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Highlights

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- Impact of climate change on gravitational mass movements in the European Alps: Theory and observations
- Overall failure continuum framework for the Alpine mass movements
- The complexity of the natural system and data limitations complicate quantifying the impact of climate change on alpine mass movements.
- Climate change signal is visible directly or indirectly in observations of all processes but large rock avalanches

Detecting the impact of climate change on alpine mass movements in observational records from the European Alps

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Abstract

Anthropogenic climate change is rapidly altering high mountain environments, including changing the frequency, dynamic behavior, location, and magnitude of alpine mass movements. Here, we review three decades of scientific literature (~ 1995 to early 2024) to assess to what degree observational records from the European Alps – as the region with the most comprehensive records – reveal these changes. We do this for the processes that are most common in this region, namely rockfall, rock avalanches, debris flows, ice avalanches, and snow avalanches. The systematic literature search and review yielded 335 publications, of which we omitted publications that did not focus primarily on observational records. The remaining 103 publications used observations from over 100 sites and 30 inventories to investigate the connection between climate change and mass movements. About one third of the relevant studies found a measurable impact of climate change on the investigated alpine mass movement processes (with the exception of large rock avalanches). The clearest climate-controlled trends are (i) increased rockfall frequency in high-alpine areas due to higher temperatures, (ii) fewer and smaller snow avalanches due to scarcer snow conditions at low and mid elevations, and (iii) a shift towards avalanches with more wet snow and fewer powder clouds. While there is (iv) despite a clear increase in debris-flow triggering precipitation, debris-flow activity has not been found to uniformly increase, though there is some evidence for increasing activity above treeline and at locations without historical precedence. The trends for (v) ice avalanches are spatially very variable with no clear direction. Ice temperatures are measurably increasing, but – despite a theoretical expectation – this has not impacted ice avalanche activity to date. The reviewed literature also reveals that quantifying the impact of climate change on these mass movements remains difficult in part due to the complexities of the natural system, but also because of limitations in the available datasets,

confounding effects, and existing statistical processing techniques. Better assessments could be achieved if we would more broadly support the compilation and maintenance of large standardized data catalogs, bring together various dispersed datasets (in said catalogs), including from social and citizen science projects, invest in long-term natural observatories, and develop suitable processing techniques. Better observations will additionally support the development and performance of process-based models. If we can advance natural hazard research on these fronts, more quantitative predictions of future change are well within our reach.

Keywords: climate change, alpine mass movements, failure continuum, observations, theoretical basics, rockfall, rock avalanche, debris flow, ice avalanche, snow avalanche,

1. Introduction

Anthropogenic climate change is rapidly altering the Earth's system, with various effects becoming visible at local, regional, and global scales. Mountain regions are experiencing some of the fastest and most drastic changes, warming at two to three times the global rate (MRI EDW Working Group, 2015; Pepin et al., 2022). This has a particularly strong impact on mountain areas that are still dominated by snow, ice, frozen ground (i.e., permafrost) and subzero atmospheric temperatures (Hock et al., 2019). Since the turn of the 21st century, worldwide glacier retreat has accelerated substantially (Hugonnet et al., 2021), leading, among others, to the formation of many new (+53 %) and larger (+51 %) glacial lakes (Shugar et al., 2020). Permafrost temperatures measured between 2007 and 2016 in boreholes globally increased by 0.3 °C (Biskaborn et al., 2019), and almost 80 % of all mountain regions are seeing shorter periods and shrinking snow cover (Notarnicola, 2020).

Following a year of record-breaking global land and ocean temperatures in 2023 (WMO, 2024), spring 2024 brought several stark reminders to the European Alps that this region is just as susceptible and vulnerable to catastrophic alpine mass movements as other parts of the world. On April 14, a large rock-ice avalanche detached from Piz Scerscen on the Swiss-Italian border, luckily occurring in one of the lesser-traveled valleys early in the morning, nevertheless narrowly missing an alpine hut and one group of mountaineers (Petley, 2024). In late June, intense convective storms raged across France, Switzerland and Italy, unleashing disastrous floods, debris flows, and rock falls twice in a month, damaging infrastructure and claiming more than a dozen lives (Le Monde and AFP, 2024). These events illustrated that we are far from being able to provide accurate predictions of where and when mass movements are most likely to happen.

Dominated by steep relief, gravity-driven mass movements continually shape alpine landscapes (Dietrich et al., 2003; Korup et al., 2010). Under the force of gravity, rock, snow, and ice can detach, slide, or flow, sometimes slowly, sometimes at great speeds (Fig. 1). Beyond being important geomorphic agents, rockfall, debris flows, rock-, ice-, and snow avalanches can threaten the ever-expanding human activities and infrastructure in mountain regions, generating disaster risk (Simpson et al., 2021; Masson-Delmotte et al., 2021a; Eckert and Giacona, 2023). There is general agreement that the changes in glacier volume and coverage, permafrost distribution and temperature, snow cover extent and duration have profound impacts on the magnitude, frequency, nature, and location of alpine mass movements (Hock et al., 2019), but incomplete observational records, analyses and understanding make it hard to quantify these changes at regional or global scales. However, these insights are needed to advance natural hazard management and adaptation strategies in alpine regions, especially given their increasing commercial (e.g., renewable energy production) and recreational use. Because they are easy to understand, robust observational

records showing climate change impacts are also valuable for the political and public discourse around climate change activism.

Figure 1: Mass movements such as rockfall and rock avalanches, debris flows, snow and ice avalanches have always shaped alpine landscapes. Here, we review studies using observational records of mass movements to assess to what degree changes of mass movement activity can be detected in subalpine, high- and low-alpine regions of the European Alps.

Early on, studies predicted that the amplified warming of mountain regions would lead to fundamental changes in mountain hazards, specifically alpine mass movements, in many cases increasing their frequency and severity (Stoffel and Huggel, 2012). For example, Gruber and Haeberli (2007) hypothesized that “permafrost degradation can cause slope instabilities that are unexpected and unprecedented in location, magnitude, frequency, and timing”, while Huggel et al. (2010) anticipated that “data and analysis support the view that recent, current and future climatic change increases the likelihood of large slope failures in steep glacierized and permafrost terrain.” Though an early study suggested that snow avalanche activity had remained unchanged in the late 20th century (Laternser et al., 1997), other studies – somewhat intuitively – predicted early on that snow avalanches would become less frequent and/or change in their type with increased warming (Martin et al., 2001). Despite intense efforts, assessments of natural hazard changes are often based on limited direct evidence combined with knowledge from laboratory experiments, theoretical considerations, and numerical modeling. In this context, increasingly extensive observational records can bring clarity.

The densely populated European Alps have one of the most comprehensive records of alpine mass movements worldwide, making them well-suited to investigate how mass movement

activity is evolving due to anthropogenic climate change. They have also been the site of many well-known and sometimes catastrophic mass movements, such as the Mattmark (CHE) ice avalanche in 1965 (Vivian, 1966; Faillettaz et al., 2012), the Val Pola (ITA) rock slope failure in 1987 (Dramis et al., 1995), the avalanche disasters in Galtür (AUT), Evolène (CHE) and Montroc-Chamonix (FRA) in 1999, the Pizzo Cengalo (CHE) rock slope failures in 2011 and 2017 with the related debris flows in the Bondasca Valley (CHE) (Walter et al., 2020; Mergili et al., 2020), the Marmolada (ITA) glacier collapse in 2022 (Bondesan and Francese, 2023), the Fluchthorn (AUT) rock slope failure in 2023 (Krautblatter et al., 2024), or the Piz Scerscen (CHE) rock slope failure in 2024 with an extremely long run-out distance on the Vadret da Tschierva glacier. These events have directly contributed to the long-standing tradition of natural hazards research in the region, often providing the starting points for in-depth research and motivating further studies, inventories, and observations.

In this paper, we gather studies that leverage observational records from the European Alps to review whether (predicted) changes of frequency, magnitude, the dynamic behavior, or location of alpine mass movements can be detected and attributed to climate change. Given the accelerated warming and increasing observational period (see Fig. 2), we hypothesize that changes in mass movements should become more clearly visible. We focus the review on rockfall and rock avalanches, debris flows, and snow and ice avalanches because they are the most common mass movement processes in the European Alps and have a long history of documentation and recorded impacts. We chose to review the literature for all four processes combined, because they can form complex process chains and it is important to understand their interconnectedness. We omit processes that (i) are more common elsewhere (e.g., glacier lake outburst floods), (ii) have a very long reaction time, or (iii) for which the final failure is rarely documented (e.g., creeping rock

glaciers, deformation of deep-seated instabilities in response to glacial debudding). We primarily consider changes documented in alpine areas and distinguish, when helpful, between high alpine (periglacial areas where snow cover can persist year-round and permafrost is widespread, typically above ~ 3000 m asl (above sea level – henceforth implied), low alpine regions (areas that lie below the perennial snow line and above the treeline, typically between about 2000 m and 3000 m) and subalpine areas below the treeline (see Fig. 1). Section 2 summarizes the measured changes in air temperature, precipitation, rock and ice temperatures, and snow and glacier coverage in the European Alps. In Section 3, we lay out the *failure continuum* as a conceptual framework to review how preconditioning, triggering, and runout propagation of the different processes are expected to change based on theoretical considerations. In Section 4, we summarize existing data on observations of the selected processes and assess to what degree observed changes – if any – can be attributed to climate change. Finally, in Section 5, we discuss the observed findings, their limitations and implications under continued warming, as well as challenges and opportunities for future studies.

Figure 2: Hillshade map with the European Alps highlighted in yellow and temperature time series with significant trends ($p < 0.01$) as well as temperature anomalies (each stripe represents the average temperature for a single year, relative to the average temperature over the period as a whole - blue for colder and red for warmer years) for the three selected locations Aiguille du Midi (3842 m asl, France), Jungfrauoch (3465 m asl, Switzerland) and Zugspitze (2962 m asl, Germany), showing the effects of climate change on mean annual air temperature (Data source: European Environment Agency, 2016; meteoblue, 2024).

2. Observed climate change in the European Alps

Human activities, primarily the release of greenhouse gases, are leading to rapid global warming: Relative to the average of 1850 to 1900, the global surface temperature (average from 2011 to 2020) has risen by 1.09 °C, while the mean land temperature – which does not take into account the cooling effect of the oceans – has increased by 1.59 °C (Masson-Delmotte et al., 2021b). Similar to polar regions, warming in the Alps is greater, and temperatures since 1880 have already increased by 1.8 °C (Begert and Frei, 2018). An analysis of 23 high-elevation weather stations in the European Alps revealed that annual mean air temperature for the period 1991–2020 increased by 0.9 °C with respect to the 1961–1990 (Nigrelli and Chiarle, 2023). In the Swiss Alps, where systematic records date back to 1864, temperatures have even risen by 2.5 °C. The rate of warming has increased since the 1980s to reach around 0.5 °C per decade, corresponding to roughly a 100 m increase of the zero-degree isoline every ten years. As a result of accelerating anthropogenic warming, the frequency and intensity of summer heatwaves and droughts are increasing (Scherrer et al., 2022), as seen recently in 2003, 2015, 2018, and 2022, even at higher elevations (Pepin et al., 2022). Model outputs forced with reanalyzed 20th-century data point to a generalized and significant increase of intense daily precipitation across all four seasons, with up to 20 % to 40 % over major parts of the Alps. This increase in extreme precipitation has accelerated since the 1970s, even if earlier periods with intense precipitation can also be found, particularly during the 1950s and 1960s (Ménégoz et al., 2020).

The warming is also visible in winter air temperatures. In the 50-year period 1968-2017, winter temperatures have increased by 0.3 °C to 0.4 °C per decade across the Alps, with a stronger signal at lower elevations (Monteiro and Morin, 2023). While only a small reduction in winter precipitation has been recorded in the Alpine region during the same period, it is primarily the

warming that affected snowfall patterns and the duration of snow cover on the ground. Winter snow depth and snow cover duration have declined by 7 % to 15 % per decade and 5 to 7 days per decade, respectively, especially at low and intermediate elevations (Monteiro and Morin, 2023). A decrease in mean snow depth of 8.4 % per decade could also be evidenced between 1971 and 2019, with a strong elevation-dependent pattern (Matiu et al., 2020). Similarly, contrasted trends could be evidenced in extreme snowfall due to concomitant increases in temperature and extreme precipitation (Le Roux et al., 2021). These changes in the timing and amount of snowfall can have cascading effects on the alpine ecosystems (Rumpf et al., 2022).

