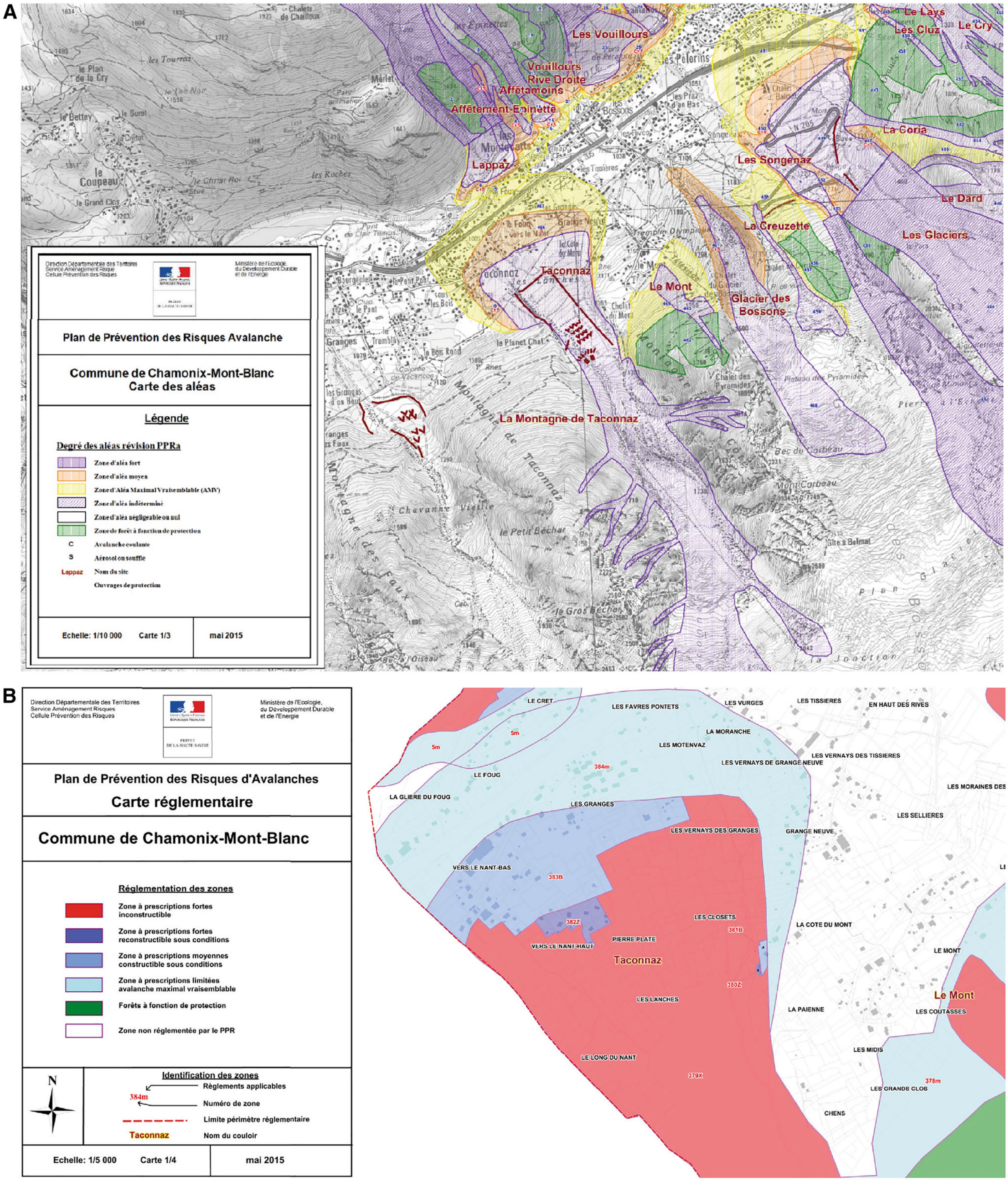

Fig. 4 Avalanche hazard and land-use planning maps resulting from current disaster risk management approaches in the vicinity of Taconnaz avalanche path. **A** Official avalanche hazard map highlighting areas threatened by hazard levels classified as "moderate", "strong" and "exceptional", protective forests and defence structures (Taconnaz protective system at the centre); **B** Corresponding land-use planning map (zoom on Taconnaz runout zone). According to the current French legislation, there is no explicit risk map "between" the hazard and land-use planning maps. Both **A**–**B** are from the 28 May 2015 edition of the local avalanche risk prevention plan—PPRA (MEDDE 2015), details and full legend at https://www.chamonix.fr/environnement-et-prevention-des-risques/prevention-des-risques/129-les-plans-opposables-ppri-ppra.html

327 articles (17% of the total of snow avalanche articles). For those two latter categories of articles, the increasing trend over the study period is almost continuous, from ∼ 10 to ∼ 45 articles/year and from ∼ 5 to ∼ 35 articles/year over the 2000–2021 period, respectively (Fig. 5B).

For all snow avalanche articles, “Earth and planetary science”, “Environmental science”, “Engineering” and “Physics and astronomy” are by far the dominant scientific fields/disciplines. These are supplemented by i) social sciences (the “Social science” field sensu stricto and “Arts and Humanities”) and further fields related to physics (“Material Science” and “Energy”), biological sciences, medical sciences, and mathematical/computing sciences. In both article corpuses that correspond to restricted searches, the respective weight of the different fields/disciplines is modified, but only slightly, with “Earth and planetary science” and “Environmental science” still largely dominating in all corpuses. Yet, it can be noted that the proportion of articles involving social and biological sciences in articles that target (long-term) snow avalanche risk is higher than in all snow avalanche articles. By contrast, the proportion of articles involving physics (in a broad sense) is lower, although it remains high. Eventually, in the three corpuses, articles explicitly referred as “Multidisciplinary” remain seldom (Fig. 5A).

Figure 5 results highlight that, in the recent scientific literature related to snow avalanches, most studies concern snow avalanche activity, its snow and weather drivers and the physical processes involved in snow avalanche release, propagation and possible interaction with obstacles, such as defence structures. Biological sciences are involved when interactions between avalanches and ecosystems, notably forests are addressed (protective role of forests, impact of avalanche activity on biodiversity, etc.). Medical sciences correspond mostly to articles focusing on avalanche accidents. Social sciences relate to studies of the social dimension of snow avalanche risk (risk awareness, behaviour in risky situations) and to historical analyses of past events. Hence, within the snow avalanche research, preferred approaches remain by far those related to the hazard component of the risk and even those devoted to elucidating physical processes, notably at small scales. The weight of these approaches/disciplines is lower in articles that target (long term) snow avalanche risk, a topic which is by essence more interdisciplinary than snow avalanche activity and related hazard. Also, the correspondence between increasing trends in long-term avalanche risk articles and their more integrated nature suggests an inflexion over the recent years towards more diverse and integrated studies. Yet, the remaining low number, even over the recent years, of articles either multidisciplinary and/or from fields different from geoscience, environmental sciences and/or physics indicates that research is still far from addressing the different dimensions and factors involved in long-term snow avalanche risk in a equilibrated way.

Current approaches for snow avalanche risk mitigation

To identify the main characteristics of the current state of the art of long-term snow avalanche risk, we further conducted a broad review of scientific, technical and institutional literature related to snow avalanche long-term risk. Following aspects were considered: hazard assessment, hazard mapping, risk mapping and zoning, land-use planning, design of mitigation measures, risk management and resilience. We focused on the conceptualization and operationalization currently existing in research and on their uses in practice. Resulting material was used to synthetize current approaches, notably their pro’s and con’s. We also identified how the knowledge specific to the snow avalanche field relates to broader literature on environmental risks, notably within the DRR community.[8]

This analysis first confirmed that methods currently developed and used in long-term snow avalanche risk management are clearly well suited to reduce the disaster risk and related death tolls and direct costs. For example, Ammann and Bebi (2000) assessed the efficiency of land-use planning strategies to limit the impact of the exceptional 1999 winter, and different studies demonstrated the cost effectiveness of existing mitigation strategies (e.g. Fuchs et al. 2007). More qualitatively, without the protective system, the risk in the Taconnaz runout area would probably be unacceptable for its current high population (Figs. 2–4). However, our review also indicated that current approaches/methods suffer from various limitations that makes them unable to account for all dimensions of long-term snow avalanche risk and notably to define optimal solutions that minimize total losses for a mountain community and its environment on the long range. What follows summarizes why this is the case.

Approaches mostly hazard oriented

The literature related to snow avalanche risk uses the classical definition of the different hazard, vulnerability

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[8] We did not produce a full review of existing methods regarding snow avalanche long-term risk assessment and mitigation already in use in different countries or published in the scientific literature. Such reviews already exist (e.g. IRASMOS consortium, 2009b), even if they should be updated with recent publications and approaches. We used these existing reviews, together with other relevant references, to understand and sum up the current situation.