The observed warming has led to a rapid retreat of glaciers in the Alps. Between the years 2000 and 2019, European glaciers thinned at roughly 1 m yr^{-1} (Hugonnet et al., 2021) and around 40 km^2 became ice-free every year between 2000 and 2014 (Sommer et al., 2020). Swiss glaciers lost about 43 % of their total ice volume between the early 1980s and 2016 (Grab et al., 2021), with individual-year losses becoming larger and larger. Notably, the years 2022 and 2023 alone contributed an unprecedented 10 % loss of ice volume in Switzerland (6 % and 4 %, respectively; GLAMOS, 2024). The same trends have been observed in Austria, where measurements on Hintereisferner in 2022 revealed an annual mass balance that was three times lower than the 1952 – 2022 average (Voordendag et al., 2023), or in France, where the regional, glacier-wide mass balance of glaciers decreased from $-0.44 \text{ m w.e. yr}^{-1}$ to $-1.26 \text{ m w.e. yr}^{-1}$ between the 1970s and 2010s (Bolibar et al., 2020).

Less visible than the glacier retreat, both ice and ground temperatures have increased, the latter directly affecting mountain permafrost dynamics. In the Swiss Alps, long-term ground temperature trends (1997 to 2019) at the instrumented sites of the Swiss Permafrost Monitoring program (PERMOS) show increasing temperatures at all depths (i.e., 5, 10, and 20 m), in particular

at steep and nearly snow-free sites (PERMOS, 2019). Additionally, the active layer – the uppermost part of the ground that thaws every summer – has thickened at most sites, and strong acceleration of rock glacier velocities over the last decade has been documented, interrupted only by years with snow-poor winters (Haberkorn et al., 2021). In France, where time series are much shorter, measurements show that ice-poor and cold permafrost at high-elevation, north-facing rock walls has warmed by up to > 1 °C at 10 m depth between 2011 and 2020 (Magnin et al., 2023). In NW Italy (Aosta Valley), active layer thickening and warming of about $+0.2$ °C/10 yr are observed at 15 m depth at an elevation of 3500 m (Pogliotti et al., 2023). Ice temperature measurements from France and Italy show distinct warming trends as well: At Dôme du Goûter (4250 m), warming has penetrated deep into the ice, leading to 1.5 °C of warming between 1994 and 2017 (Vincent et al., 2020). At the Whymper hanging glacier on Grand Jorasses in Italy (4200 m), measurements in one borehole indicate that warming has reached the glacier bed, leading to temperate conditions (0 °C) at the ice-rock interface. In agreement with the observations from Dôme du Goûter, this is around 2 °C warmer than what had been measured at the same location in 1997 (Troilo et al., 2021; Perret et al., 2021).

3. Expected impacts of climate change on gravitational mass movements

3.1. Definitions and conceptual basics

Gravity-driven mass movements release when the equilibrium between downward-driving and resisting forces is exceeded (Abramson et al., 2002). Apart from gravity, the mechanisms driving this transition are strongly controlled by the involved materials and local conditions, where the latter respond to weather and climate at different temporal and spatial scales. To discuss the

impacts of climate change on rapid mass movements, we introduce the conceptual framework of a *failure continuum* that describes the transition from a stable to an unstable state and eventually to release in phases of preconditioning, triggering, and runout (see Fig. 3a).

We consider preconditioning factors to be all physical (i.e., mechanical, thermal, and hydrological) or chemical changes that cause rock, debris, ice, snow, or a mixture thereof to shift from a stable to an unstable state and eventually to fail. Figure 3b illustrates that this process can take place at varying temporal scales: For a large rock avalanche, gradual weathering and erosion may weaken the structural integrity of the rock over the years. In a snowpack, on the other hand, changes in the snow microstructure resulting from melting, refreezing, metamorphism, or settling can alter the mechanical properties in just hours or days, priming the snow for an avalanche release. The impact of climate change on preconditioning factors can be manifold: Warming and thawing of permafrost in high-alpine rock faces, downwasting of a valley glacier that removes support from a hanging glacier above, the snowline gradually moving to higher elevation as temperatures rise.

Triggering and runout occur on short timescales, typically no more than minutes or hours, sometimes days (Gorum et al., 2014). Note that there are triggers – i.e. an event or action that sets a mass movement – can also be earthquakes or construction activities and are therefore not necessarily related to climate and weather. In some cases, there may not be a specific trigger, but an instability instead develops through progressive deterioration of the geomechanical properties under the action of gravity (Phillips et al., 2017). Where triggers are directly weather-related – and therefore inherently affected by climate change – they include rising air temperatures (Stoffel et al., 2024b), heatwaves (Raveland et al., 2017), intense and/or prolonged precipitation events (Krautblatter and Moser, 2009; Bajni et al., 2021), rapid snowmelt (Draebing et al., 2014), or a

rapid drop in temperature with freezing of the water sources that drain the slope and build-up of water pressure (Chiarle et al., 2022). Once released and in motion, the material falls or flows downhill. The runout characteristics are heavily influenced by the physical properties of the released material and the ground/surface conditions that the mass movement encounters along its trajectory. Both of these latter factors can be affected by climate change, possibly altering runout distances, flow velocities, or the generated impact forces in measurable ways.

The above description and the examples of the failure continuum illustrate that climate change can affect many aspects of mass movements in diverse ways. In the following, we describe, for each process, how climate change is expected to change preconditioning factors and processes, triggers, and runout characteristics.

Figure 3: (a) Conceptual illustration of the failure continuum of gravitational mass movements. Preconditioning factors and processes initiate a shift from a stable to an unstable configuration. Once destabilized, any triggering event can lead to failure, prompting the material to fall or flow under the influence of gravity. (b) Depending on the mass movement type, preconditioning, triggering, and runout processes happen over widely varying time scales: While a gradual weakening of a rock slope in response to fluctuating groundwater levels (preconditioning), for example, takes place over the years, the metamorphosis of snow and the creating of a triggering-prone weak layer can take only hours to days. Triggering and runout are comparatively fast: a convective rainstorm that triggers rockfall or a heavy snowfall event that triggers avalanches. In both cases, the runout usually lasts only minutes or maybe hours before a new state of equilibrium is reached.

3.2. *Preconditioning factors and processes*

3.2.1. *Rockfall and rock avalanches*

The stability of steep rock slopes is determined by mechanical weaknesses in the rock structure, such as joints or faults, rather than the strength of the rock itself (Terzaghi, 1962). Therefore, a rock slope's susceptibility to failure is typically related to geological setting, lithology, structural predisposition, and topography (Stead and Wolter, 2015). Besides these factors, the thermal and hydrological conditions and related acting processes such as weathering can precondition rock slope failures.

Rockfall and **rock avalanches** are mass-wasting processes that describe the downslope motion of rock masses released from steep rock faces and subsequent transport to deposition zones. We distinguish rockfall from rock avalanches based on the size and the downslope motion: rockfall is characterized by the impact of individual rocks and boulders that interact solely with the ground substrate along the downslope trajectory (e.g. Bourrier et al., 2013; Hungr et al., 2014). Rock avalanches, by contrast, are associated with volumes of several hundred thousand to millions m^3 where particles interact with each other and move as a semi-coherent granular flow (e.g. Loew et al., 2022). For this review, we make no further subdivision of rockfall into different classes by event volume or fragment/clast diameter.

Figure 4: Definition of rockfall and rock avalanche.

The thermal expansion and contraction of rock in response to temperature fluctuations (Watson et al., 2004; Weber et al., 2017) and changes in water pressure (Terzaghi, 1962; Krautblatter and Hauck, 2007; Krautblatter et al., 2010) are two of the dominant preconditioning

factors. When water is available, frost weathering processes including changes in cryostatic pressure resulting from volumetric expansion (Matsuoka, 1990; Prick, 1997; Hall et al., 2002; Matsuoka and Murton, 2008), ice segregation (Konrad and Morgenstern, 1982; Walder and Hallet, 1985; Murton et al., 2006), or ice wedging (Matsuoka, 2001; Matsuoka and Murton, 2008) can induce high stresses. Rock fracturing can occur either if the emerging pressure exceeds the tensile strength of the rock or if fatigue occurs as a result of periodic loading of discontinuities (Jia et al., 2015; Murton et al., 2016), causing crack propagation and thereby precondition rockfall or rock slope failures.

The decline of snow cover and the retreat of glaciers lead to changes in larger-scale stresses. For example, the retreat of cold-based glaciers can lead to the formation of an active layer above pre-existing permafrost (Hartmeyer et al., 2020) or permafrost with an active layer can evolve in recently deglaciated areas (i.e., in areas previously covered with temperate ice Wegmann et al., 1998). Where temperature-controlled temperate ice disappears, the rock becomes subject to greater temperature fluctuations, which can lead to thermal stress fatigue, both through rapid temperature changes (Hall, 1999) or by repetitive low-magnitude temperature cycles (Murton, 2007). These effects are primarily limited to the near-surface because surface temperature amplitudes are exponentially dampened with depth (Williams and Smith, 1991; Nigrelli et al., 2022). At depth, by contrast, the stress release due to glacial unloading can result in the development of failure planes at larger depth; often within, the resulting events can also be delayed (often by millennia) (e.g. Gischig et al., 2011a,b; Ballantyne, 2013). Finally, the disappearance of glacier ice can also expose previously weakened or destabilized rock masses that become prone to failure because the buttressing effect of the ice is lost.

At high elevations, permafrost exerts a key control on rock wall stability. In the European

Alps, this typically applies to bedrock areas above 2700 m on north-west to north-east and above 3000 m on south-east to south-west facing slopes (Magnin et al., 2015; Kenner et al., 2019). In these areas, the thickening of the active layer (the near-surface rock that freezes/thaws annually and that can reach several meters depth) and warming of the underlying permafrost body lead to a significant decrease of the tensile and shear strength of both intact rock (Mellor, 1973) and ice-filled discontinuities (Mamot et al., 2018), albeit at different spatial and temporal scales. The mechanical properties of the ice-filled discontinuities are sensitive to rising temperatures at shallow depths (<20 m according to Krautblatter et al., 2013) and may therefore respond to short-term climate signals (Stoffel et al., 2024b). At depths >20 m, the mechanical properties of the intact rock are more relevant, though these react to climate changes across centuries and millennia (Krautblatter et al., 2013). This means that rising temperatures would be expected to lead to an increase in both rockfall and rock avalanches, but that detecting a climate-change driven regime-change will be easier for those involving only the uppermost 20 m, rather than more deep-seated failures unless water infiltration following ice loss is involved that can quickly reach great depths.

Liquid water from rainfall or ice and snow melt is often limited at high elevations. Still, it can greatly impact rock wall stability when available, primarily where it interacts directly with permafrost. Though the hydraulic permeability of rocks in permafrost has rarely been investigated in detail (Krautblatter et al., 2013), warming or thawing permafrost is assumed to coincide with an increase in hydraulic permeability (Weber et al., 2017) or erosion of the ice-infill in fractures (Weber et al., 2018). Water can percolate through cracks into the active layer and advect heat to the ice level much more efficiently than is possible via pure conduction, potentially forming thawing corridors (Krautblatter and Hauck, 2007; Magnin and Josnin, 2021), thereby leading to a heat

transport shortcut between the surface (or atmosphere) and the ice level at depth (Hasler et al., 2011). Through this, the response time of rock masses to warming temperatures can be significantly shorter than outlined above. In addition to shortcutting the heat transfer process, infiltrating water can get trapped by ice-infill in fractures, causing high hydraulic pressures (Pogrebiskiy and Chernyshev, 1977; Wegmann, 1998; Magnin and Josnin, 2021), which can lead to the destabilization of rock slopes. In addition to rock temperature, the history and duration of snow cover exert additional control on water infiltration and related thermal and mechanical effects (Ben-Asher et al., 2023). If a thin layer of ice forms between snow and rock, it can prevent the infiltration of meltwater (Phillips et al., 2016) at the onset of the thawing season. At the same time, the snow presents the primary water source for infiltration.

3.2.2. Debris flows

Debris-flow activity is controlled by two main factors: sediment availability and water input. Because both factors are expected to increase during the 21st century, debris flows are considered to be sensitive to climate change (Gariano and Guzzetti, 2016). The susceptibility of a catchment to produce debris flows also depends on relief because it is related to the hydrological and sediment connectivity, and therefore defines sediment delivery to the debris-flow channels (Reid et al., 2007; Hoffmann, 2015; Micheletti and Lane, 2016). Geology is key as it controls the weathering resistance of bedrock, properties of the weathering products, size and type of the loose material, and storage capacity within the system. In addition, channel slope controls the occurrence of debris flows, as the triggering of events is typically restricted to slopes steeper than 30° but may also propagate on slopes less than 10° (Iverson, 2014; Hungr et al., 2014).

Debris flows are rapid flows of water-saturated rock debris in steep channels, with volumetric solid concentrations that exceed 40 % (Hungri et al., 2014). The grain sizes involved can range from clay to boulders, generating high pore fluid pressures that strongly enhance the mobility and runout (Delannay et al., 2017). A debris flow can consist of single or multiple surges and typically concentrates the largest clasts at the front of the surge, magnifying the peak discharge and impact forces (Rickenmann, 2016). Debris flows often entrain substantial amounts of channel material, soil, and water along the flow path (Hungri et al., 2014). In the Alps, debris flows are usually triggered by rainfall, but other triggers can involve glacial lake outburst floods, as well as snow and ice melt (e.g. Guzzetti et al., 2007; Breien et al., 2008; Prenner et al., 2019; Evans et al., 2009).