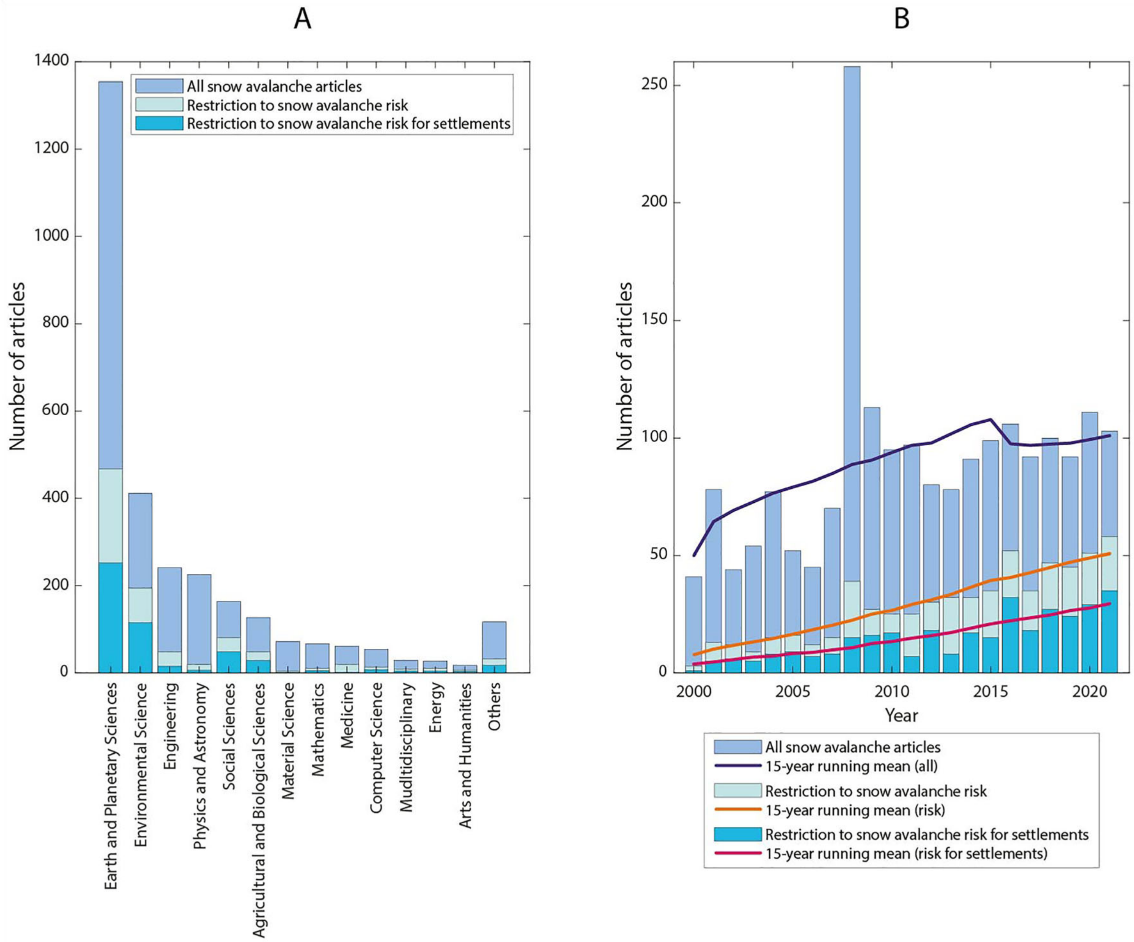

Fig. 5 Bibliometric analysis of scientific literature published between 2000 and 2021 regarding snow avalanches and related risk. **A** By scientific field/discipline. **B** By publication year

and exposure components of risk (Renn 2008a; 2008b; IPCC 2014). The latter is also largely adopted by most of the stakeholders in charge of snow avalanche disaster risk. Hence, a few approaches and countries propose maps of individual risk for buildings and people inside that combine avalanche hazard expressed in a proper probabilistic way (see below) with elements at risk and their vulnerability (Keylock et al. 1999). Land-use planning maps are then achieved on the basis of (supposed) accepted disaster risk levels (Arnalds et al. 2004). Such developments have seen growing interest over the recent years, with refinements even including cost–benefit considerations to optimally design simple defence structures (e.g. Eckert et al. 2009). However, most of the existing land-use planning approaches remain focused on the sole hazard component of the risk, with zones where construction is impossible, or possible with restrictions only, being defined on the basis of hazard levels (e.g. Irasmos consortium 2009b). In such approaches, risk is not explicitly quantified and mapped (Fig. 4).

Insufficient consideration of the stochastic nature of snow avalanche hazard

Existing approaches remain largely deterministic, using mostly knowledge stemming from physical sciences. As a striking example, Harbitz (1999) listed the impressive number of existing avalanche numerical models, and, since this last comprehensive review, their number has continued to increase dramatically (e.g. Bartelt et al. 2012; Gaume et al. 2018). However, in most guidelines/countries, reference hazards are defined on the basis of return periods[9] (e.g. Salm et al. 1990; IRASMOS Consortium 2009b; MEDDE 2015), technically the mean time in years separating two events of a given intensity, assuming independence and the same distribution for the successive events. This raises several difficulties. First, high-return period events are truly probabilistic concepts (Eckert et al. 2008a), so that "rules of thumbs" need to

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[9] Notably, the definition of land-use zones on the basis of 30–300-year return period avalanches is rather universal.

be used to associate a percentile (and, hence, a return period) to the simulation of a "large" avalanche. The classical technique is to assume that the return period of the avalanche can be assimilated to the one of an extreme snowfall that defines the input conditions in the release areas (e.g. Salm et al. 1990). Second, snow avalanche hazard is by essence multivariate (runout distance, impact pressure, etc.), whereas there is a one-to-one mapping between a percentile and a return period for a univariate variable only. This involves additional shortcuts in practice, such as (i) assuming that friction parameter values required for avalanche simulations can be defined in a deterministic way as function of some topographical characteristics of avalanche paths (Salm et al. 1990) and/or (ii) mixing probabilistic and deterministic concepts/thresholds to define land-use limits.[10] This improper use of the return period concept in snow avalanche modelling, and, more generally, the relative poverty of probabilistic models in this field (e.g. Perona et al. 2012) extends to the existing risk-based approaches that include elements at risk and their vulnerability. Indeed, many of them rely on one or a few scenarios for the hazard (e.g. Fuchs et al. 2004), which neglects its intrinsic stochastic nature. This overall situation relates to the prevalence in the snow avalanche field of approaches based on physics and geoscience already established by the bibliometric analysis. It is very different from, e.g. hydro-climatology where deterministic and probabilistic approaches (and, more widely, interdisciplinary approaches) cohabitate for long in more equilibrated ways (e.g. Clark et al. 2015).

Insufficient consideration of uncertainty sources

From a different perspective, all components of the risk suffer from high uncertainty levels, and this especially applies to rare events, such as those on which land-use planning decisions are taken. For instance, despite increasingly precise and exhaustive measurements on full-scale experimental sites (Köhler et al. 2018), specification of a realistic friction term representing the rheological behaviour of snow in motion is still a major open problem. The widely used Voellmy (1955) formulation has many advantages (e.g. Casassa et al. 1989), but remains partially *ad hoc*, with no fully explicit relation between the values of its coefficient and terrain and/or snow conditions. Hence, not only numerical models which are used to simulate the characteristics of high-return period avalanches still need to be locally calibrated to provide robust predictions, but, for each study case, different models with different rheologies should, in theory, be used and confronted with adequate metrics (Gneiting and Raftery 2007). Yet, in practice used calibration techniques often remain crude (Dent and Lang 1980; McClung and Lied 1987), which, e.g. addresses the issue of possible equifinality between friction parameter values only partially (Eckert et al. 2010b). Similarly, the vulnerability of buildings varies strongly with only slight modifications of construction technology (Favier et al. 2014), which introduces considerable uncertainty in risk assessment in practice since the exact nature of true buildings is often largely unknown. These different uncertainties should theoretically be accounted for in risk assessment, but they are currently very rarely considered. For instance, confrontation of different probabilistic-numerical models and validation of their predictions corresponding to high-return periods with independent data sources and proper scoring rules is almost never undertaken (Schläppy et al. 2014). More widely, even if some examples already demonstrated that calibration uncertainty may be very large (e.g. Ancey 2005; Gauer et al. 2009) and may even modify optimal decisions in avalanche engineering (Eckert et al. 2008b), this uncertainty is generally simply neglected in risk mapping and mitigation.

Assumed stationarity

All existing engineering procedures and most of research articles regarding land-use planning approaches make, explicitly or implicitly, the assumption of stationary conditions in all components of the risk. Yet, this is completely rebutted by the quick and strong changes ongoing in mountain socio-environmental systems ("Introduction" section). Hence, there exist safe zones that may become dangerous and existing defence structures ineffective in the future due to changes in hazard nature and levels, and the other-way round (e.g. reduction of avalanche hazard with warming and afforestation). Also, rising real estate pressure may render additional mitigation strategies useful to restrict the corresponding rise in total risk. Eventually, the high-return period events required by most zoning methods that focuses on the hazard component of the risk are extremely difficult (if not impossible) to properly define in a non-stationary context, both for practical (lack of data on sufficiently long time periods) and theoretical (no identification of the return period to a mean waiting time, e.g. Salas and Obeysekera 2014) reasons.

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[10] Often, the boundaries of red and/or blue zones in land-use maps result from the combination of an avalanche return period defined according to the return period of the snowfall with a 30-kPa maximal impact pressure threshold (e.g. IRASMOS Consortium, 2009b). Yet, in reality, for the same return period, "an infinity" of maximal impact pressures can occur (e.g. Eckert et al., 2010b), which makes the definition of a unique combination/limit theoretically impossible.

Approaches not holistic enough

The growing number of interdisciplinary research articles on long-term snow avalanche risk documented by the bibliographic search has resulted in an increasing focus on various aspects of the social, political and historical dimension of snow avalanche risk, including (i) documentation of risk perception and its evolution through time, (ii) importance of risk communication in the efficiency of risk management strategies and (iii) cost effectiveness of defence structure strategies taking into account protection, construction and reparation/maintenance costs (e.g. Fuchs and Bründl 2005; Bründl and Margreth 2021; Favier et al. 2022). Also the growing interest in ecosystem services has renewed analyses of interactions between (forest) ecosystems and snow avalanche activity (Teich et al. 2012). Yet, most of these approaches remain focused on the sole disaster risk. For instance, reference to SDGs as a whole remains largely absent: protection and application of standardized procedures (generally related to hazard levels) often come first, as well as economic interests related to land-use regulations. Also, even in the most risk-oriented approaches of snow avalanche long-term risk, the systemic risk conceptualization (Renn 2016; UNDRR 2019a), which is arguably the main novelty raised by Sendai's framework for DRR remains largely ignored. This overall lack of holistic perspective is arguably the most severe limitation of current approaches that precludes grasping and acknowledging the numerous physical, societal and ecosystemic dimensions that jointly shape avalanche long-term risk and how it changes through time.

Relation to SDGs, their targets and indicators

We eventually conducted a specific analysis of references to long-term snow avalanche risk assessment and mitigation within SDGs and their specific targets and indicators. This revealed that the introduction of the UN declaration that launched the 2030 Agenda (United Nations General Assembly 2015) highlights several points that relate, in a more or less direct way, to snow avalanche long-term risk: natural disasters increasingly numerous and intense, adverse effects of land degradation, urgent need of more resilient human infrastructures, actions required against climate change and in favour of biodiversity conservation. This introduction also points to the necessary development of integrated approaches to address these challenges. As a consequence, snow avalanche long-term risk relates more or less strongly to a high number of SDGs and targets (Table 1) and indicators that are used to monitor the progress towards SDGs (Table 2), some of the latter being almost identical to the targets themselves.

Specifically, the different aspects of snow avalanche long-term risk largely refer (i) for the disaster risk to SDG 11 (sustainable cities and communities) and SDG 13 (climate action) and, to a lesser extent, to SDG 1 (end poverty), in full coherence with the Sendai Framework and (ii) for adverse impacts of grey protection to SDG 15 (life on land). Hence, the SDG perspective clearly provides a broad view on snow avalanche long-term risk. However, no specific SDG/target/indicator really fits all the different aspects of snow avalanche risk and the potential conflicts and trade-offs that it encompasses, notably the competition between safety and other goals (development, biodiversity conservation) which is at the heart of the problem. Indeed, even if target 11.b explicitly calls for holistic disaster risk management, conflict exists between targets of SDGs 11 and 13 (protection conveyed by grey protection efficient in reducing the disaster risk versus its adverse impact on life on land). Also, non-sustainable trajectories for a mountain community through the choice of excessive land-use restrictions or building of too large defence structures refer to some targets of SDG 11, but with conflicts with other targets of SDG 11 (development with limited restrictions versus protection). As a consequence, the SDG perspective may be seen as not specific enough to support the elaboration of mitigation strategies more efficient than those currently in use and monitor the evolution of the overall risk on the long range. To fulfil this need, the following section formulates a paradigm that aims at being both holistic and adapted to the characteristics of the problem.

TOWARDS A MORE HOLISTIC PARADIGM

Guidelines

Our paradigm aims at managing long-term snow avalanche risk with a systemic approach able to define optimal compromises between protection and overall sustainability of mountain communities and their environment. Grounding on the state of the art summed-up in the previous section, it is formulated within a sustainability science perspective (Kates et al. 2001) and connects with major environmental policy guidelines and their ongoing convergence: SDGs, Sendai framework and the explicit mapping between their targets (UNDRR 2019b), the "disaster risk, global change and sustainability nexus" (Peduzzi 2019), and "the challenge of achieving risk reduction across Sendai, Paris and the SDGs" (Handmer 2019). "Discussion, conclusion and outlooks" section discusses its novelty with regards to the state of the art of the field.

More concretely, and, by contrast to existing approaches, our paradigm can be summed up with the keywords risk-based, variability, uncertainty, non-stationarity and

Table 1 SDGs and specific targets relevant for long-term snow avalanche risk assessment and mitigation

Target 11.3	By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries
Target 11.5	By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations
Target 11b	By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels
Target 13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries
Target 15.1	By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements
Target 15.2	By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally
Target 15.4	By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development
Target 15.9	By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and account
SDG 1 (without specific target)	Enhancing resilience of the most vulnerable towards extreme climate events and environmental disasters

Table 2 SDG indicators relevant for long-term snow avalanche risk assessment and mitigation

Indicator 11.3.1	Ratio of land consumption rate to population growth rate
Indicators 11.5.1 and 13.1.1	Number of deaths, missing persons and persons affected by disaster per 100,000 people
Indicator 11.5.2	Direct disaster economic loss in relation to global GDP, including disaster damage to critical infrastructure and disruption of basic services
Indicator 11.b.1	Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030
Indicator 11.b.2 and 13.1.3	Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies
Indicator 15.1.1	Forest area as a proportion of total land area
Indicator 15.2.1	Progress towards sustainable forest management
Indicator 15.4.1	Coverage by protected areas of important sites for mountain biodiversity
Indicator 15.4.2	Mountain Green Cover Index

holistic (Fig. 6). Hence, instead of current at-risk zones that generally correspond to the extension of reference avalanche events without real consideration of process randomness, uncertainty sources, changes in time of the different risk components and with sole focus on the disaster risk with, often, an insufficient consideration of its social, economic, political, historical and environmental components, we suggest:

- To systematize the expression of disaster risk as a casualty/destruction rate, integrating all possible avalanches, small, large and extremes and the uncertainty affecting the different hazard, exposure and vulnerability components of the risk;
- To explicitly consider real estate pressure, as well as other economic, social and environmental constraints within the analysis, so as to asses all potential sources of losses at the scale of the considered mountain community and to propose strategies that minimize them altogether. This means switching from land-use limits defined on the basis of the sole hazard and in a strict top-down manner to land-use limits and further risk management options defined as optimal compromises between different types of losses. Those typically

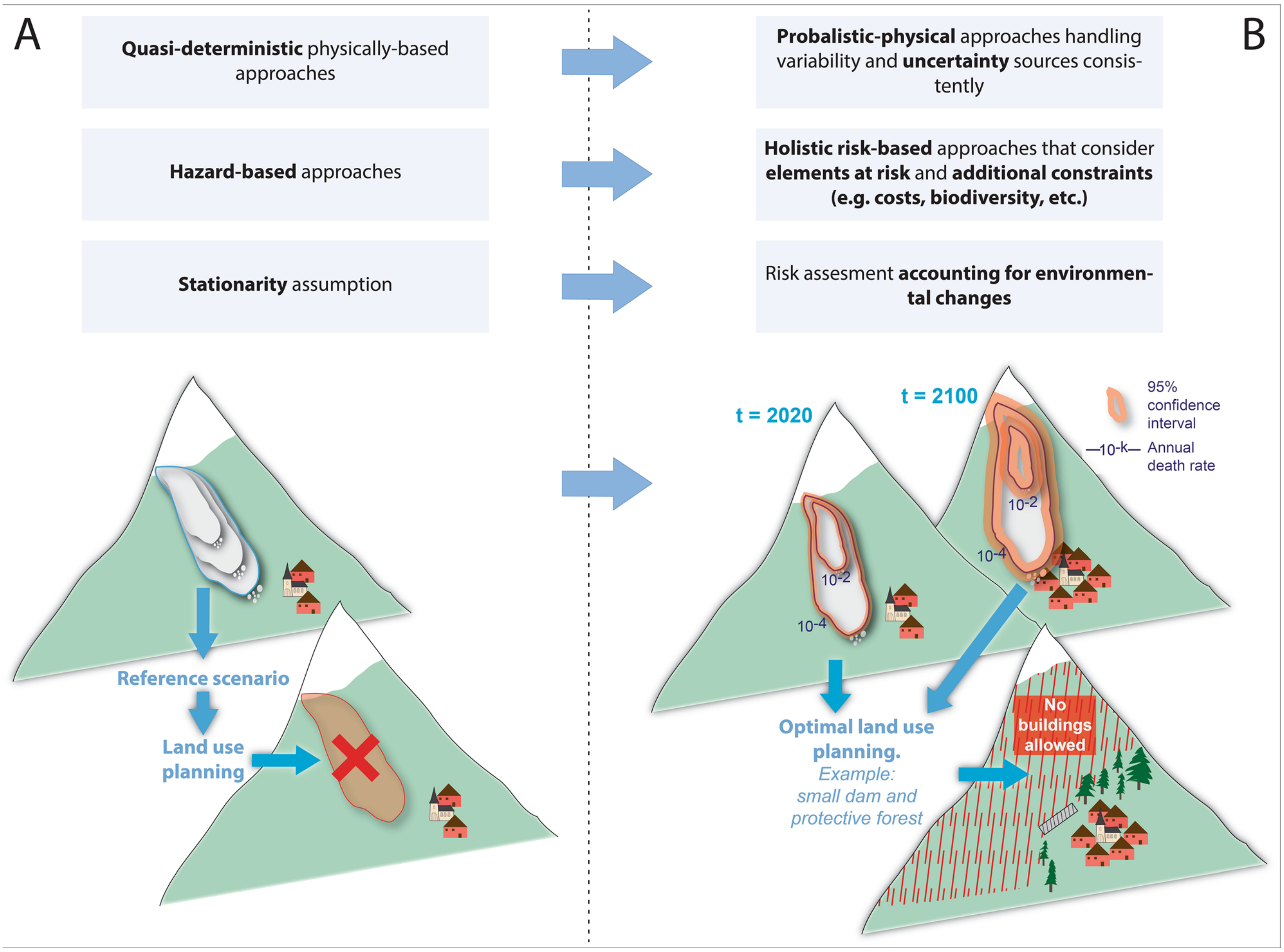

Fig. 6 From **A** to **B** the proposed paradigm shift in long-term snow avalanche risk assessment and mitigation. Simplified illustration for a synthetic mountain slope. From the current (**A**) to the proposed (**B**) land-use map, one switches from a red zone defined by the sole extension of a reference avalanche event to a red zone based on risk estimates (death rates) and integrating uncertainty sources (larger in the future than in the current situation), various constraints (cost–benefit efficiency, ecosystem conservation and aesthetics) and changes through time of hazard and elements at risk

require co-construction with all concerned parties, integration of local risk awareness and adapted communication strategies to be properly defined and later accepted.[11] In the example provided by Fig. 6, the association of a small dam and a protective forest is thus promoted as the most suitable option that jointly mitigate disaster risk, other losses and respects wildlife. Illustration is provided with a simplified land-use map highlighting only areas where construction in possible/forbidden, with no further refinements, such as blue zones;

- To work in an explicit non-stationary setting that analyses the full past to future trajectories of considered mountain systems (Fig. 7). This starts with considering past avalanche events within their socio-environmental context, which may be strongly different from the current one, and evaluates from these and additional sources of knowledge past to future hazard and risk trajectories. Eventually, the influence of different land-use strategies and their respective efficiency towards a chosen temporal horizon may be compared (Fig. 7), leading to land-use maps integrating projected changes over the chosen time period. Analysis requires careful consideration of numerous uncertainty sources, notably those related to the evolution of the whole socio-environmental system (society, ecosystems, climate). The illustrative example provided by Fig. 7 highlights

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[11] This involves that all parties, from citizens to the state, agree on the principle that risk should be managed in a transparent and objective manner, with the goal of minimizing overall losses/costs, and not to favour individual interests and/or, e.g. deliberately sacrifice some people (or other elements at risk). This is not always true in practice and may even be seen as an utopia. Yet, such an approach is arguably the only one that will lead to trust building and to solutions that will have a chance to be understood and respected by all parties on the long range. A required starting point it to carefully analyse and understand the drivers of the risk in each local situation.