Figure 5: Definition of debris flow.

In terms of debris-flow activity, a fundamental difference exists between catchments of fresh (i.e., newly produced) and 'inherited' (or old) sediment (Stiny, 1918). Old sediment has typically been deposited under different climatic conditions and is often available in vast quantities. Here, debris flows will be initiated from talus slopes, weak and deeply weathered soils, and till or glaciofluvial materials with limited cohesion whenever a rainfall threshold is exceeded. We refer to these systems as "transport-limited" catchments.

By contrast, in watersheds consisting essentially of competent bedrock with very low sediment production rates, fresh sediment needs to be produced by weathering processes before a debris flow can occur (Rengers et al., 2020; Hirschberg et al., 2022). As a rule of thumb, however, in these "supply-limited" watersheds, it may take decades for enough sediment to be produced on hillslopes and the channel system for another debris flow to occur (Bovis and Jakob, 1999; De Haas et al., 2018). This also means that even an extreme rainstorm occurring prior to a threshold

sediment recharge being reached will only result in a flood, or perhaps debris flood (Borga et al., 2014; Church and Jakob, 2020), but not in a debris flow. The debris-flow intermittency will also depend on lithology in these watersheds as certain rock types are known to weather more efficiently and to produce large concentrations of fines (e.g., limestone, shale, sandstone Stoffel et al., 2024a). Here, debris flows will more likely be mobilized because the finer sediment can retain higher volumes of water (Iverson et al., 2010; Iverson, 2014).

In a warmer climate, changes in debris-flow susceptibility can be expected in areas with considerable glacier retreat and/or permafrost thawing, exposing large amounts of sediments on slopes or within topographic depressions where debris can accumulate temporarily, thereby expanding current debris-flow source areas to new regions (Stoffel et al., 2024a). In many regions of the European Alps, rock glaciers are an essential source of material for debris flows, and their accelerating creep rates lead to an increased transfer of sediment into debris-flow gullies, where it becomes available for mobilization (Lugon and Stoffel, 2010; Kummert et al., 2018; Marcer et al., 2021). Due to glacier retreat, lateral hillslopes may become destabilized and glacial till uncovered, forming large areas of easily erodible debris (Evans and Clague, 1994; Fischer et al., 2013; Legg et al., 2014). In addition, warming and thawing permafrost is expected to lead to an increase in rockfall activity, the deposits of which can present important sources of erodible debris (Coe et al., 2018; Harris et al., 2009). If such new debris deposits get mobilized, this can also lead to new debris-flow channels in places where none previously existed (Tobler et al., 2014, 2015).

Climate change can also affect weathering and, thus, the production of fresh sediment. In the European Alps, physical weathering can be considered as the predominant process of producing fresh sediments. Chemical weathering is considered as of minor influence over the considered time scale. It can be assumed that under wetter climates, chemical weathering could

increase and, in turn, increase bedrock erodibility (Murphy et al., 2016), making it more sensitive to frost-weathering processes. However, the interaction between frost weathering and chemical weathering remains unexplored to the authors' knowledge. Furthermore, the greater the weathering susceptibility of the bedrock, the stronger the effect climate change has on its production (Stoffel et al., 2024a). In general, changes in weathering have, among others, been linked to decreases in snow depth and snow season shortening. Indeed, soil and bedrock will be increasingly exposed to physical weathering and temperature fluctuations, which can lead to increased sediment supply by frost-weathering processes (Anderson, 1998; Hales and Roering, 2007; Matsuoka and Murton, 2008; Bennett et al., 2013; Draebing et al., 2017). Studies considering frost-weathering for debris-flow activity predictions have found that, on the one hand, the debris-flow activity is likely to decrease at lower elevations (subalpine areas, < 2000 m) due to a decrease in frost-weathering efficacy. On the other hand, snow cover reductions in higher elevations will lead to less insulation and increased bedrock exposure to frost-weathering (Jomelli et al., 2009; Hirschberg et al., 2021).

In transport-limited watersheds with quasi-unlimited sediment supply, more frequent and/or intense rainfall can increase erosion in the watershed, thus increasing material input into the system. Likewise, precipitation patterns and snowmelt may affect the stability of loose material. As a result, large amounts of material can become unstable and break loose as debris flows or increase the bedload potential for debris-bearing floods. Finally, in the context of massive glacier retreat, large new deposits of loose material arise, which can significantly change the bedload budget and debris flow activity in a catchment area (Rickenmann and Zimmermann, 1993).

3.2.3. *Ice avalanches*

The main preconditioning factors for ice avalanches are topography and ice thermal conditions. Topography interacts with glacier geometry, controlling a glacier's susceptibility to failure. Under current climate change, geometric changes driven by glacier retreat are the most rapidly changing preconditioning factor. Where glaciers retreat from flat areas into steep terrain and lose the buttressing effect of the valley floor or main glacier trunk, they may become more susceptible to break-offs (Dalban Canassy et al., 2011; Preiswerk et al., 2016; Meier et al., 2018). Conversely, if they retreat beyond an incline or cliff face, the hazard potential is reduced or may disappear altogether because the glacier has regained a stable position. Due to the widespread thinning and mass loss (Farinotti et al., 2009), the volumes available for mobilization from a given source area are generally declining. At the same time, thinning makes glaciers more susceptible to crevassing, which may introduce additional weak points, primarily where glaciers flow over convex terrain (Cuffey and Paterson, 2010). Based on the geometric changes, we would not expect a clear trend in ice avalanche frequency, with conditions prone to failure appearing and disappearing depending on the geometric constellation, though the overall volumes are likely to decrease. However, the locations prone to ice avalanching may change rapidly, with new sites appearing while activity at others ceases.

Ice avalanches describe ice breaking off from glaciers, plunging downslope, gradually shattering into increasingly smaller pieces, and coming to a stop when frictional forces have completely absorbed its kinetic energy (Alean, 1985). Contrary to rock failures, even small ice detachments commonly disintegrate and turn into granular flows (Hungre et al., 2014). Ice avalanches have been categorized based on combinations of glacier thermal regimes, glacier bed geometry, glacier

accumulation and ablation processes, as well as fracture types (Alean, 1985; Pralong and Funk, 2006). For the purpose of this review, we apply a simplified categorization following Faillettaz et al. (2015) and distinguish ice avalanches from (i) cold-based glaciers, where all ice is below the pressure melting point, (ii) temperate glaciers, where ice is at the pressure melting point, and (iii) polythermal glaciers, where cold and temperate ice is present simultaneously (Cuffey and Paterson, 2010).

Figure 6: Definition of ice avalanche.

Ice thermal conditions chiefly control the failure mechanisms of ice avalanches. Ice temperature is governed by a complex interaction of the surface energy balance, geothermal heating, internal heating from ice deformation and sliding, as well as melting and refreezing processes at the surface and within the ice (Cuffey and Paterson, 2010). Based on this, glaciers can be considered cold, polythermal, or temperate (Cuffey and Paterson, 2010, see definitions on page 17). Ice avalanches from temperate glaciers can be large and involve substantial parts of a glacier tongue, typically occurring in late summer (Pralong and Funk, 2006). These instabilities are caused by a widespread loss of basal friction or decoupling of the ice from the glacier bed driven by changes in the subglacial hydrologic system. They are generally accepted to happen when a sudden pulse of meltwater encounters an inefficient (non-channelized) drainage system, leading to a widespread increase in subglacial water pressure that can decouple the glacier tongue from its bed and cause a break-off if the terrain is steep enough (Röthlisberger, 1977; Alean, 1985; Faillettaz et al., 2012, 2015). However, subtle decoupling and associated acceleration of glacier flow velocities in response to changing subglacial water pressures are often observed on temperate glaciers (Iken, 1977). Still, in most cases, this is a seasonal signal followed by a deceleration

without consequences. Therefore, the observed acceleration is a necessary but insufficient precursory indicator for a break-off (Faillettaz et al., 2015).

Avalanches from cold-based glaciers, on the other hand, predominantly affect steep and typically small hanging glaciers found on the range's highest peaks and don't show any seasonality. Ice avalanches from these glaciers are a frequent and necessary ablation process that, since the front of these glaciers cannot lose substantial mass through melt, allows the glacier to maintain a finite size (Pralong and Funk, 2006). As the geometry approaches an unstable configuration, progressive accumulation of internal damage eventually leads to the break-off of frontal sections of the glacier (Faillettaz et al., 2015). Depending on the aspect, cold firn is currently found at elevations above 3500 to 4000 m in the European Alps (Suter et al., 2001; Suter and Hoelzle, 2002; Hoelzle et al., 2011). As temperatures rise, and these cold firn areas experience more melt, the latent heat release of refreezing (melt)water can transform cold ice into polythermal or temperate ice within several years (Haerberli and Alean, 1985; Huggel et al., 2012b). Transitions from cold to polythermal or temperate ice change the failure mode, increasing basal sliding and making potentially larger ice volumes susceptible to failure (Faillettaz et al., 2015). Increased sliding may also contribute to the formation of crevasses that allow for water infiltration. This can further increase basal and internal warming and facilitate the forming of englacial water pockets (Vincent et al., 2012; Gilbert et al., 2012). Combined, the increasing water availability and climate-change-induced ice warming would, therefore, lead to larger ice avalanches, a shift of the source areas to higher and higher elevations, and a shift of seasonality to summer and fall.

In polythermal glaciers, if both the temperate and cold parts are involved, the failure is initiated in the temperate part of the glacier and propagates through the neighboring cold ice. This can occur if (melt)water infiltrates the base of a cold glacier and creates or enlarges a weak zone of

temperate ice (Faillettaz et al., 2011). Recent studies have also shown that particularly large volumes can be mobilized if water infiltrates and destabilizes soft sediment beds of polythermal glaciers, where water drainage is inhibited by cold-ice margins (Kääb et al., 2021). Such multi-million cubic meter glacier detachments have never been documented in the European Alps, but the surge-like accelerations observed on Invergnan and Belvedere glaciers (Italy) in the early 2000s did bear some similarities to the detachment precursors observed elsewhere (Chiarle et al., 2021). On glaciers with a solid bedrock bed, water infiltration into polythermal glaciers can also lead to an accumulation of water in subglacial cavities or englacial crevasses. With large enough water pressures, the water outburst and coinciding ice avalanche present a hazard (Dutto et al., 1991; Vincent et al., 2012; Gilbert et al., 2012; Chiarle et al., 2022; Bondesan and Francese, 2023).

Under the influence of climate change, a transition from polythermal to temperate conditions may alter the failure mechanism and change the expected locations. Somewhat counter-intuitively, rising temperatures may also contribute to a transition from temperate to polythermal or cold ice, especially in small glaciers (Irvine-Fynn et al., 2011; Huss and Fischer, 2016). This is because glacier thinning and the associated fragmentation of larger glaciers into small ice bodies leads to a reduction of flow velocities and internal deformation, thereby reducing basal and strain heating (Cuffey and Paterson, 2010). More significantly, the loss of firn cover leads to less retention and refreezing of meltwater, reducing the latent heat release and its warming effect (Huss and Fischer, 2016). At the same time, the winter cold wave will more easily cool these small ice bodies, particularly along the edges, where the ice may become frozen to bedrock. While fully cold ice bodies can generally be considered more stable, and the ice avalanches they produce more predictable, the potential of (invisible) water retention within or under glaciers that have become polythermal means that avalanches may suddenly originate in new and likely unexpected

locations.

3.2.4. *Snow avalanches*

Snow avalanche formation is preconditioned by two main factors: terrain characteristics, such as slope and curvature, and snowpack characteristics, including structural, thermal and physical properties. Terrain remains invariable at timescales relevant for avalanche triggering, but over longer time scales, changes in land cover (e.g., forest composition or glacier retreat) may affect avalanche activity. The snowpack structure is determined by the varying meteorological conditions throughout the winter season, leading to a vertically layered snowpack. Variations in the properties of the individual layers, such as snow grain size or density, initially arise from variations in meteorological parameters during precipitation events, specifically snowfall amount, air temperature, and wind. Following deposition on the ground, snow experiences further metamorphosis contingent on ambient conditions (Schweizer et al., 2003, 2008; Reuter et al., 2015; Mock et al., 2017). The thermal conditions of the ground play a role in specific snow avalanches such as glide snow avalanches (Fees et al., 2023), but also influence the metamorphosis by controlling the temperature gradient in the snowpack.

Snow avalanches are defined as a sudden release of snow masses (Schweizer et al., 2021). All snow avalanches require snow and a steep slope ($> 30^\circ$) to release (McClung, 2023) and are very diverse in terms of type, size, and related destructive power, the season of occurrence, and the main processes involved. They can be broadly categorized by types of release (loose-snow, slab), snow type (dry and/or wet), and flow type (dense and/or with a powder cloud) (Schweizer et al., 2003).

Figure 7: Definition of snow avalanche.