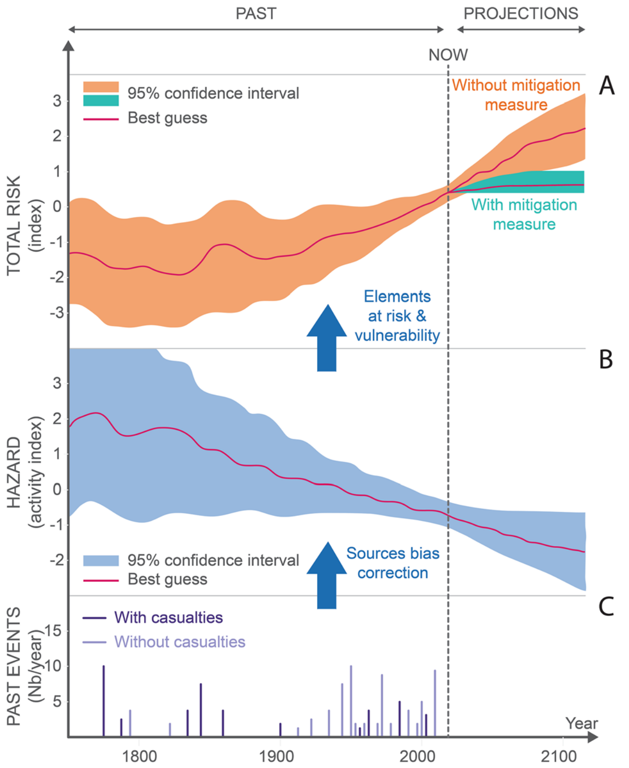

Fig. 7 Accounting for non-stationarity in snow avalanche risk assessment and mitigation. Synthetic case study with arbitrary indices as hazard and risk measures showing how from chronicles of past events (**C**), evolution with climate and society of avalanche hazard (**B**) and related risk for settlements (**A**) can be quantified, including uncertainty as function of time. A also illustrates how different land-use planning strategies affect the future of risk. Moving from C to B involves accounting for the changing nature and amount of sources related to avalanches as function of time (Giacona et al. 2021). Moving from B to A requires combining changes in hazard with changes in exposure and vulnerability (e.g. Keylock et al. 1999)

complex patterns of changes: (i) the changing amount and nature (e.g. with/without casualties and size of the events) of past events that can be retrieved from historical sources with a decreasing information as one goes back in time, (ii) an overall decrease in avalanche hazard since the late nineteenth century driven by warmer climate conditions, (iii) yet, a drastic increase in avalanche risk over the same period driven by increasing exposure,[12] and (iv) increasing uncertainty levels (larger confidence intervals around the best guess) as one moves farther and farther away from current conditions, both in the past and in the future.

A formal framework to fulfil these needs

Despite existing progresses, operationalizing our paradigm is still a tremendous task that includes numerous difficult questions amongst which: (i) the assessment of past and future changes in mountain socio-environmental systems, (ii) the accurate evaluation of the multivariate probability distribution of avalanche hazard at the slope scale, (iii) the definition of risk measures and mitigation strategies accounting for non-stationarity and/or for various behaviours towards risk / levels of risk awareness and (iv) the determination of acceptable compromises between precision and computation times, etc. Solving these different open challenges goes far beyond our prospective analysis. Yet, in what follows we propose first hints to follow the right track.

First, achieving a holistic assessment and mitigation of long-term avalanche risk requires a truly interdisciplinary effort. Relevant disciplines includes physics and engineering (mass movement mechanics and interaction with structures), but also climate science and ecology to treat the changing environment, and history, social and political science and economy to handle the social dimension of risk. The latter are notably required to understand the main drivers of local (individual and collective) risk awareness and their changes through time and to take them into account (assessment, co-construction, communication) in the design of management strategies (Fig. 8).

Second, an adequate framework needs to be used to merge and integrate these knowledge sources in a consistent manner. Qualitative geohistorical modelling (Giacona et al. 2019) is arguably a good option to describe and understand the behaviour of the whole risk system and how/why it changes through time. Yet, to provide quantitative diagnoses and notably quantitative projections at various temporal horizons (Fig. 7), a quantitative approach is required and formal statistical modelling implemented within a decisional setting may be the right option for that.

In fact, statistical modelling is nothing more than relating probabilistic models to data with rigorous treatment of uncertainty up to probabilistic predictions (Davison 2003). Different specific model classes may be usefully combined: (i) extreme value models to capture the peculiar behaviour of extreme avalanches (Coles 2001; Ancey 2012), (ii) spatio-temporal models (e.g. Wikle 2003) to bridge spatial scales ("Bridging scales" section) and account for temporal changes, (iii) probabilistic-numerical mass movement models to combine conservation constraints conveyed by numerical flow models and natural randomness in a proper way (Eckert et al. 2010b) and (iv) risk models and decision theory (Von Neumann and Morgenstern 1953) to evaluate and minimize losses (Fig. 8). Integration of different disciplines is naturally

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[12] "Variability in the risk, its drivers and management practices" section discusses the variability of such patterns of change amongst socio-environmental contexts.

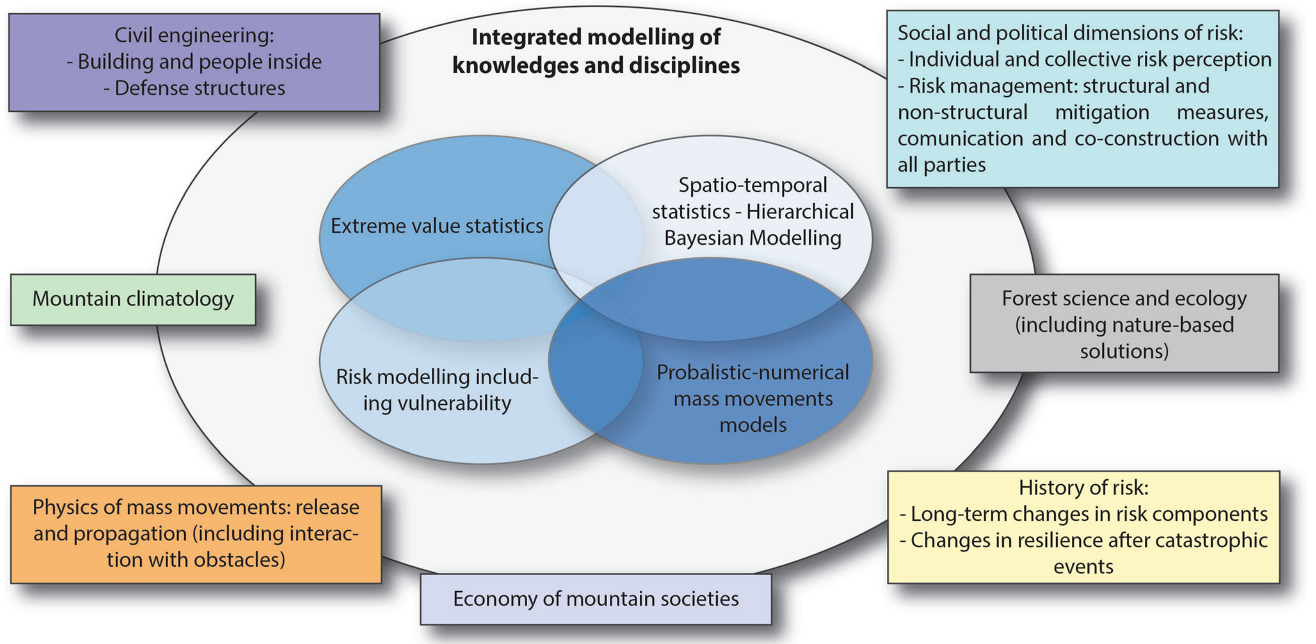

Fig. 8 Disciplines involved in the proposed holistic paradigm for long-term snow avalanche risk assessment and mitigation, and a possible formal modelling avenue to integrate them towards a common purpose

achieved within a Bayesian context, which introduces equivalence between contributions from various fields (Clark 2005) and accounts for uncertainty sources in a consistent way from flow model calibration to risk assessment and optimal design (Eckert et al. 2012; Fischer et al. 2020). Within this comprehensive formal framework, subsequent concepts, such as compound or cascading events (e.g. Zscheischler et al. 2018; Pescaroli and Alexander 2018), domino effects (Cozzani et al. 2005) and multi-risks (Curt 2020), which currently see growing interest in risk science to account for the complexity of socio-environmental system, may also proof useful for snow avalanche long-term risk.

Bridging scales

Amongst the various conceptual and technical challenges conveyed by our proposed paradigm shift, successfully articulating a wide range of spatial scales may be one of the toughest (Fig. 9A). This involves a nested modelling approach, where embedded scales and their relations are considered. Hierarchical Bayesian framework (HBM) is a straightforward way to handle such issues, and existing examples already demonstrate its ability to share information between different paths at a regional scale and to account from time trends resulting from climate change to perform spatio-temporal assessment of avalanche hazard and risk (Grêt-Regamey and Straub 2006; Eckert et al. 2010c; Rougier and Kern 2010; Lavigne et al. 2015). Combining relations inferred at the local scale between avalanche risk and its drivers with future socio-environmental scenarios and different land-use solutions should result in the desired future risk trajectories and may allow the choice, amongst competing mitigation strategies, of an optimal solution (Fig. 7). Eventually, partition of the sources of uncertainty and variability in these trajectories using a space–time variance decomposition (Evin et al. 2019) may provide (i) the respective weight of the different contributions/assumptions (e.g. Global Circulation Model—GCM, Regional Circulation Model-RCM, impact model and risk measure) and (ii) when in the future different mitigation strategies will lead to significant differences in risk (which is sometimes denoted as the time of emergency).

However, feeding this formal framework with relevant information to provide meaningful prospective diagnoses remains a formidable challenge. Indeed, the typical approach of climate modelling is to downscale global trends resulting from greenhouse gas scenarios to local impacts within a “cascading” ensemble simulation framework (IPCC 2021, Fig. 9B). In theory, a HBM strategy should allow handling resulting nested datasets in a rigorous manner to integrate future projections of snow, weather and socio-environmental drivers within a regional-to-local (slope/path scale) avalanche activity and risk model. Yet, successfully downscaling GCM-RCM outputs to the local scale remains a largely open problem (e.g. Maraun et al. 2010), especially difficult over a mountain topography due to prevailing gradients and wind effects (Lehning et al. 2011). Switching from meteorological

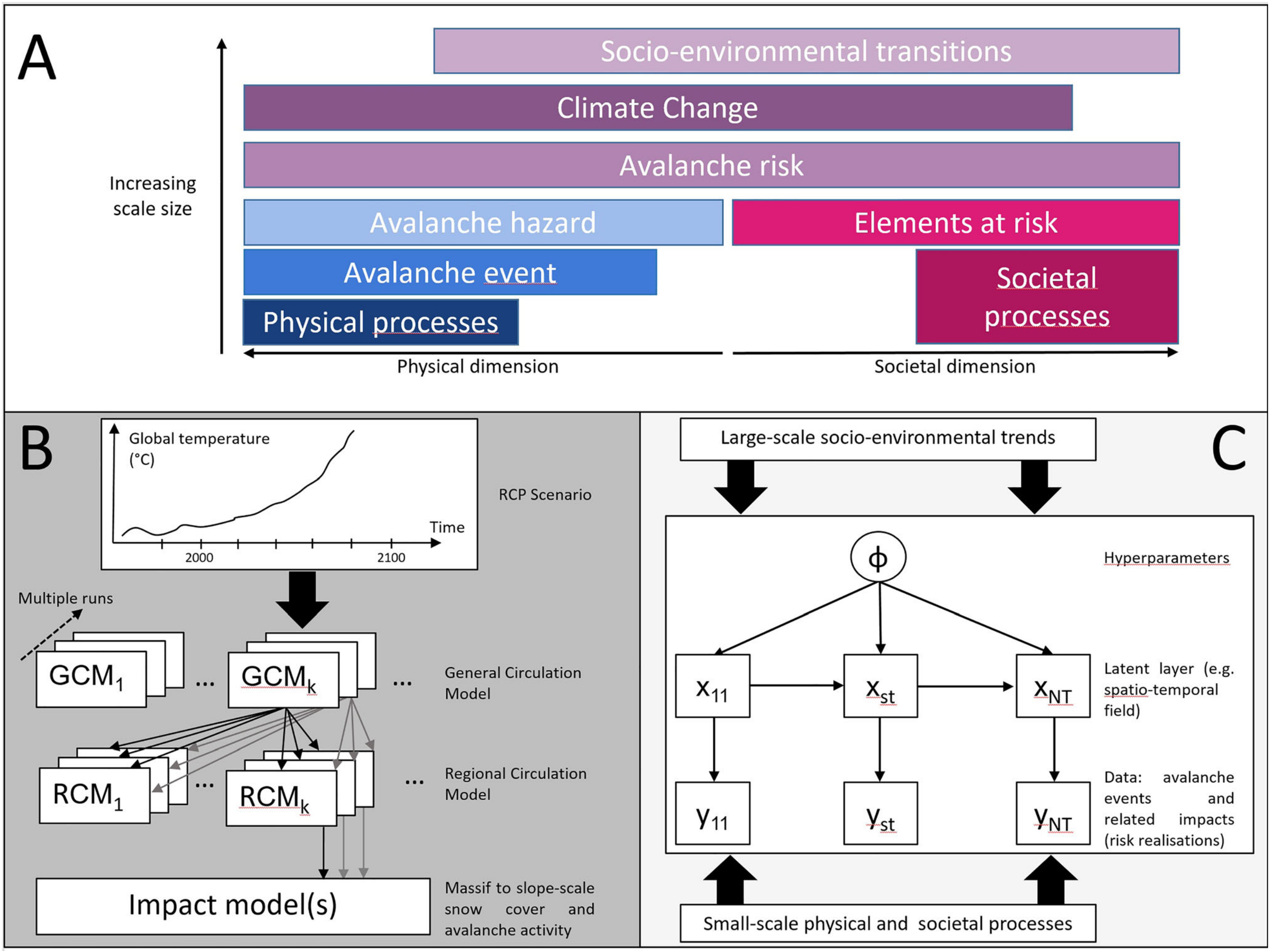

Fig. 9 Scales relevant for avalanche risk and frames to bridge them. **A** Snow avalanche risk at intermediate (slope) scales, where avalanche activity interacts with elements at risk; **B** typical top-down climate modelling approach and **C** Hierarchical Bayesian Modelling approach. In A, avalanche hazard means seeing avalanche events as random occurrences as function of changing snow and weather conditions. In **B**, at each stage/scale, different GCM/RCM realizations account for varying input conditions (uncertainty and variability sources), leading to ensemble runs. In **C**, the nested model structure links path/slope scale hazard/damage occurrences to each other's within a given massif/region. A major difficult is to feed the nested model structure with relevant information related to small-scale processes and large-scale drivers/trends

conditions to snow cover and snow stability adds another level of complexity (e.g. Schweizer et al. 2003) and how, in details, climate change affects certain critical processes such as snow drift and weak layer formation remains largely unknown (Mock et al. 2017). Eventually, converting large-scale societal trends (population, practices, etc.) to local changes in exposure and vulnerability may be even tougher. Hence, meaningfully combine at the path/slope scale i) the small-scale physical and societal processes driving hazard occurrence and magnitude and individual exposure to risk and ii) the large-scale drivers resulting from environment–society interactions (Fig. 9C) requires refined assessment and understanding of these various processes, their changes through time and their variability from one mountain context to another ("Variability in the risk, its drivers and management practices" section). This emphasizes the necessity, while improving knowledge integration within the proposed approach and nested model structure (Fig. 9C), to pursue research efforts on these processes in order to reduce most critical epistemic uncertainties and, hence, "feed the framework" in a meaningful way.

Variability in the risk, its drivers and management practices

The analysis was illustrated with the Taconnaz case and the French alpine context. In most of the European alpine space, the overall characteristics of long-term snow avalanche risk are rather similar to the French case, and methods currently in use to manage land use (and related legal prescriptions) are more or less harmonized

(IRASMOS Consortium 2009a). For instance, Fig. 7 documents patterns of change fairly common in the European Alpine valleys. Indeed, in many of these, a rapidly increasing population has been attracted over the last decades by natural resources and amenities (e.g. Gleeson et al. 2016). This has changed the long-established interactions between humans and nature and, notably, the perception of the territory and its threats by populations. Agro-pastoral activities have rapidly declined, resulting in land abandonment and afforestation, whereas favourable locations for winter tourism have seen the installation of increasingly large ski resorts. This lead to construction of dwellings in locations increasingly exposed to avalanches and, more broadly, broke the chain of risk memory in the population (Favier and Granet-Abisset 2000). Also, overall, the protective effect of forests has increased due to the rising tree line. However, even in the European Alps, due to local physical and/or societal peculiarities, the risk and its components may have evolved very differently at some locations (Zgheib et al. 2022). An obvious example is that, after a wildfire, the risk may have brutally strongly increased due to the loss of the forest protective effect.

More broadly, spatial variability in snow avalanche long-term risk components and their patterns of change is extremely high amongst mountain environments worldwide. This variability is due to different physical and/or socio-environmental contexts and trajectories (Mathieu 2005; Borsdorf and Braun 2008), e.g. different and/or differently changing climate conditions and prevalent avalanche activity regimes, lower or higher real estate pressure in avalanche-prone terrain as function of population density, space available and attractiveness of the territory, existence or not of specific elements at risks such as critical infrastructures, different risk awareness and behaviour towards risk and possible interactions between all these factors. For example, differences in risk experiences and past occurrence of catastrophic events contribute to explain and shape existing differences in risk state of fate and management policies, e.g. a more or less high number of elements at risk, implying a more or less high implicitly accepted risk level. Also, the loss of the memory of the risk explains patterns of change in levels of exposure in certain mountain contexts (Favier and Granet-Abisset 2000).

As examples of this variability, snow avalanche hazard has been shown to decrease with climate warming and shrinkage of snow amounts in some areas of the US (Peitzsch et al. 2021) and more dramatically in the Vosges mountains, North-East France (Giacona et al. 2021), which decreased the risk for settlements downslope. A similar decrease in risk could be attributed to land abandonment and afforestation in the Asturian range, North-West Spain (García-Hernández et al. 2017). The opposite pattern has been evidenced in the Himalayas, presumably because of higher wet-snow instability at elevations where snow amounts are still sufficient (Ballesteros-Cánovas et al. 2018). Vera-Valero et al. (2016) and Rheinberger et al. (2009) pointed to the importance in overall long-term risk due to snow avalanche of mining activities and major traffic roads in the Chilean Andes and the Swiss Alps, respectively. Eventually, Bruno, (2013), Podolskiy et al. (2014) and Brugnara et al. (2017) could document the role of very specific historical contexts in the generation of highly risky situations and, hence catastrophic events, namely the political regime of the Soviet Union, the colonization of the Sakhalin island and the preparation of WW2 by the Japanese regime, and the occupation of high-elevation military positions during WW1, respectively.[13]

Due to this variability, a risk management strategy useful in a given context is not necessarily relevant in another context. For instance, very refined metric scale land-use plans are of little interest in countries/areas where real estate pressure remains extremely low and the risk-free space is large. Hence, local conditions in hazard magnitude and frequency, elements at risk, management practices, etc., and their patterns of change always need to be assessed, understood and accounted for to elaborate efficient risk management strategies. To this aim, we posit that our approach, even if it does not provide solutions directly applicable in all contexts, may provide a benefit of rather universal value. Indeed, due to its holistic, integrative and formal nature, it may have the flexibility and theoretical grounding required to (i) adapt to the diversity of situations and (ii) sum up, in each case, the relevant knowledge and data sources (data types, scales, etc.) in a consistent manner, so as to deliver the required quantitative diagnoses and mitigation solutions.