The criteria for avalanche release related to snowpack structure and stability vary depending on the type of avalanche. Loose-snow avalanches occur when snow grains on the snow surface have low internal cohesion, leading to the rapid descent of unconsolidated snow down a slope in the form of an inverted V shape (or pear shape) attributed to snow friction (De Biagi et al., 2012). By contrast, slab avalanches form when a cohesive slab of snow releases due to the mechanical failure of a fragile, weak layer within the snowpack (Schweizer et al., 2003). In dry-snow slab avalanches, weak layers commonly consist of low-density precipitation particles that induce instabilities either during or shortly after a snowfall event (Bair et al., 2012). Alternatively, they may comprise weakly-bonded persistent grain types that develop under specific meteorological and snowpack conditions after snow deposition (Birkeland, 1998). When such pre-existing weak layers are infiltrated by meltwater or rain, they may lose strength, resulting in wet-snow slab avalanches. Finally, glide-snow avalanches occur when liquid water at the ground-snow interface reduces friction (and possibly cohesion) between the snowpack and the ground. Herein, liquid water may originate from various sources, such as the percolation of meltwater, geothermal heat melting snow at the ground/snow interface, and capillary suction (Mitterer and Schweizer, 2013; Fees et al., 2023).

Long-term changes in meteorological conditions (e.g., snow-rain partitioning, extreme precipitation events), snow cover, and snow stratigraphy will inevitably impact avalanche release. Scarcer snow conditions should directly reduce the number and size of spontaneously triggered avalanches, shorten the avalanche season, shrink terrain prone to avalanches, and shift it to higher elevations (Gądek et al., 2017; Giacona et al., 2021). Warming also leads to snow melt and more

liquid water within the snowpack (Castebrunet et al., 2014; Součková et al., 2022; Mayer et al., 2024), which generally favors wet- and glide-snow avalanche releases (Ancey and Bain, 2015; Dreier et al., 2016; Hendrick et al., 2023), even in high winter and/or at high elevations. However, the detailed understanding of how climate change affects snow stratigraphy and, ultimately, snow avalanche release remains limited (Eckert et al., 2024), with devoted studies on changes in typical avalanche situations just now emerging (Haegeli et al., 2021; Reuter et al., 2022, 2023b).

3.3. *Changing triggers*

In the failure continuum (see Fig. 3), triggering events are the immediate causes that initiate the failure of unstable rock, debris, ice, or snow. Theoretically, a trigger typically alters the subsurface properties in the short term, reducing friction and/or cohesion in or between materials. Beyond the climate change context, earthquakes and human activities (skiers, blasting, changes of reservoir levels, etc.) can serve as triggers. In the context of climate change, triggers of alpine mass movements are often related to short-term meteorological events, primarily intense and/or prolonged precipitation (rain and/or snow), high temperatures, and abrupt temperature changes.

Intense precipitation is the most common trigger for debris flows (Borga et al., 2014; Bogaard and Greco, 2018; Prenner et al., 2019; Kaitna et al., 2024) and rockfalls (Krautblatter and Moser, 2009; Matsuoka, 2019), and – when it falls as snow – the primary trigger for intense avalanche activity (Schweizer et al., 2009; Eckert et al., 2010b). For all these processes, the snowfall level plays a key role, as rain-on-snow events can deliver large amounts of water through a combination of direct water input and snow melt (Fehlmann et al., 2019), serving as triggers for debris flows, rockfalls, wet or glide-snow avalanches (Stoffel and Corona, 2018). High-elevation rain events may lead to, often short-term, inputs of large amounts of liquid water even during

spring and autumn (Kotlarski et al., 2015; Giorgi et al., 2016; Gobiet and Kotlarski, 2020; Kuhn and Olefs, 2020). With the snow-cover duration declining, such events may cause a larger proportion of rain to become directly available for infiltration and runoff rather than percolating through snow, making it more readily available for mass movements involving rock/ground material.

High temperatures and heat waves can trigger mass movements directly (Allen and Huggel, 2013; Paranunzio et al., 2019), primarily by thawing permafrost and melting ice in fissures that lead to rockfall or rock avalanches (Collins and Stock, 2016; Legay et al., 2021). Additionally, temperature changes may affect slope stability indirectly by altering the mechanical properties of the material, such as its permeability, water retention capacity, or shear strength (Scaringi and Loche, 2022; Gunzburger et al., 2005, in particular for slopes with high clay content). More commonly, above-zero air temperatures indirectly create a surplus of water through snow and ice melt. This meltwater can percolate into the snowpack and trigger wet-snow avalanches (Baggi and Schweizer, 2009; Mitterer and Schweizer, 2013). It can also erode ice-cemented fissures and trigger rockfall or rock avalanches (Stoffel et al., 2024b), or it may trigger debris flows (Mostbauer et al., 2018). The presence of liquid water is also a relevant triggering factor for ice avalanches, especially from polythermal and temperate glaciers. Still, the exact mechanisms and relevant time-frames are poorly understood.

The impact of changing triggers is sometimes difficult to predict because they can exhibit opposing trends. For example, despite the fact that rainfall magnitudes from convective storms are projected to increase, summers will generally become drier (Stoffel et al., 2014; Giorgi et al., 2016; Pichelli et al., 2021). Similarly, earlier snow melt may shift the season during which we observe most melt-triggered debris flows (Kaitna et al., 2023), rockfall (Stoffel et al., 2024b), ice

avalanches from temperate glaciers (Faillettaz et al., 2012), or wet-snow avalanches (Reuter et al., 2023a), but this early melt events may also be limited by the seasonality of solar irradiation. Which effect is stronger can depend on a variety of factors that may vary at local scales.

3.4. Influence on runout propagation

In the first instance, the mobility of mass movements is controlled by the volume and condition of the involved material. The transported volume is initially given by the failure volume but can be altered by entrainment and deposition along the flow path (Iverson et al., 2011; Mangeney, 2011). In addition to increasing the volume, sometimes by several orders of magnitude, entrainment can affect the rheology (Sovilla et al., 2001; Hungr et al., 2005; Huggel et al., 2005; Liu et al., 2019; Pudasaini and Krautblatter, 2021; Mani et al., 2023), thereby changing the behavior of the flow. The material temperature can also be a relevant factor. The runout distance of ice avalanches depends directly on the temperature of the ice at release (Maggioni et al., 2018). In rock-ice avalanches (Schneider et al., 2011), the material temperature determines how soon excessive energy becomes available for the production of liquid water through melting (Shugar et al., 2020). Runout distances of snow avalanches are also highly variable. Due to lower friction for dry/cold snow, the most mobile avalanches are typically dry-snow avalanches (Schweizer and Lütschg, 2001; McClung, 2023). A complex non-linearity exists between temperature and runout distance: An increase in material temperature initially leads to an increase in friction/cohesion and thus to a reduction in the runout distance until melt water is produced, which then leads to an increase in the runout distance (Naaim et al., 2013).

The ground material properties and path roughness also affect mass movement propagation, either by impacting the cohesion, friction, and/or rheology of the mass flow or by

influencing the energy absorption (Dorren et al., 2005; Vick et al., 2019; Albaba et al., 2019; Ringenbach et al., 2023). The ground conditions – e.g., frozen vs. thawed ground, solid bedrock vs. weathered regolith – affect the water availability and quantity of material that can be entrained (Iverson et al., 2011; Pudasaini and Krautblatter, 2021). Water incorporation and production along the runout path may result from the entrainment of snow or ice, the interaction with open water bodies, or release through impact loading (Cicoira et al., 2022). For example, the flow resistance of grain-fluid mixtures is susceptible to minor changes in water content (e.g. Coussot, 1997; Ancy, 2007), which is of major importance for the runout of debris flows (e.g. Delannay et al., 2017; Chen et al., 2022). Under extreme circumstances, the addition of large amounts of water can lead to a complete change of the flow regime, for example, by turning a rock avalanche into a debris flow (Mani et al., 2023), leading to a substantial increase of the mobility (Huggel et al., 2005; Evans et al., 2009; Walter et al., 2020). Ground pore-water pressures drop when water can suddenly drain from a flow, leading to a quick slowdown. Similarly, a thick snowpack in the runout path may dissipate impact energy, which in turn will slow or stop mass movements (e.g., rockfall), especially if their kinetic energy is low. Conversely, the presence of snow can also reduce the surface roughness, potentially increasing the runout distances (Brožová et al., 2021). Trees and vegetation, in healthy or damaged states (fire, wind-fall, beetle-kill, etc.) conditions have (time-)variable impacts on runout propagation (Ringenbach et al., 2022, 2023).

The above considerations illustrate that substantial interactions and feedbacks exist between the volume, path, and material properties, all of which can influence runout propagation. With regard to runout, the availability of water is one of the most important factors, and this may be directly impacted by climate change. The rising temperatures lead to a higher rain-to-snow ratio (Morán-Tejeda et al., 2016; Beniston and Stoffel, 2016) or higher runoff from ice melt (Huss et al.,

2008; Farinotti et al., 2012; Huss and Hock, 2018; Farinotti et al., 2019), both of which may be important water sources. On the other hand, the associated decline in snow cover may reduce the availability of snow for entrainment by rock/ice/snow avalanches and debris flows, potentially decreasing runouts.

Climate change can also alter the structure and properties of the runout path, especially with regard to protecting forests. Increasing temperatures at elevations above 1500 m will stimulate forest growth and enable the colonization of areas where tree growth has been inhibited due to low temperatures (Bebi et al., 2009; Lingua et al., 2020; Moos et al., 2023). The increasing biomass of these forests and the re-vegetation of areas where trees have temporarily been removed will likely enhance their capacity to dissipate energy from mass movements and reinforce soils with their roots. On the other hand, more frequent and severe droughts at lower elevations, typically below 1500 m, can reduce growth and increase mortality, potentially leading to abrupt changes in the species distribution and, at least temporarily, a decreased energy dissipation and root reinforcement capacity of forests (Moos et al., 2021; Hillebrand et al., 2023). Additionally, increasing natural disturbances, such as forest fires, insect outbreaks, or wind storms, temporarily alter the surface conditions by reducing the standing stock but increasing surface roughness (Costa et al., 2021; Ringenbach et al., 2022).

4. Observed impact of climate change on alpine mass movements

4.1. Literature sources, search & selection

We attempted to extract a complete set of research articles that investigate the relation between alpine mass movements and climate change. To achieve this, we systematically searched and reviewed English-language journal articles indexed in Google Scholar, Scopus, or Web of

Science from combinations of specific search words such as "climate change", "European Alps", and/or "warming" as well as the specific mass movement processes "rockfall", "rock avalanche", "debris flow", "ice avalanche", or "snow avalanche". The initial search was focused on information in the title, abstract and keywords. We then reviewed the results (see Fig. 8) and omitted publications that were based exclusively on modeling or laboratory experiments, retaining only publications that used observational data to investigate the connection between mass movements and climate change. Finally, we also classified the retained publications by whether or not the authors had found climate change to be the (or a) driving process behind the observed changes.

Figure 8: Outcome of the literature search and review for each type of mass movement, initially yielding 335 scientific publications for all processes combined. Omitting publications that were based exclusively on modeling or laboratory experiments, 103 publications remained in the category 'considered'. Thereof, around 30 studies (darkest blue bars) identified a measurable impact of climate change on the respective alpine mass movements (all except large rock avalanches).

Table 1: Data types considered in studies for the different alpine mass movements. The period that can typically be investigated with the different datasets decreases from top to bottom.

[Image]

4.2. Data types and methodological approaches

Various types of data records have been used to investigate the occurrence of mass

movements and their connection to climate change. The longest records – spanning centuries to millennia – are provided by proxy data and historical archives. These include the analysis of pollen, lichen, or lake sediments (e.g., McCarroll et al., 1995; Blikra and Selvik, 1998; Jomelli and Pech, 2004; Nesje et al., 2007; Dietrich and Krautblatter, 2017; Kiefer et al., 2021), dendrogeomorphic investigations (the dating of broken or injured trees; e.g., Butler and Sawyer, 2008; Corona et al., 2013; Trappmann et al., 2013; Stoffel and Corona, 2014; Favillier et al., 2018), the mapping and dating of geomorphic features such as process deposits (e.g., Soldati et al., 2004, 2006; Kellererpirklbauer et al., 2012), and various types of inventories (e.g., Ravanel and Deline, 2015; Allen and Huggel, 2013; Guerin et al., 2020; Paranunzio et al., 2019; Nissen et al., 2022; Wood et al., 2020). Such long archival and proxy records are highly valuable, but their spatial coverage is generally limited and the reconstructions suffer from various limitations, e.g., related to a loss of efficiency of the proxy to record events as one moves further into the past (Favillier et al., 2023). Compilations spanning multiple centuries only exist within a limited number of regions with longstanding human occupation, and even the most systematic records are often incomplete. Chronicles compiled from archives are inherently affected by biases in historical sources, such as the fact that large and disastrous events are often better documented or that only events that damaged infrastructure or livelihoods were recorded in the first place, thereby omitting most remote events (Giacona et al., 2017, 2022). To date, no international databases exist for rockfall, rock avalanches, debris flows, or ice avalanches. Therefore, studies tend to rely on regional agencies and on event catalogs maintained by individual research groups.