DISCUSSION, CONCLUSION AND OUTLOOKS

In mountain environments, snow avalanches are a prevalent threat. Risk management in valley bottoms faces the difficult challenge to define meaningful compromises between protection and overall sustainability of communities and their environment. Methods holistic enough to (i) consider all potential sources of losses, (ii) account for the high uncertainty levels that affect all the components of the risk, and (iii) cope for complex and marked non-stationarities should theoretically be employed. By contrast, so far, research and operational methods remain dominated by "traditional" engineering approaches that can be

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[13] This is only a selection of the variability of situations currently documented in the literature. A full review remains to be written, and, arguably, many other different cases exist but have not been specifically studied so far.

summed up as deterministic, hazard oriented, and stationary. Shortcuts are then required to convert inputs provided by, e.g. numerical flow models into land-use maps and design values for defence structures. Even though these approaches are clearly efficient in reducing exposure to disaster risk, they suffer from many theoretical and practical shortcuts that makes them unable to fully address the challenge of sustainability of mountain communities and their environment. We notably argue that, by focusing on the disaster risk or even on its physical component only, they (i) neglect different types of potential losses and (ii) do not consider interlinkages and competing targets related to the numerous interactions between snow avalanche activity, social practices and ecosystems that altogether define long-avalanche risk and its changes through time. More widely, current approaches may result in non-optimal solutions that may lead to non-sustainable trajectories on the long range.

These conclusions were reached on the basis of a broad literature review and an analysis of the relations between snow avalanche long-term risk and SDGs. A finer quantitative bibliometric study that the one we performed could have been conducted to refine the findings (e.g. exact disciplines used by authors instead of Scopus outputs only and location of studied cases). Similarly, a deeper review of existing methods to assess and mitigate snow avalanche risk could have been produced. However, we argue that our analysis is sufficient to support our conclusions. Specifically, we showed that important progresses have been clearly made over the recent years towards, e.g. a better consideration of the risk concept and of its vulnerability and exposure components within long-term snow avalanche risk management (e.g. Bründl and Margreth 2021). However, existing risk assessment and mitigation approaches remain more oriented towards physics, and, therefore, less interdisciplinary, holistic and formalized than in other fields of DRR, e.g. mitigation of risks related to floods or tsunamis. This may come from the fact that research on snow avalanche long-term risk has a long tradition with most of developments currently in use that have been proposed by people with background in geosciences, physics and engineering (e.g. Salm 2004; Giacona et al. 2017b). Also, snow avalanche risk concern areas of (rather) limited geographical extent (mountain environments), which makes it a small field of research where paradigm shifts are slow. This pleads for, in the future, better connect the research efforts within this specific community with the broad DRR and risk modelling literature and community and the various disciplines these encompass. To this aim, it is hoped that this work will contribute to attract and involve in research on snow avalanche long-term risk more people working on various types of risks and on various dimension of risks.

Moreover, even if the systemic vision is now well shared amongst the DRR community (UNDRR 2019a), we highlighted that long-term snow avalanche risk includes aspects that require an even wider perspective and we tried to answer this need with an analysis based on SDGs. As SDGs offer by essence an extremely encompassing vision of environmental issues, this lead elements that may be seen at first glance as not specific enough. Yet, they were helpful to provide a broad "look outside the box", which allowed reconsidering certain practices of the field and contributed to better identify linkages, trade-offs and interactions that shape long-term snow avalanche risk beyond the sole DRR perspective. However, it appeared that, within the 2030 Agenda, no specific target and indicator exist that perfectly fits long-term snow avalanche risk, notably the competition between protection and overall sustainability which is at the heart of the problem. Specific indicators could/should therefore be developed in further work to follow the development of long-term snow avalanche risk in the various mountain contexts described in "Variability in the risk, its drivers and management practices" section. Conclusions of the analysis also highlighted the need for a specific holistic framework able to both (i) grasp the complexity of the processes at play and (ii) support the elaboration of efficient mitigation strategies usable in practice for land-use planning in avalanche-prone terrain.

As an answer, we eventually elaborated a paradigm for long-term snow avalanche risk assessment and mitigation that formally integrates knowledge from relevant disciplines within data science and probabilistic techniques, notably using Hierarchical Bayesian Modelling, extreme value statistics and decision theory. Some elements of our approach have already been implemented or even combined in research (e.g. risk modelling and extreme value statistics in Favier et al. 2016), sometimes even in operational risk management, such as risk-based assessment with destruction or casualty rates, integration of the protective effect of forest cover within risk management, "full" probabilistic modelling of avalanche activity or co-construction with concerned parties of better accepted mitigation solutions. Yet, these approaches that go in an arguably desirable direction remain far from dominant in the field (see before). Also, we argue that a comprehensive paradigm that formulates snow avalanche long-term risk in an integrated sustainability perspective and, in addition, provides a quantitative framework to implement it was still lacking. The one we are proposing potentially does that and notably explicitly accounts for non-stationarity and various sources of uncertainty up to the land use solutions, which is, e.g. different from "simply" establishing that non-stationary and/or uncertainty sources exist and may affect the results.

Yet, our analysis was, at this stage, rather theoretical, so that our framework now still needs to be put at work. Expected benefits in operational contexts may include projections of overall long-term risk due to snow avalanches at various temporal horizons, how these projections are modified by land-use decisions, assessment of the impact of different green and/or grey defence structures and subsequent choice of optimal solutions that minimize total losses towards a chosen temporal horizon. To this aim, existing formal development should be combined and expanded to better integrate data, knowledge and disciplines in a consistent manner. This effort should include the outcomes of developments that were proposed, sometimes for long, apart from the framework we propose (e.g. research focusing on the sole hazard component of risk or neglecting its probabilistic nature) but will in fine contribute to the overall objective of a more efficient assessment and mitigation of the risk. To this aim, we recall that going on with the reduction of uncertainty regarding most critical processes with continuous research efforts remains critical.

Finally, our analysis focused on long-term snow avalanche risk only and could be expanded in the future i) to short-term snow avalanche risk for traffic road regulation, safety of ski resorts and further mountain activities and/or ii) to related problems (risks due to rock fall, periglacial processes, debris flows, etc.) that share many common characteristics with snow avalanche risk: complexity and knowledge gaps, climate sensitivity, lack of holistic view and formal framework in current management strategies, etc. We posit that such enlargements would help addressing the issue of sustainability of mountain environments even more broadly.

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Declarations

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

REFERENCES

Altaweel, M., Virapongse, A., Griffith, D., Alessa, L., Kliskey, A. (2015). A typology for complex social-ecological systems in mountain communities. Sustainability: Science, Practice and Policy, 11, pp. 1–13.

Ammann, W., Bebi, P. (2000). WSL Institute for Snow and Avalanche Research SLF, Der Lawinenwinter 1999, Ereignisanalyse. SLF Davos, 588 p.

Ancey, C. 2005. Monte Carlo calibration of avalanches described as Coulomb fluid flows. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 363: 1529–1550.

Ancey, C. 2012. Are there “dragon-kings” events (ie genuine outliers) among extreme avalanches? *The European Physical Journal Special Topics* 205: 117–129.

Arnalds, P., K. Jonasson, and S.T. Sigurdson. 2004. Avalanche hazard zoning in Iceland based on individual risk. *Annals of Glaciology* 38: 285–290.

Ballesteros-Cánovas, J.A., D. Trappmann, J. Madrigal-González, N. Eckert, and M. Stoffel. 2018. Climate warming enhances snow avalanche risk in the Western Himalayas. *Proceedings of the National Academy of Sciences* 115: 3410–3415.

Bartelt, P., Bühler, Y., Buser, O., Christen, M., Meier, L. 2012. Modeling mass-dependent flow regime transitions to predict the stopping and depositional behavior of snow avalanches. Journal of Geophysical Research: Earth Surface, 117.

Bebi, P., D. Kulakowski, and C. Rixen. 2009. Snow avalanche disturbances in forest ecosystems—State of research and implications for management. *Forest Ecology and Management* 257: 1883–1892.

Beniston, M., M. Farinotti, D. Stoffel, L. Andreassen, E. Coppola, N. Eckert, A. Fantini, F. Giacona, et al. 2018. The European mountain cryosphere: A review on past, current and future issues. *The Cryosphere* 12: 759–794.

Borsdorf, A., Braun, V. (2008). The European and global dimension of mountain research. An Overview. Journal of Alpine Research| Revue de Géographie Alpine, 96, pp. 117–129.

Braun, T., B. Frigo, B. Chiaia, P. Bartelt, D. Famiani, and J. Wassermann. 2020. Seismic signature of the deadly snow avalanche of January 18, 2017, at Rigopiano (Italy). *Scientific Reports* 10: 1–10.

Brugnara, Y., S. Brönnimann, J.M. Zamuriano Carbajal, J. Schild, C. Rohr, and D. Segesser. 2017. Reanalysis sheds lights on 1916 avalanche disaster. *ECMWF Newsletter* 151: 28–34.

Bründl, M., Margreth, S. (2021). Integrative risk management: The example of snow avalanches. In Snow and Ice-Related Hazards, Risks, and Disasters, Elsevier, pp. 259–296.

Bruno, A. 2013. Tumbling snow: Vulnerability to avalanches in the Soviet North. *Environmental History* 18: 683–709.

Bühler, Y., E.D. Hafner, B. Zweifel, M. Zesiger, and H. Heisig. 2019. Where are the avalanches? Rapid SPOT6 satellite data acquisition to map an extreme avalanche period over the Swiss Alps. *The Cryosphere* 13: 3225–3238.

Casassa, G., H. Narita, and N. Maeno. 1989. Measurements of friction coefficients of snow blocks. *Annals of Glaciology* 13: 40–44.

Clark, M.P., B. Nijssen, J.D. Lundquist, D. Kavetski, D.E. Rupp, R.A. Woods, J.E. Freer, E.D. Gutmann, et al. 2015. A unified approach for process-based hydrologic modeling: 1. Modeling concept. *Water Resources Research* 51: 2498–2514.

Clark, J.S. 2005. Why environmental scientists are becoming Bayesians. *Ecology Letters* 8: 2–14.

Coles, S. 2001. *An introduction to statistical modelling of extreme values*. Berlin: Springer.

Cozzani, V., G. Gubinelli, G. Antonioni, G. Spadoni, and S. Zanelli. 2005. The assessment of risk caused by domino effect in quantitative area risk analysis. *Journal of Hazardous Materials* 127: 14–30.

Curt, C. 2020. Multirisk: What trends in recent works?—A bibliometric analysis. *Science of the Total Environment* 763: 142951.

Davison, A.C. 2003. *Statistical models*. Cambridge: Cambridge University Press.

Dent, J.D., and T.E. Lang. 1980. Modeling of snow flow. *Journal of Glaciology* 26: 131–140.

Eckert, N., C. Coleou, H. Castebrunet, M. Deschatres, G. Giraud, and J. Gaume. 2010a. Cross-comparison of meteorological and avalanche data for characterising avalanche cycles: The example of December 2008 in the eastern part of the French Alps. *Cold Regions Science and Technology* 64: 119–136.

Eckert, N., C.J. Keylock, D. Bertrand, E. Parent, T. Faug, P. Favier, and M. Naaim. 2012. Quantitative risk and optimal design approaches in the snow avalanche field: Review and extensions. *Cold Regions Science and Technology* 79: 1–19.

Eckert, N., C.J. Keylock, H. Castebrunet, A. Lavigne, and M. Naaim. 2013. Temporal trends in avalanche activity in the French Alps and subregions: From occurrences and runout altitudes to unsteady return periods. *Journal of Glaciology* 59: 93–114.

Eckert, N., M. Naaim, F. Giacona, P. Favier, A. Lavigne, D. Richard, F. Bourrier, E. Parent, et al. 2018. Repenser les fondements du zonage règlementaire des risques en montagne «récurrents». *La Houille Blanche* 2: 38–67.

Eckert, N., M. Naaim, and E. Parent. 2010b. Long-term avalanche hazard assessment with a Bayesian depth-averaged propagation model. *Journal of Glaciology* 56: 563–586.

Eckert, N., E. Parent, T. Faug, and M. Naaim. 2008a. Optimal design under uncertainty of a passive defense structure against snow avalanches: From a general Bayesian framework to a simple analytical model. *Natural Hazards and Earth System Sciences* 8: 1067–1081.

Eckert, N., E. Parent, T. Faug, and M. Naaim. 2009. Bayesian optimal design of an avalanche dam using a multivariate numerical avalanche model. *Stochastic Environmental Research and Risk Assessment* 23: 1123–1141.

Eckert, N., E. Parent, R. Kies, and H. Baya. 2010c. A spatio-temporal modelling framework for assessing the fluctuations of avalanche occurrence resulting from climate change: Application to 60 years of data in the northern French Alps. *Climatic Change* 101: 515–553.

Eckert, N., E. Parent, M. Naaim, and D. Richard. 2008b. Bayesian stochastic modelling for avalanche predetermination: From a general system framework to return period computations. *Stochastic Environmental Research and Risk Assessment* 22: 185–206.

Evin, G., B. Hingray, J. Blanchet, N. Eckert, S. Morin, and D. Verfaillie. 2019. Partitioning uncertainty components of an incomplete ensemble of climate projections using data augmentation. *Journal of Climate* 32: 2423–2440.

Favier, P., N. Eckert, D. Bertrand, and M. Naaim. 2014. Sensitivity of avalanche risk to vulnerability relations. *Cold Regions Science and Technology* 108: 163–177.

Favier, P., N. Eckert, T. Faug, D. Bertrand, and M. Naaim. 2016. Avalanche risk evaluation and protective dam optimal design using extreme value statistics. *Journal of Glaciology* 62: 725–749.

Favier, P., N. Eckert, T. Faug, D. Bertrand, I. Ousset, G. Candia, and J.C. de la Llera. 2022. A framework to account for structural damage, functional efficiency and reparation costs within the optimal design of countermeasures: Application to snow avalanche risk mitigation. *Cold Regions Science and Technology* 199: 103559.

Favier, R., and A.M. Granet-Abisset. 2000. Histoire et mémoire des risques naturels. Maison des Sciences de l'Homme-Alpes.

Fischer, J.T., A. Kofler, A. Huber, W. Fellin, M. Mergili, and M. Oberguggenberger. 2020. Bayesian inference in snow avalanche simulation with r. avaflow. *Geosciences* 10: 191.

Fuchs, S., and M. Bründl. 2005. Damage potential and losses resulting from snow avalanches in settlements of the canton of Grisons, Switzerland. *Natural Hazards* 34: 53–69.

Fuchs, S., M. Bründl, and J. Stötter. 2004. Development of avalanche risk between 1950 and 2000 in the Municipality of Davos, Switzerland. *Natural Hazards and Earth System Sciences* 4: 263–275.

Fuchs, S., M. Thöni, M.C. McAlpin, U. Gruber, and M. Bründl. 2007. Avalanche hazard mitigation strategies assessed by cost effectiveness analyses and cost benefit analyses—Evidence from Davos, Switzerland. *Natural Hazards* 41: 113–129.

García-Hernández, C., J. Ruiz-Fernández, C. Sánchez-Posada, S. Pereira, M. Oliva, and G. Vieira. 2017. Reforestation and land use change as drivers for a decrease of avalanche damage in mid-latitude mountains (NW Spain). *Global and Planetary Change* 153: 35–50.

Gauer, P., Z. Medina-Cetina, K. Lied, and K. Kristensen. 2009. Optimization and probabilistic calibration of avalanche block models. *Cold Regions Science and Technology* 59: 251–258.

Gaume, J., T. Gast, J. Teran, A. Van Herwijnen, and C. Jiang. 2018. Dynamic anticrack propagation in snow. *Nature Communications* 9: 1–10.

Giacona, F., B. Martin, N. Eckert, and J. Desarthe. 2019. La modélisation en géohistoire des risques: de la chronologie (saptialisée) des événements au fonctionnement du système par la mise en concordance spatiale et temporelle. Physio-Géo. *Géographie Physique Et Environnement* 14: 171–199.

Giacona, F., N. Eckert, C. Corona, R. Mainieri, S. Morin, M. Stoffel, B. Martin, M. Naaim, et al. 2021. Upslope migration of snow avalanches in a warming climate. *Proceedings of the National Academy of Sciences* 118: e2107306118.

Giacona, F., N. Eckert, R. Mainieri, B. Martin, C. Corona, J. Lopez-Saez, J.M. Monnet, M. Naaim, et al. 2018. Avalanche activity and socio-environmental changes leave strong footprints in forested landscapes: A case study in the Vosges medium-high mountain range. *Annals of Glaciology* 59: 111–133.

Giacona, F., N. Eckert, and B. Martin. 2017a. A 240-year history of avalanche risk in the Vosges Mountains based on non-conventional (re) sources. *Natural Hazards and Earth System Sciences* 17: 887–904.

Giacona, F., N. Eckert, and B. Martin. 2017b. La construction du risque au prisme territorial: dans l'ombre de l'archétype alpin, les avalanches oubliées de moyenne montagne. *Natures, Sciences, Sociétés* 25: 148–162.

Gleeson, E.H., S.W. von Dach, C.G. Flint, G.B. Greenwood, M.F. Price, J. Balsiger, A. Nolin, and V. Vanacker. 2016. Mountains of our future earth: Defining priorities for mountain research—A synthesis from the 2015 Perth III conference. *Mountain Research and Development* 36: 537–548.

Gneiting, T., and A.E. Raftery. 2007. Strictly proper scoring rules, prediction, and estimation. *Journal of the American Statistical Association* 102: 359–378.

Grêt-Regamey, A., and D. Straub. 2006. Spatially explicit avalanche risk assessment linking Bayesian networks to a GIS. *Natural Hazards and Earth System Sciences* 6: 911–926.

Handmer, J. 2019. Achieving risk reduction across Sendai, Paris and the SDGs. Policy Brief. International Science Concil.

Harbitz, C. 1999. A survey of computational models for snow avalanche motion. Fourth European Framework. Programme (ENV4-CT96-0258) Avalanche Modelling, Mapping and Warning In Europe.

Hock, R., G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, et al. 2019. High mountain areas: In: IPCC special report on the ocean and cryosphere in a changing climate.

IPBES. 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In E.S. Brondizio, J. Settele, S. Díaz, and H.T. Ngo (eds) IPBES secretariat, Bonn, Germany.

IPCC. 2014. Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. In C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, et al. (eds.) Contribution of Working Group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2020. The concept of risk in the IPCC Sixth Assessment Report: A summary of cross-Working Group discussions [Reisinger, A., Howden, M, Vera, C., Garschagen, M., et al.]. 15p.

IPCC. 2021. Climate change 2021: The physical science basis. In V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, et al. (eds.) Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge.

IRASMOS Consortium. 2009a. Hazard mapping of extremely rapid mass movements in Europe. Best practice of integral risk management of snow avalanches, rock avalanches and debris flows in Europe. Delivrable 5.4. Sixth Framework Programme (2002–2006). http://irasmos.slf.ch/results_wp5.htm.