At the level of medium to short-term records, data from networks of local observers (uniquely available for avalanches; Bourova et al., 2016; Höller, 2009) offer direct observations now spanning several decades. Due to the subjective assessment by varying local observers,

however, these records are also prone to inhomogeneity and errors that can be hard to assess (Laternser and Schneebeli, 2002; Hafner et al., 2023). Beyond that, most records, regardless of the mass movement they are designed to observe, are (still) relatively short. Data sources include automatic monitoring and detection systems based on seismic, infrasound, doppler radar, or time-lapse imagery, to name a few (e.g., Köhler et al., 2016, 2018a,b; Meier et al., 2018; Mayer et al., 2020; Perret et al., 2021; Chmiel et al., 2023), mapping on satellite images or orthophotos (e.g., Hafner et al., 2022; Rom et al., 2023; Savi et al., 2021), sediment traps (e.g., Krautblatter and Moser, 2009; Müller et al., 2014), or repeat terrestrial laser scanning (e.g., Gallach et al., 2020; Hartmeyer et al., 2020; Courtial-Manent et al., 2024). Such data are often available only from a limited number of locations, and, due to their relative novelty and or complexity, time series of sufficient length are only just becoming available.

These relatively short records of direct observations mean that only a few studies are able to investigate the relation between mass movement activity and climate change in the strictest sense. Rather, many investigations focus on patterns of weather and mass movements over the course of several years. While this may not be long enough to unambiguously attribute observed changes to long-term climate change (which typically requires several decades of continuous observations; Easterling et al., 2016), it does provide highly valuable insights into the processes that are driving the changes in different locations. Additionally, data on preconditioning factors such as rock surface temperatures, sediment availability, glacier geometries, or snowpack stability is often available in a more continuous or long-term form, offering vital supporting information on the ongoing changes (e.g., Schweizer et al., 2003; Dalban Canassy et al., 2011; Deline et al., 2021). To provide a comprehensive review, we included all studies that revealed climate-driven changes and patterns in alpine mass movements.

4.3. *Observational records from the European Alps*

In this section, for each of the four alpine mass movement processes, we assess to what extent the impact of climate change has been documented through scientific studies based on observational records from the European Alps.

Figure 9: Study locations and data sources of all studies reviewed in this publication. The differentiation of study types is based on the following logic: Single site: studies that investigate the mass movement record at one site, e.g., a single debris flow channel, the north face of a specific peak, etc. Multi site: studies that bring together data from multiple sites in small regions, e.g., all torrents in a valley, several glaciers in the French Alps, etc. Inventory: studies based on data catalogs compiled by external institutions, e.g., governmental agencies or publicly available (scientific) inventories. The Zermatt Valley (Mattertal) and the Mt. Blanc massif stand out as two hot-spot locations that concentrate a lot of the available observations. Tick marks denote degrees of latitude and longitude.

4.3.1. *Rockfall and rock avalanches*

We identified 45 studies that address the climate-related dynamics of rockfall and rock avalanches in the European Alps. Many of the existing studies rely on site-specific observations or remotely-sensed approaches spanning several years to almost two decades (Noetzli et al., 2003; Soldati et al., 2004, 2006; Borgatti and Soldati, 2010; Allen and Huggel, 2013; Ravanel and Deline, 2015; Guerin et al., 2020; Knoflach et al., 2021; Mamot et al., 2018; Courtial-Manent et al., 2024). Others use proxies (predominantly growth-ring records of trees damaged by rockfall) to reconstruct rockfall activity over the past decades to centuries (Stoffel et al., 2005b; Trappmann et

al., 2013; Mainieri et al., 2020, 2022). Regional inventory studies, to date, remain the exception (Paranunzio et al., 2019; Nissen et al., 2022). Likewise, detailed post-event documentations are typically only available for single, "low frequency - high magnitude" events (e.g. the Piz Cengalo rock avalanche; Walter et al., 2020), and documentation of smaller rockfall events are often limited to events that happened in locations where humans are affected, as for example on access routes to mountains huts or on popular mountaineering routes (Mourey et al., 2022; Ravanel et al., 2017).

Among the clearest findings are observations that establish a connection between the warming of air and/or rock temperatures and increased rockfall activity, especially from permafrost areas. Significantly warmer surface and bedrock temperatures have been observed prior to failure in a series of case studies or local assessments (e.g., Ravanel and Deline, 2011; Huggel et al., 2012b; Stoffel and Huggel, 2012; Keuschnig et al., 2015; Gariano and Guzzetti, 2016; Ravanel et al., 2017; Nigrelli et al., 2018; Legay et al., 2021; Hendrickx et al., 2022). It has been shown that this influence of positive temperature anomalies also leads to peaks in rockfall activity during summer, both at medium (2400–3300 m asl) and high (> 3300 m asl) elevations (Luethi et al., 2015; Phillips et al., 2017; Paranunzio et al., 2016). In addition to temperature impact on permafrost areas, significant rockfall activity has also been documented from newly deglaciated areas (Hartmeyer et al., 2020; Viani et al., 2020), often with major consequences on mountaineering routes and practices (Mourey et al., 2019, 2020). The impact of temperature is also felt indirectly, via snowmelt, which has been found to lead to peaks in rockfall activity that follow peak air temperature with a typical delay of two hours (Mourey et al., 2021), underlining the importance of liquid water availability.

Despite this evidenced impact of temperature on rockfall activity at high elevations at

shorter time-scales, only few studies have been able to analyze this effect in datasets spanning more than two decades. A regional study of rock slope failures between the 1990s and 2007 ($n=52$; volume $> 1000 \text{ m}^3$) in the Swiss Alps and adjacent areas of France and Italy found an increasing trend in the frequency of events larger than $> 10^5 \text{ m}^3$ at elevations above 2000 m asl (Fischer et al., 2012). Likewise, relying on a unique terrestrial laser-scanning-derived rockfall catalog (2005–2022), Courtial-Manent et al. (2024) documented 210 rockfalls from the east face of Tour Ronde (3440–3792 m asl) in the Mont-Blanc massif. They show that rockfalls with volumes ranging from 1 m^3 to 15500 m^3 occurred predominantly during heat waves and from surfaces that had been recently deglaciated. These findings are in good agreement with investigations from the Sulden Valley (Italy), an increase in rockfall activity since the year 2000 and coincident rise of the rockfall release-area elevation by 300 m (Savi et al., 2021). Leveraging one of the longest records, Stoffel et al. (2024b) reconstructed 100 years of periglacial rockfall activity at Täschgufer (Swiss Alps) relying on damage in 375 treeline forming European larch trees. The study evidences that ongoing warming favors the release of rockfall and that changes in activity correlate significantly with summer air temperatures at interannual and decadal timescales. However, the correlation is not uniform through time. After an initial increase in rockfalls in the late 1940s to early 1950s (following the Early Twentieth Century Warming), activity dropped to a new low-point during the 1960s and 1970s, before increasing again in the late 1980s and 1990s. In agreement with cyclic rockfall patterns documented at the Drus in the French Alps (Guerin et al., 2020), findings from Täschgufer also suggest that bedrock that is newly exposed after periods of increased rockfall first needs to be weakened to become available for future rockfalls.

At low elevations, the factors controlling the release of rockfall events are more diverse, and uniform trends in rockfall activity are currently not evident. Long-term records are rare here as

well. Extensive, 60-year dendrogeomorphic reconstructions from two low-elevation sites in the Vercors and Diois massifs in France did not reveal any changes in rockfall frequency, despite the fact that yearly precipitation totals and mean temperatures could be identified as rockfall drivers in the Diois Mainieri et al. (2022). Similarly, an analysis of 252 rockfall events in Austria between 1900 and 2010 did not reveal any evidence of increased rockfall during warm periods Sass and Oberlechner (2012), nor did the evaluation of two decades of inventory and remote sensing data from South Tyrol in Italy (Schlögel et al., 2020). The analysis of 358 rockfall events that occurred between 2000 and 2016 in the Italian Alps at elevations ranging from 1500–4200 m found that rockfall often occurred after one or several temperature anomalies, albeit with contrasting spatial patterns: While rockfall was associated with above average temperatures in the Western Alps, lower-than-average temperatures appeared to drive rockfall in the Eastern Alps (Paranunzio et al., 2019). Several studies also assessed the impacts of freeze-thaw cycles. While these can be identified as important controls on rockfall activity, climate-driven changes are currently not evident (Rupp and Damm, 2020; D’Amato et al., 2016; Bajni et al., 2021).

Precipitation was found to be a critical rockfall trigger in several studies, but the relation between it and rockfall activity remains varied. Studies have evidenced correlations with the amount of precipitation on the day of the event (Nissen et al., 2022), explained the timing of 90 % of rockfall activity by rainfall intensity Krautblatter and Moser (2009), detected an increased rockfall activity when mean rainfall intensity is higher than 5 mm h^{-1} D’Amato et al. (2016), or found seasonal differences in precipitation dependence (e.g., precipitation as the main controlling factor in autumn Bajni et al., 2021). While these studies show highlight the importance of precipitation as a rockfall trigger, consistent changes driven by climate change remain elusive.

Figure 10: Studies on observed climate change impacts on rockfall activity and rock avalanches. (a) Publications considered in this review with corresponding study period. (b) Bar plot showing the number of publications and whether they detected an impact of climate change, by elevation.

4.3.2. Debris flows

We found 16 studies that explicitly analyzed past debris-flow events about observed climate or climatic triggers. 50 % of the studies found an increase in debris-flow activity, while the other 50 % observed no significant change and one a decrease. The studies covered the Swiss (6), Italian (5), French (3), Austrian (3) and German (1) Alps. Eight studies were conducted in alpine environments. Three studies analyzed basins with subalpine source areas (< 2000 m asl, permafrost occurrence unlikely), and five studies conducted lumped regional analyses with elements of both alpine and subalpine environments (see Fig. 11).

At the local scale, debris flows have been documented at locations where they were before unprecedented, and these debris flows initiated in proglacial streams where unconsolidated and unvegetated sediment is abundant due to glacial retreat (Chiarle et al., 2007; Huggel et al., 2012a). Besides these singular events, case studies have analyzed changes in debris-flow frequencies and their climatic triggering conditions from multi-year documented or reconstructed event catalogs. One extremely active and well-investigated study site is the Ritigraben (Zermatt Valley, Swiss Alps), for which more than 120 debris-flow events have been compiled and reconstructed by dendrogeomorphic methods dating back to the year 1570 until 2009 (Stoffel et al., 2005a, 2008; Stoffel, 2010). It was found that increased activity in the late 20th century (Rebetez et al., 1997) is not unprecedented, as periods with enhanced debris-flow frequency have occurred after the end of the Little Ice Age in the late 19th century and even more so between the 1920 and 1940s. Although

the reasons for this increase in frequency are manifold, they can, among others, be ascribed to enhanced summer precipitation and more abundant thunderstorms in summer during the late 19th century as well as to warm-wet conditions between the 1920s and 1940s, corresponding to the latter half of what is known as the Early Twentieth Century Warming period (Hegerl et al., 2018). Over the past 170 years, debris flows with high event magnitudes typically occurred in late summer when the active-layer thickness of permafrost in the source area was largest, underpinning the sensitivity of changes of the cryosphere to debris-flow activity (Stoffel, 2010; Lugon and Stoffel, 2010). By expanding the reconstruction to eight torrents in the Zermatt Valley (Bollschweiler and Stoffel, 2010), it was possible to identify typical weather patterns (e.g., very localized summer thunderstorms vs. large-scale low-pressure systems in fall with long-lasting rainfall) (Toreti et al., 2013) as well as the likely duration and intensity of rainfall (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012) associated with debris-flow occurrence. The anticipated changes in rainfall patterns in a warmer climate are expected to lead to further changes in both debris-flow frequency and magnitude in the Zermatt Valley (van den Heuvel et al., 2016), with a tendency for less but possibly larger debris flows which additionally will likely also occur outside the warm-season months (June - September) during which debris flows have occurred so far.

Also, at other study sites, there are indications that sediment production shifted to higher elevations in the recent past. Savi et al. (2021) report that rockfall initiation areas in the Sulden basin (Italian Alps) have shifted 300 m upwards due to changes in temperature and frost-cracking intensities since the year 2000. At the same time, the frequency of triggering rainfall events has increased since the 1960s, especially in summer, such that the combination of these changes has led to increased debris-flow frequency since 2010. Less clear results were reported for a study site

at Schnalstal (Italian Alps). Here, Sattler et al. (2011) report of an increase in debris-flow activity from 1986 to 2006 but cannot relate the locations of recent release areas to the lower boundary of the (modeled) permafrost distribution. Since release areas were located at higher elevations, the authors speculate that a thickening active layer after deglaciation could have been related to increased debris-flow activity. Similarly, Jomelli et al. (2007) identified an increasing trend in debris-flow frequency at higher elevations (> 1800 m asl) between 1960 and 2000 in the Massif des Ecrins (France). By contrast, at lower elevations, the number of freezing days (i.e. frost-cracking) dropped and resulted in fewer debris flows.

For a study site at Plansee (Northern Calcareous Alps, Austria), where glaciers and permafrost are absent at elevations < 1800 m asl, the analysis of lake sedimentation records reveals an increase of debris-flow activity over the last three decades for the period 1947 to 2014 (Dietrich and Krautblatter, 2017). This observation coincided with an increase in rainstorm frequency (≥ 35 mm) of 10 % per decade. An extension of this dataset confirmed that current debris-flow activity has been unprecedented in the past 4000 years (Kiefer et al., 2021). Other case studies from the Eastern Alps also identified changes in debris-flow frequency but could not directly link them to atmospheric warming or climate change. Procter et al. (2011) reconstructed debris-flow events in Gamperdonatal (Austrian Alps) by dendrogeomorphic dating for low-elevation catchments (< 2200 m asl) and found a peak activity in the 1990s but no overall trend and no relation to precipitation. Based on image analysis Rom et al. (2023) studied debris-flow activity in the valley of Horlachtal (Austrian Alps) from 1947 to 2020. They find no trend but three active phases with the largest volumes in the 1990s, which could not be attributed to changes in precipitation. The hypothesis that changes in sediment supply are a likely reason, could not be tested.

Studies on climatically induced changes of debris-flow activity at larger spatial scales are available for the French, Italian, and Austrian Alps. By linking recorded debris-flow activity and climate parameters in two regions of the French Alps, it could be shown that debris flows have doubled over the period from 1970 to 2005 and that this is associated with an increase in daily temperature and rainy days (Pavlova et al., 2014). For the Italian Alps, debris flows documented at elevations > 1500 m asl during the period 2000 and 2016 correlate with short-term precipitation anomalies, but no trends in event frequencies were detected due to temporal inhomogeneities in the event catalogs (Paranunzio et al., 2019). For a subset of the Italian Alps, the province of South Tyrol (Alto Adige), however, a weak increasing trend in debris-flow frequency has been detected based on an event catalog reconstructed from satellite data (Schlögel et al., 2020). This observation could not be unambiguously associated with changes in both satellite-derived and ground-based observations of climate variables such as rainfall and temperature. A database study of torrent events, including debris flows in the Austrian Alps between 1962 and 2017, did not find evidence of a recent increase in debris-flow frequency even though indices of triggering precipitation had increased (Schlögl et al., 2021). The authors attribute this to the compensating effect of mitigation measures.

Figure 11: Studies on observed climate changes impacts on debris flows. (a) Publications considered in this review with corresponding study period. (b) Bar plot showing the number of publications and whether they detected an impact of climate change, by elevation.

4.3.3. Ice avalanches

Although more extensively studied and monitored than in other regions of the globe, data

on ice avalanches in the European Alps is sparse. Nevertheless, attempts to compile the available data into inventories have been undertaken by various actors: Possibly the most comprehensive effort was made within the GLACIORISK EU project in 2003, which led to the compilation of a database of glacier-related hazards in France, Italy, Switzerland, Austria, Norway and Iceland (Glaciorisk GRIDATABASE, <http://www.nimbus.it/glaciorisk/gridabasemainmenu.asp> Richard and Gay, 2003). This database contains entries of 177 ice avalanches originating from roughly 80 glaciers¹, but has not been updated since its original release. The Fluctuations of Glaciers database maintained by the World Glacier Monitoring Service (WGMS) contains a Special Event table with 231 entries of ice avalanches, 164 of which happened in the European Alps and span from 1597 to 2020. The inventory of hazardous glaciers in Switzerland compiled by the Laboratory of Hydraulics, Hydrology and Glaciology at ETH Zurich (archived at <https://www.glacier-hazards-2018.glaciology.ethz.ch/inventar.htm> Raymond et al., 2003) contains around 150 events related to ice avalanches dating from 1476 to 2022, but updates in recent years have not been systematic. Finally, a recent analysis of data from the Italian Alps from 1930 to 2022 documented 68 ice avalanches larger than 10000 m³ released 29 different glaciers (Chiarle et al., 2022). There is a substantial amount of overlap between these different databases, and a lack of standardization, systematic data collection, and upkeep has largely prevented comprehensive analyses of these datasets.

In addition to these extensive inventories, a few studies specifically investigated the

¹ Kellerer-pirklbauer et al. (2012) wrongly state that ice avalanches originated from 177 different glaciers, but this is not in line with the original report from Richard and Gay (2003). Therefore, we tried to count the glaciers with reported ice avalanches directly from the original database.

changing frequencies and relation to the climate of ice avalanche activity at individual locations (e.g. Fischer et al., 2011; Kellerer-pirklbauer et al., 2012; Fischer et al., 2013; Maggioni et al., 2018; Perret et al., 2021). Most other studies focus on the few locations with frequent events that pose a direct threat to human livelihoods and infrastructure and are primarily aimed at improving process understanding for warning and monitoring practices. Combined, however, they can shed some light onto what processes are driving changes in ice avalanche occurrence, which we do in the following.

Investigations of the compiled databases of ice avalanches in the European Alps have shown several changes in ice avalanche activity related to climatic changes over the past decades (Fig. 12). An analysis of an updated version of the inventory of hazardous glaciers in Switzerland revealed heightened activity in the late 1980s following a short period of higher precipitation and lower temperatures, which led to some years with positive or stable mass balances (Buerki, 2021). In Italy, a sharp increase in activity appears to have started in the 1990ies and may be ongoing, with events concentrated during the summer months (primarily August). The observed increase is therefore attributed to increasing air temperatures (Chiarle et al., 2022). Additionally, the analyzed catalog of events in Italy hints at a slight increase starting elevation of ice avalanches and a shift in seasonality to earlier months, though neither of the trends are statistically significant. A multi-temporal analysis of ice avalanche activity at Monte Rosa east face for the period 1956 – 2007 revealed that the face experienced repeated ice (and rock) avalanches starting in 1990. A climatic analysis revealed that this increase coincided with the increase in mean annual temperatures in the region. Still, the authors also note that the fast changes in surface geometry and disappearance/recovery of hanging glaciers are known to be comparatively independent of climatic conditions (Fischer et al., 2013). Acknowledging that overarching studies and

standardized datasets are rare, these observations show that climate directly influences ice avalanche activity but also that changes can be driven under warming as well as cooling climatic conditions.

Figure 12: Studies on observed climate changes impacts on ice avalanches. (a) Publications considered in this review with corresponding study period. (b) Bar plot showing the number of publications that considered climate change as the primary motivation for the study.

Looking at individual locations, there is evidence that the geometric changes induced by the rapid glacier retreat directly impact ice avalanche activity. In some cases, the changing glacier geometries lead to fewer and smaller ice avalanches; in other places, they lead to a shift of source locations or an increase in frequency. A decrease in ice avalanche activity has been reported for Allalin (Switzerland; Buerki, 2021), Nördliches Bockkarkees (Austria; Kellerer-pirklbauer et al., 2012), Frèboughe and Palon de La Mare glaciers (both Italy; Chiarle et al., 2022), and can also be assumed for Glacier du Tour (France; Deline et al., 2012). In all of these cases, the glacier's retreat onto less steep terrain and/or away from a steep cliff has led to the observed regime change. Ice avalanche activity from the Eiger hanging glacier also seems to be decreasing, at least for larger ice falls: Three major events (1982, 1990, 1991) were documented for the Eiger hanging glacier in Switzerland since monitoring began in 1980 (Raymond et al., 2003; Margreth et al., 2017). The next large failure involving 15000 m^3 occurred in 2016, making it the largest event since the 1991 failure, which involved 100000 m^3 (Preiswerk et al., 2016; Chmiel et al., 2023). Prominent cases of locations where ice avalanches suddenly began to occur from new locations include Trift Glacier (Saas valley, Switzerland Preiswerk et al., 2016; Meier et al., 2018) and Lys and Brenva

glaciers (both Italy Chiarle et al., 2022). At Trift Glacier, thinning of the main glacier trunk led to a loss of buttressing and subsequent destabilization of a small hanging glacier part around the year 2015 (Meier et al., 2018, referred to as Weissmies Glacier in). Lys and Brenva glaciers, on the other hand, both underwent a separation of the valley tongue from the higher part of the glaciers at steep rock steps. The new active fronts are now above the rock steps (Chiarle et al., 2022). Finally, an increase of ice avalanche activity was recorded on Bis Glacier in Switzerland since the year 2000. However, these ice avalanches originated from two different locations: the main tongue flowing down a steep rock ramp and a hanging glacier near the summit, and the preliminary analysis of Buerki (2021) does not distinguish between them, nor does it identify the likely reason for the increase.

At several locations, changes in ice avalanche activity are not immediately obvious. For example, no change in ice failure activity has been reported for the Tacconnaz glacier in France (Vincent et al., 2015; Faillettaz et al., 2015). Similarly, the situation at the Whymper serac (Italian side of the Grand Jorasses, Mt. Blanc massif) is inconclusive, with the time between ice avalanches ranging from a few years to more than a decade (Perret et al., 2021). No ice avalanches were documented before 1993, when an 80000 m^3 ice avalanche killed 8 climbers; since then there have been 6 other major $>10^4 \text{ m}^3$ ice failures (Chiarle et al., 2022). In June 1998, almost the entire Whymper Serac (around 150000 m^3) sheared off, and the resulting ice avalanche stopped only 500 m above the valley road. Despite intense monitoring, the observations from this location do not show a clear trend. The same is true for Planpincieux glacier (Italy), which lies immediately below the Whymper serac and has been the site of intense monitoring since 2010. Though increases in flow velocities are frequent during the summer months and have led to break-offs with volumes of up to 55000 m^3 (29 August 2017), clear trends cannot be discerned (Perret et al.,

2021; Dematteis et al., 2022).

Though englacial temperature measurements show a clear warming trend (see Sec. 2), direct observations of the impact of ice temperature changes on ice avalanche activity cannot currently be found in the scientific literature. However, two prominent examples where these effects mattered shall be showcased here. For one, investigations of the largest ice failure ever observed in the Alps, the $4 \times 10^6 \text{ m}^3$ ice avalanche from Altels in Switzerland in 1895, revealed that infiltrating meltwater, generated by warmer-than-usual temperatures during that and the previous summers, had likely created or enlarged a weak zone of temperate ice, reducing the basal friction to below the point of stability (Heim et al., 1895; Faillettaz et al., 2011). More recently, the 2022 ice avalanche at the Marmolada Glacier, which tragically killed eleven climbers and injured seven others, highlighted how glacier fragmentation due to glacier thinning could be responsible for dramatic changes in the mechanical and thermal characteristics. The collapsed ice mass had been connected to the main body of the Marmolada Glacier until ten years ago, with no known ice avalanches: due to ice fragmentation, it remained isolated and confined to a slight bedrock depression (Bondesan and Francese, 2023). This configuration is suspected to have caused a lack of basal support and a transition from temperate to polythermal conditions that allowed the frontal part to become frozen to the bedrock below. The latter can be caused by a loss of firn cover, which reduces warming of the snow and eventually ice through a release of latent heat as water refreezes (Gilbert et al., 2012; Huss and Fischer, 2016), and the enhanced cooling of the thinned ice in winter. Post-failure optical and thermal infrared images of Marmolada glacier suggest that a cold-ice margin may have prevented a water-filled crevasse from draining in a controlled manner, leading to a sudden collapse of the frontal part of the glacier (Bondesan and Francese, 2023) as a result of hydrostatic pressure.

4.3.4. *Snow avalanches*

Decades-long studies report decreases in i) the mean number of avalanches per winter and path across the French Alps over the c. 1980-2010 period (Castebrunet et al., 2012; Eckert et al., 2013), and ii) the number of days with conditions favorable for avalanche releases in forests in the Swiss Alps between 1970 and 2011 (Teich et al., 2012a). These trends for slight to more marked decreases in avalanche occurrences, now documented in several mountain environments, are consistent with accelerating climate warming and scarcer snow conditions (Hock et al., 2019). However, in several studies, no clear trend could be evidenced, presumably because of the strong interannual and/or inter-path variability, and various artifacts due to inhomogeneity of data sources (Schneebeli et al., 1997; Laternser and Schneebeli, 2002; Baggi and Schweizer, 2009; Eckert et al., 2010c; Valt and Cianfarra, 2013; Favillier et al., 2023).

Opposing trends were evidenced in different areas of the French Alps for the 1980-2010 period: a threefold reduction in avalanche occurrence frequency in paths with release areas located mostly below 2000 m asl versus an increase in paths with release areas located above 2000 m asl (Lavigne et al., 2015; Zgheib et al., 2022). This elevation-dependent trend can be attributed to the simultaneous increase in temperature and extreme precipitation (Le Roux et al., 2021).