IRASMOS Consortium. 2009b. Hazard mapping of extremely rapid mass movements in Europe. State of the art methods in practice. Technical evaluation report of current methods of hazard mapping of debris flows, rock avalanches, and snow avalanches. Delivrable 3.1. Sixth Framework Programme (2002–2006). https://irasmos.slf.ch/results_wp3.htm.

Jóhannesson, T., and T. Jónsson. 1996. Weather in Vestfirdir before and during several avalanche cycles in the period 1949 to 1995. Vedurstofa Íslands Internal Rep. VÍ-G96015-Ur15.

Kates, R.W., W.C. Clark, R. Corell, J.M. Hall, C.C. Jaeger, I. Lowe, J.J. McCarthy, H. Schellnhuber, et al. 2001. Sustainability science. *Science* 292: 641–642.

Keylock, C.J., D.M. McClung, and M.M. Magnússon. 1999. Avalanche risk mapping by simulation. *Journal of Glaciology* 45: 303–314.

Kleiber, F., and F. Vey. 2017. Indicateurs de la transition écologique vers un développement durable. Comparaisons internationales. CGEDD (French General Council for the Environment and Sustainable Development), Paris, France.

Köhler, A., J.N. McElwaine, and B. Sovilla. 2018. GEODAR data and the flow regimes of snow avalanches. *Journal of Geophysical Research: Earth Surface* 123: 1272–1294.

Lavigne, A., N. Eckert, L. Bel, and E. Parent. 2015. Adding expert contributions to the spatiotemporal modelling of avalanche activity under different climatic influences. *Journal of the Royal Statistical Society: Series C (applied Statistics)* 64: 651–671.

Le Roux, E., G. Evin, N. Eckert, J. Blanchet, and S. Morin. 2021. Elevation-dependent trends in extreme snowfall in the French Alps from 1959 to 2019. *The Cryosphere* 15: 4335–4356.

Lehning, M., T. Grünewald, and M. Schirmer. 2011. Mountain snow distribution governed by an altitudinal gradient and terrain roughness. *Geophysical Research Letters*. https://doi.org/10.1029/2011GL048927.

Mainieri, R., A. Favillier, J. Lopez-Saez, N. Eckert, T. Zgheib, P. Morel, M. Saulnier, J.L. Peiry, et al. 2020. Impacts of land-cover changes on snow avalanche activity in the French Alps. *Anthropocene* 30: 100244.

Maraun, D., F. Wetterhall, A.M. Ireson, R.E. Chandler, E.J. Kendon, M. Widmann, S. Brienen, H.W. Rust, et al. 2010. Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. *Reviews of Geophysics*. https://doi.org/10.1029/2009RG000314.

Mathieu, J. 2005. The specific nature of mountains: A historical review. *Revue D'histoire Moderne Contemporaine* 522: 9–25.

McClung, D., and K. Lied. 1987. Statistical definition of snow-avalanche runout. *Cold Regions Science and Technology* 13: 107–119.

MEDDE. 2015. Plans de Prévention des Risques Naturels, risques d'avalanches. Guide Méthodologique. Version aout 2015.

Mock, C.J., K.C. Carter, and K.W. Birkeland. 2017. Some perspectives on avalanche climatology. *Annals of the American Association of Geographers* 107: 299–308.

Morin, S., S. Horton, F. Techel, M. Bavay, C. Coléou, C. Fierz, A. Gobiet, P. Hagenmuller, et al. 2020. Application of physical snowpack models in support of operational avalanche hazard forecasting: A status report on current implementations and prospects for the future. *Cold Regions Science and Technology* 170: 102910.

Naaim, M., T. Faug, F. Naaim, and N. Eckert. 2010. Return period calculation and passive structure design at the Taconnaz avalanche path, France. *Annals of Glaciology* 51: 89–97.

O'Gorman, P.A. 2014. Contrasting responses of mean and extreme snowfall to climate change. *Nature* 512: 416–418.

Peduzzi, P. 2019. The disaster risk, global change, and sustainability Nexus. *Sustainability* 11: 957.

Peitzsch, E.H., G.T. Pederson, K.W. Birkeland, J. Hendrikx, and D.B. Fagre. 2021. Climate drivers of large magnitude snow avalanche years in the US northern Rocky Mountains. *Scientific Reports* 11: 1–13.

Perona, P., E. Daly, B. Crouzy, and A. Porporato. 2012. Stochastic dynamics of snow avalanche occurrence by superposition of Poisson processes. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 468: 4193–4208.

Pescaroli, G., and D. Alexander. 2018. Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. *Risk Analysis* 38: 2245–2257.

Podolskiy, E.A., K. Izumi, V.E. Suchkov, and N. Eckert. 2014. Physical and societal statistics for a century of snow-avalanche hazards on Sakhalin and the Kuril Islands (1910–2010). *Journal of Glaciology* 60: 409–430.

Pörtner, H.O., H.O. Pörtner, R.J. Scholes, J. Agard, E. Archer, A. Arneth, X. Bai, et al. 2021. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change; IPBES secretariat, Bonn, Germany. 10.5281/zenodo.4659158.

Renn, O. 2008a. Concepts of risk: An interdisciplinary review. Part 1: Disciplinary risk concepts. GAIA 17/1, pp. 50–66.

Renn, O. 2008b. Concepts of risk: An interdisciplinary review. Part 2: Integrative approaches. GAIA 17/2, pp. 196–204.

Renn, O. 2016. Systemic risks: The new kid on the block. Environment: Science and Policy for Sustainable Development, 58, pp. 26–36.

Rheinberger, C.M., M. Bründl, and J. Rhyner. 2009. Dealing with the white death: Avalanche risk management for traffic routes. *Risk Analysis: An International Journal* 29: 76–94.

Rougier, J., and M. Kern. 2010. Predicting snow velocity in large chute flows under different environmental conditions. *Journal of the Royal Statistical Society: Series C (applied Statistics)* 59: 737–760.

Salas, J.D., and J. Obeysekera. 2014. Revisiting the concepts of return period and risk for nonstationary hydrologic extreme events. *Journal of Hydrologic Engineering* 19: 554–568.

Salm, B. 2004. A short and personal history of snow avalanche dynamics. *Cold Regions Science and Technology* 39: 83–92.

Salm, B., A. Burkard, and H.U. Gubler. 1990. Calcul des avalanches : une méthode pour le praticien avec des exemples. Communication de l'institut fédéral suisse pour l'étude de la neige et des avalanches, C. Ancey traducteur.

Schläppy, R., N. Eckert, V. Jomelli, M. Stoffel, D. Grancher, D. Brunstein, M. Naaim, and M. Deschatres. 2014. Validation of extreme snow avalanches and related return periods derived from a statistical-dynamical model using tree-ring techniques. *Cold Regions Science and Technology* 99: 12–26.

Schweizer, J., J. Bruce Jamieson, and M. Schneebeli. 2003. Snow avalanche formation. *Reviews of Geophysics*. https://doi.org/10.1029/2002RG000123.

Stoffel, M., and C. Corona. 2018. Future winters glimpsed in the Alps. *Nature Geoscience* 11: 458–460.

Takeuchi, Y., H. Torita, K. Nishimura, and H. Hirashima. 2011. Study of a large-scale dry slab avalanche and the extent of damage to a cedar forest in the Makunosawa valley, Myoko, Japan. *Annals of Glaciology* 52: 119–128.

Teich, M., P. Bartelt, A. Grêt-Regamey, and P. Bebi. 2012. Snow avalanches in forested terrain: Influence of forest parameters, topography, and avalanche characteristics on runout distance. *Arctic, Antarctic, and Alpine Research* 44: 509–519.

UNDRR. 2019a. Global assessment report on disaster risk reduction. Geneva, Switzerland. United Nations Office for Disaster Risk (UNDRR).

UNDRR. 2019b. The Seidai framework and the SDGs. https://www.undrr.org/ar/node/32.

United Nations. 2015. Paris agreement.

United Nations. 2020. The sustainable development goals report 2020.

United Nations General Assembly. 2015. Transforming our world: The 2030 Agenda for Sustainable Development. Division for Sustainable Development Goals: New York, NY, USA.

United Nations Office for Disaster Risk Reduction (2015). Sendai framework for disaster risk reduction 2015-2030.

Vera Valero, C., N. Wever, Y. Bühler, L. Stoffel, S. Margreth, and P. Bartelt. 2016. Modelling wet snow avalanche runout to assess road safety at a high-altitude mine in the central Andes. *Natural Hazards and Earth System Sciences* 16: 2303–2323.

Vincent, C., E. Thibert, M. Harter, A. Soruco, and A. Gilbert. 2015. Volume and frequency of ice avalanches from Taconnaz hanging glacier, French Alps. *Annals of Glaciology* 56: 17–25.

Voellmy A. 1955. Über die Zerstörungskraft von Lawinen. Schweizerische Bauzeitung, 73, pp. 159–162, 212–217, 246–249,280–285.

Von Neumann, J., and O. Morgenstern. 1953. *Theory of games and economic behaviour*. New Jersey: Princeton University Press.

Wikle, C.K. 2003. Hierarchical models in environmental science. *International Statistical Review* 71: 181–199.

Zgheib, T., F. Giacona, A.M. Granet-Abisset, S. Morin, and N. Eckert. 2020. One and a half century of avalanche risk to settlements in the upper Maurienne valley inferred from land cover and socio-environmental changes. *Global Environmental Change* 65: 102149.

Zgheib, T., F. Giacona, A.M. Granet-Abisset, S. Morin, A. Lavigne, and N. Eckert. 2022. Spatio-temporal variability of avalanche risk in the French Alps. *Regional Environmental Change* 22: 1–18.

Zscheischler, J., S. Westra, B.J. Van Den Hurk, S.I. Seneviratne, P.J. Ward, A. Pitman, A. AghaKouchak, D.N. Bresch, et al. 2018. Future climate risk from compound events. *Nature Climate Change* 8: 469–477.

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