In contrast to the number of avalanches, data on changes in their extent, runout, and/or size are less numerous. However, if they exist, they are more conclusive, as climatic conditions control snow stratigraphy, avalanche release, and flow conditions all at once (Eckert et al., 2010a). Regarding avalanche magnitude, for example, the mean elevation of runouts reached by avalanches increased by around 55 m in the French Alps between 1980 and 2005 (Eckert et al., 2013), indicating that avalanche runouts are, on average, decreasing. The runout elevation reached every ten years in mean even rose by ~ 80 m over the same period (Eckert et al., 2013),

indicating that runout reduction is especially pronounced for large avalanches, which has been confirmed by proxy records (Jomelli et al., 2004).

Regarding avalanche typology, a decrease in the proportion of powder-snow avalanches has been reported in the French Alps, from 25 % in 1973 to approx. 13 % in 2009 (Eckert et al., 2013) while at the same time, the proportion of wet snow avalanches increased substantially (Naaïm et al., 2016). Similar trends have been reported in the Swiss Alps (Pielmeier et al., 2013). These trends are consistent, as colder snow conditions tend to favor the formation of powder-snow avalanches, while warmer winter conditions result in more rain-on-snow events and snow surface melt, thus a higher proportion of wet snow avalanches. To our knowledge, no quantitative study of the evolution of glide snow avalanches in the European Alps exists.

In terms of hazards, although a clear statistical argument is still lacking, i) an increasing number of slow, yet high impact, wet avalanches have been reported in the Alps over the recent period (Ancey and Bain, 2015); and ii) the relative increase of rain-on-snow events at high elevations (Beniston and Stoffel, 2016; Morán-Tejeda et al., 2016) makes the occurrence of wet-snow avalanches more likely, even in areas or at times during the avalanche season that have not hitherto been exposed.

Finally, different types of change may combine to exacerbate the response of avalanche activity to climate change. For example, land use and land cover changes have been repeatedly shown to be strong drivers of avalanche activity on decadal to centennial time scales (Giacona et al., 2018; Mainieri et al., 2020). These drivers include the set-up of defense structures and the natural and/or anthropogenically driven evolution of forests, including devoted protection forests. Such effects may combine with the impact of climate change as evidenced by the increase by 45 m of runout elevation in Haute Savoie over the 1955-1975 time period (Lavigne et al., 2017). For

instance, with climate change, the elevation of the treeline is rising, implying a reduction of avalanche activity, but, on the other hand, the increase of droughts causing direct forest dieback and increase in fire propensity might have locally an opposite effect (Bebi et al., 2009).

Figure 13: Studies on observed climate changes impacts on snow avalanches considered in this review (a) Publications considered in this review with corresponding study period. (b) Bar plot showing the main data source for the considered studies.

5. Synthesis and future perspectives

Predictions that human-caused climate change will alter the frequency, magnitude, dynamic behavior, and locations of alpine mass movements have existed for almost three decades. The IPCC's First Assessment Report (IPCC, 1990) stated that permafrost degradation "*could lead to increases in terrain instability, erosion and landslides*", that "*areas from which glaciers retreat would be converted into morphologically highly unstable moraine slopes and forefields which could contribute to landslides, mudflows and increased sediment loads in rivers*", or that avalanches were a "*type of catastrophic event that may be affected as a result of climatic changes and potential changes in snowpack quantity and quality*". While the years and decades following the First Assessment Report, up until the most recent Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC Hock et al., 2019), have led to increased confidence in the direction the changes are taking, better quantification of the trends and more clarity on whether they relate to climate change are needed to advance natural hazard management. In this review, we therefore investigated the current understanding of the impact of climate change on most alpine mass movements in the European Alps. Specifically, we asked to what extent clear(er) trends are

emerging from the ever-expanding observational records and to which extent a linkage to climate change could be demonstrated or not. The problem remains complex and not without challenges (see Sect. 5.2), but the observational records currently reveal these primary findings (see Fig. 14):

Rockfall and rock avalanche: There is clear evidence for increasing rockfall activity in alpine areas affected by permafrost thaw and glacier retreat, primarily driven by rising summer temperatures. In subalpine regions, despite clear meteorologic controls on rockfall frequency, climate-change-driven trends are not evident. One challenge in extrapolating these results to larger regions is that many observations come from a few hotspots (Fig. 9), the temporal coverage in most cases is still short, and the increasingly dense and complete records introduce an observation bias. This issue is exacerbated in the case of rock avalanches, where the limited number of observations currently prevents a clear climate change attribution.

Debris flow: Debris-flow triggering factors show clear trends, but the response of debris-flow activity to these changes remains less clear. Half of the studies did not find significant changes or found decreases, while the other half found increases albeit often only marginal. There is evidence of increasing activity in the highest alpine regions (above treeline), which is in line with the expectations of permafrost thaw increasing sediment availability. However, as shown by the three longest data catalogs from the same region (e.g. Stoffel and Beniston, 2006), this increase may not exceed the activity of the late 19th century after the LIA. In the alpine-subalpine transition (treeline), all studies find a correlation to climatic triggers but an increase is only evident in half of the studies, while in the subalpine regions the trend may go in both directions. The fact that changes in triggering factors are evident but often not reflected in debris-flow observations is likely because of the missing

information or understanding of the sediment supply processes and their climatic controls (e.g. Rom et al., 2023).

Ice avalanche: Analysis of the only regional dataset of ice avalanche activity reveals that ice avalanche frequency in Italy has increased since the turn of the century. Statistically significant trends are lacking, but it appears that the starting elevation may be increasing while ice break-offs are happening earlier in the year (Chiarle et al., 2022). At individual locations, trends in ice avalanche activity are divergent, with some locations showing increasing activity, while others point to a decrease, changes that are largely controlled by the varying geometric configurations that glaciers encounter as they retreat. Englacial temperatures are measurably rising (Vincent et al., 2020; Perret et al., 2021; Troilo et al., 2021), but no effect of this on ice avalanches has been observed so far. Similarly, the effect of ice cooling through decreasing firn cover and latent heat release (Huss and Fischer, 2016) remains largely hypothetical.

Snow avalanche: There is now clear evidence for a gradual reduction of overall avalanche numbers and their sizes, and for a shift towards i) a higher proportion of avalanches involving wet snow than dry snow, and ii) a lower proportion of avalanches with a powder part (Eckert et al., 2013; Pielmeier et al., 2013; Naaïm et al., 2016). The observed changes depend on elevation and are controlled by the influence that the freezing level has on the rain-snow partitioning. At low elevations the decrease in avalanche activity is exacerbated, whereas increased extreme snowfall drive increased activity at high elevations (Le Roux et al., 2021).

By and large – with snow avalanches being the notable exception – studies investigating the impact of climate change on alpine mass movements have focused almost exclusively on

the preconditioning, triggering and resulting frequency of events. Despite their high relevance for society, studies investigating the changes of event magnitude, runout propagation and mass movement impacts are still very rare (see Sect. 5.2).

Figure 14: Observed (labeled) and expected changes of climate-change driven alpine mass movements in the European Alps between colder (above) and warmer conditions (below). Rising temperatures (I) primary cause for the observed increase of rockfall (a) in alpine regions. Above treeline, increased sediment availability and increased intense precipitation (II) lead to increased debris-flow activity, potentially in locations without historical precedence (b). Warmer winters are leading scarcer snow conditions (III) at low elevations and a transient state of increased snowfall at high elevations. This shift is leading to more wet snow avalanches (c), fewer and smaller avalanches (d) at low and mid elevations, and increased avalanche activity at high elevations (e). No trends have been detected for rockfall below treeline, and findings for debris flows are highly variable. Expected, but not yet visible in observations, are more rock avalanches (despite a measurable increase of rock temperatures), changing ice avalanche activity (despite higher ice temperatures), deteriorating protection forests. We note that elements not related to mass movements (e.g., human infrastructure, ecosystems) are shown to remain constant, though in reality they may evolve faster than the discussed mass movements.

5.1. What lies ahead? Lessons for hazard assessment and management

The trajectory of future climate change depends strongly on global socioeconomic decisions and their related emissions. Ranging from a highly sustainable future with minimal additional warming to entirely fossil-fuel driven development, the Shared Socioeconomic

Pathways (SSPs; Masson-Delmotte et al., 2021b) describe the different climate change scenarios. Irrespective of the exact trajectory, the 1.5 °C and 2 °C thresholds defined at the 2015 Conference of Parties (COP) are likely to be crossed (with probabilities of 83 % and 55 %; Frei et al., 2018). For the Alps, this means warming between 2 °C to 4 °C by 2100, depending on the chosen SSP, with summer warming reaching up to 5 °C and more in the Southern Alps (Kotlarski et al., 2023). Yearly rainfall totals are not projected to change much, but summer rainfall is expected to decrease by 9 % to 21 %, depending on the region (northwestern, southwestern, or southern Alps), while winter precipitation will increase 14 % to 17 % (Kotlarski et al., 2023). These changes are accompanied by marked reductions in the return periods of intense precipitation events (Rajczak and Schär, 2017) and a strong reduction of winter snowfall (24 % to 45 % by 2100 depending on the SSP; Frei et al., 2018). The ice volume of European glaciers is estimated to drop by about half, relative to 2017, by 2050. Depending on the chosen SSP, between 5.6 % to 36.8 % of glacier ice can be preserved by the end of the century (Zekollari et al., 2019). Alpine permafrost will continue to warm. Under the most pessimistic SSPs, it may disappear completely from south-facing rock walls even at the highest elevations by the end of the century (Magnin et al., 2017).

Our understanding of the changes expected is most mature for snow avalanches and debris flows. This is primarily because their triggering factors are most closely connected with meteorological events, which can be relatively well explored in climate models. In agreement with findings from the European Alps, observations from around the world show that the increasingly scarce snow conditions lead to a continued reduction of avalanche numbers and size, particularly at low elevations (e.g., Rocky Mountains (US), Vosges- (FR) and Tatra Mountains (PL); Peitzsch et al., 2021; Giacona et al., 2021; Gądek et al., 2017). By contrast, a transient state of increased avalanche activity is likely for (very) high elevations (Castebrunet et al., 2014), where

winter conditions, for some time, will still be cold enough for the anticipated, increased precipitation to fall as snow (Katsuyama et al., 2022; Le Roux et al., 2023). However, the elevation at which this trend reverses will continue to rise with warming (Le Roux et al., 2023). At smaller scales, glacier retreat can affect avalanche release areas, making them larger and steeper, thereby increasing the hazard. At the same time, this may increase the distance between a release area and relevant infrastructure, leading to a reduction in risk (Margreth and Schaer, 2023). A source of concern, especially for at-risk infrastructure, is the likely increase in the occurrence of wet snow avalanches, notably during peak winter conditions. This phenomena is currently underexplored, though tree-ring analyses from a single study site in the Western Himalayas (Ballesteros-Cánovas et al., 2018) and projections for several sites in the Swiss Alps (Mayer et al., 2024) do suggest increasing wet-snow avalanche activity. Overall, even though many uncertainties still hamper predictions of future avalanche hazard, the aforementioned examples show the importance of including this knowledge in hazard assessments and mitigation practices (Eckert et al., 2024).

Future triggering conditions of debris flows have also been investigated in-depth with climate models. These studies make use of (hydro-) meteorological criteria associated with debris-flow triggering in the past and test how these criteria change in a future climate (Jomelli et al., 2009; Stoffel et al., 2014; Turkington et al., 2016; van den Heuvel et al., 2016; Kaitna et al., 2023). In line with current observations, most of these studies find limited changes of debris-flow frequency on an annual time scale, but distinct seasonal changes. In increasingly dry summers, short but intense rainfall events are expected to decrease by the end of the century in most regions of the Alps (Jomelli et al., 2009; Stoffel et al., 2014; Kaitna et al., 2023). By contrast, debris flows are expected to occur more frequently in both the spring and the fall, as those same intense rainfall events become more frequent (Berg et al., 2013; Hirschberg et al., 2021). Importantly,

snowmelt-related triggering conditions, as a consequence of wetter and warmer winters, will shift to earlier in the year, a phenomenon that can be observed already now (Stoffel and Corona, 2018). Debris flow regimes will also be impacted by changes to the sediment supply. At mid-elevations, the increasing temperatures will likely lead to fewer freeze-thaw cycles, limiting sediment production (Jomelli et al., 2009; Hirschberg et al., 2021). At higher elevations, the opposite may happen, as temperature fluctuations intensify and accelerate weathering, concurrently driving debris flow initiation areas to higher elevations. These contrasting trends highlight that preconditioning cannot be viewed independently, but that assessments of future hazards need to take into account sediment production, sediment connectivity, and debris-flow initiation together. Currently, there are no regional studies combining changes of geomorphological boundary conditions and rainfall triggers. At the local scale, a study in Illgraben, Switzerland, for example, revealed that debris-flow occurrence is expected to decrease by 20 % (Hirschberg et al., 2021). In regions with more arid climates than the Alps, wildfires have been identified as major drivers of debris-flow activity, heavily altering the runoff conditions and sediment mobility in burned catchments (Kean et al., 2011; Nyman et al., 2015; Langhans et al., 2017; Kean and Staley, 2021; Graber et al., 2023). To date, post-wildfire debris flows are rare in the European Alps (Tiranti et al., 2021), but fire danger is expected to increase in all regions and will require proactive fire management (Miller et al., 2024).

For rockfall, rock- and ice avalanches, the assessments of future conditions rely more strongly on theoretical considerations rather than quantitative statistical models. For rockfall and rock avalanches, these theoretical considerations focus predominantly on preconditioning factors, rather than triggering, and predict – supported by the current observation – a complex picture. For example, an upward shift of the ice segregation process – the growth of larger ice lenses that can

exert pressure on surrounding rock – is expected with warming (Weber, 2018). On its own, this process would lead to a decrease of rockfall activity, because the amount of exposed terrain decreases with elevation. However, this trend may be masked by freeze-thaw cycles that reach higher and higher elevations and lead to increasingly weakened rock (Draebing et al., 2017). Simultaneously, changes in rock weakening can be transient, as erosion rates peak immediately after deglaciation in response to unloading, increased thermal stresses, or (increasing) water infiltration (Draebing et al., 2022). With the upward progression of glacier retreat, these processes lead to highly variable controls on rock stability in both space and time that are additionally superimposed on local lithologic and structural characteristics. This combination makes it clear that creating spatially or temporally explicit predictions of future trends is incredibly challenging, but that the currently observed trends of increasing rockfall will continue to be driven by warming temperatures and the related warming/loss of ice in fractures.

At the level of large rock-(ice) avalanches, studies from other places in the world appear to paint a clearer picture of the climate change influence. In particular, Alaska has emerged as a region in which large-scale analyses show a quantifiable increase in rock avalanche activity concentrated at high elevations and at the permafrost boundary, often during unusually warm years (Huggel, 2009; Coe et al., 2018; Hibert et al., 2019; Bessette-Kirton and Coe, 2020; Smith et al., 2023). In northern British Columbia, the frequency of large landslides was suspected to have increased as a consequence of climate change early on (Geertsema et al., 2006). Permafrost degradation has also been highlighted as the main factor responsible for rock avalanche failure in Norway, Greenland, Iceland, or the Himalayas (e.g., Frauenfelder et al., 2018; Svennevig et al., 2020; Morino et al., 2021; Svennevig et al., 2022; Zhong et al., 2024). Despite these evidences, however, uncertainties about the certain trigger or causal relationship between climate (change)

and rock avalanches almost always remain (e.g., Shugar et al., 2020). However, the large rock avalanches at Piz Cengalo in 2012 and 2017 (Switzerland; Walter et al., 2020; Mergili et al., 2020), Fluchthorn (June 2023, Austria Krautblatter et al., 2024), and, most recently, the rock-ice avalanche at Piz Scerscen, Switzerland, in April 2024 serve as stark reminders that the Alps are no less susceptible to such events than other regions.

Finally, the future perspectives for ice avalanche hazards are almost completely unexplored. In places where glaciers disappear completely, the hazard will also disappear. Before that, locations of activity will shift as glaciers retreat, cold ice will continue to warm, and temperate ice may in some places get colder. The changing locations of ice avalanches could be relatively easily explored by intersecting terrain models with glacier retreat models (e.g. like the one used by Zekollari et al., 2019), which would paint both a spatial and temporal picture of how this hazard may evolve in the future. While we know that high-elevation ice is warming, how and where this is most likely to impact ice avalanche activity remains unclear. Research from outside the Alps is limited to a very recent body of work that investigated large-volume detachments of low-angle mountain glaciers (Kääb et al., 2021). These catastrophic glacier detachments differ from ice avalanches in the way that they have been described in Europe in several ways: They generally involve larger volumes of ice ($4.2 \times 10^6 \text{ m}^3$ to $130 \times 10^6 \text{ m}^3$ compared to the largest event in the Alps with $4 \times 10^6 \text{ m}^3$), they originate from low-angle glaciers with surface slopes around 10° to 20° , and they are highly mobile, with apparent friction coefficients (the ratio of fall height to runout distance) as low as 0.1 (compared to the values of 0.3 to 0.8 typically observed in the Alps; Alean, 1985; Kääb et al., 2021; Chiarle et al., 2022). Though the processes governing these events are far from understood, glacier detachments appear to originate predominantly from glaciers sitting on thick sediment beds and possibly with a polythermal temperature regime.

Because the conditions favoring glacier detachments do not seem to occur in the European Alps, the transferability of the gained understanding from these places is limited and a connection with climate change, while plausible, remains largely hypothetical.

5.2. *Linking alpine mass movements and climate change: Challenges and needs*

Even though the impact of climate change on alpine mass movements is becoming increasingly relevant, quantifying this impact and linking the observed changes to climate change remains a challenging task. The reasons for this are manifold and relate to (i) the quality, reliability, and limitations of the data catalogs as well as observation biases, (ii) the challenges of statistical analyses, (iii) the non-linear and locally variable responses of the natural systems to changes, (iv) the impact of human and climate-change driven alterations of terrain and ecosystems, or (v) unforeseen, occasionally catastrophic process cascades.

- (i) Creating and maintaining standardized and complete data catalogs is challenging, and systematic documentation of alpine mass movements, especially over larger regions, remains largely unachieved (Wood et al., 2020). Even where (large) catalogs exist (e.g. Raymond et al., 2003; Pavlova et al., 2014; Luethi et al., 2015; Ravanel and Deline, 2015; Bajni et al., 2021; Chiarle et al., 2023,), events that directly impact human infrastructure or livelihoods are typically better and more consistently documented, an effect that becomes more pronounced the further in the past. At the level of individual events, relevant information such as the exact timing, the precise location of the starting zone, the full runout path and distance, or volume estimates are often missing. On a more technical level, the lack of metadata describing existing data catalogs, the loss of access to the products of past efforts, or missing (financial) support to maintain existing data collections have also

impeded the creation and analysis of better datasets.

- (ii) Partly due to the drawbacks described in (i), statistically robust time series analyses face numerous difficulties. Though improved statistical tools are better at accounting for various sources of noise and biases (e.g., Giacona et al., 2021; Favillier et al., 2023), existing approaches still encounter challenges distinguishing climate-related trends from confounding effects. These effects may include real changes in activity with other causes, such as land-cover and land-use changes (e.g., the installation of mitigation structures) or interannual and decadal variability (e.g., ocean-atmosphere oscillations leading to oscillating signatures in snow avalanche records; Birkeland et al., 2001; Keylock, 2003). As interannual variability at short time scales may be misinterpreted as a climate change signal, using long observation periods and complete datasets is crucial. At longer time scales, however, both the quality of the records and confounding effects become harder to track and disentangle. A lack of change may also arise because opposing signals cancel each other out over large spatial or temporal scales (e.g., precipitation trends on either sides of a mountain range, transient effects of rising snow lines on avalanche activity). Finally, how to extrapolate trends inferred from records of limited spatial extent to an entire mountain range and beyond remains an open question.
- (iii) While synoptic views on large datasets can be helpful and revealing, the various confounding effects point to the larger problem of non-linear responses of natural systems and to the importance of threshold- and local effects. For example, it has been shown that an increasing frequency of debris flows in a particular catchment can lead to smaller debris-flow magnitudes and shorter runout distances if the catchment suddenly becomes supply-limited (Jakob, 2022). Temperature threshold effects are important when

considering the effect of rising temperatures on rock avalanches and rockfall from permafrost. While a rock mass may show little or no response to warming as long as rock temperatures remain well below freezing, it may experience a sudden shift towards instability when temperatures approach the melting point (Krautblatter et al., 2013). These effects are hard to forecast, especially at larger scales (both regional and temporal).

- (iv) Mass movements cannot be considered independently of the environments through which they travel. The increasing use of mitigation efforts such as tunnels, snow fences, rockfall, or debris-flow protection barriers impact both the release and runout of mass movements. For one, this renders comparisons of regional or country-wide event catalogs based on reported damage extremely challenging. At the same time, runout (and release) zones are themselves affected by climate change (e.g., glacier retreat (Zekollari et al., 2019) or changes to treeline elevation and protection forest cover, composition, and health (Moos et al., 2021; Hillebrand et al., 2023)). These complex interactions directly affect how and where mass movements are most likely to impact infrastructure and livelihoods, and are, unfortunately still among the least investigated and understood.
- (v) Finally, all of the discussed processes can occur as parts of complex process chains. Hazard cascades such as the 2017 rock-avalanche triggered debris flows which occurred in the Bondasca valley (Switzerland) (Walter et al., 2020) or the 2021 Chamoli rock-ice avalanche in Uttarakhand (India), which rapidly transitioned into a large and highly mobile debris flood (Shugar et al., 2021), exemplify the complexity of events where one process triggers or predisposes another. Creating standardized datasets that allow systematic statistical analyses of such complex events is even more challenging than for the individual processes. In an attempt to alleviate this issue, Mani et al. (2023) suggest a classification

scheme that allows for a simpler categorization and intercomparison. While they found only weak trends relating the occurrence of such hazard cascades to climate change, they postulate that the accelerating climate warming will likely increase the mobility and runout distances of process chains in the future.

The aforementioned challenges impede a better climate attribution for most alpine mass movements, especially rock- and ice avalanches. Several of these challenges are linked to the available datasets that currently do not provide an adequate foundation to analyze the ongoing changes in a sufficiently robust way. Creating these datasets is challenging, but we believe that expanding our observational data basis would help pave the way for more quantitative predictions that can be integrated into decision making and planning. Importantly, the high-quality catalogs need to be created and maintained while simultaneously advancing the theoretical understanding of the underlying physical processes. Additionally, improving statistical models that can adequately disentangle the different signals in such records is crucial.

There are several ways in which an expansion of these datasets could be achieved, but one of the key issues is that the creation and maintenance of databases should be valued by universities, scientific funding agencies, and the scientific community as a whole. Currently, many dispersed datasets exist, either collected by municipal or state agencies (such as www.storme.ch or <https://infoterre.brgm.fr/page/mouvements-terrain>) or as part of independent research projects. Where measurements have been conducted in the past, the extension of such measurements can provide longer time series without needing to wait multiple decades (as done for example by Kiefer et al., 2021). Mourey et al. (2021) have demonstrated that bridging social and natural sciences can yield intriguing insights. If executed well, citizen science efforts can also contribute additional observations. We believe that the

existence of well-curated, open-access data repositories that adhere to FAIR data standards (as suggested, for example by Wood et al., 2020) could bring together a wealth of data to advance this research field. In this regard, it would be extremely useful to define standardized procedures for collecting and compiling data, which would greatly facilitate data aggregation and comparison.

In addition to bringing together various dispersed datasets, we should consider creating (and funding) well-instrumented long-term natural laboratories, similar to the way this is done in the LTER (Long Term Ecological Research) Network since the 1980s (!) (<https://lternet.edu/>). Such sites would help collect detailed long-term observations of mass movements and their interactions within larger environmental changes. An example is the experimental site in the Bessanese glacial basin (Italy, Viani et al., 2020) active since 2016. Coe (2020) has suggested the creation of such benchmark sites (termed *bellwether sites* by Coe (2020)), identifying the Northern Patagonia Ice Field, the western European Alps, the eastern Karakoram Range, the southern Alps of New Zealand, and Alaska's Fairweather Range as suitable locations for collecting detailed observations about rock avalanches at regional ($> 5000 \text{ km}^2$) scales. At the torrent-scale, the long-term research sites at Illgraben (Switzerland) and Chalk Cliffs (Colorado, US) are examples of intensely studied debris flow sites, as is the Vallée de la Sionne (Switzerland) for snow avalanches. The creation of a long-term research network for alpine mass movements would need to take into account the different spatial scales at which the processes can be observed and cover a sufficiently wide range of geologic and climatic conditions to ensure the transferability of research findings. Data emerging from such a network could provide a deeper understanding of the factors influencing all three phases of the failure continuum as well as their complex interactions and time lags (Fig. 3b), and help establish the link between the mass movements and ongoing climate change.

The apparent the lack of studies evaluating changes in runout distances and impacts provides clear opportunity for future research. Here, insights from observations would provide highly valuable data to support studies have approached this experimentally (e.g., Ringenbach et al., 2022) or through modeling (e.g., Cathala et al., 2024), and to improve numerical models, which are only as reliable as the data used for their development and validation. In order to provide holistic assessments of mass movement changes (e.g., Zgheib et al., 2023), it is vital that attention is directed at the full process chain.

5.3. *Concluding remarks*

Anthropogenic climate change is rapidly changing landscapes and processes, and we are already seeing altered regimes of alpine mass movements. After more than three decades of intense research and data collection, incomplete observational records of rockfall and rock avalanches, debris flows, and snow and ice avalanches still make it hard to quantify the impact of climate change at all spatial scales. The inability to detect clear trends in some cases does not mean they are absent but rather underscores the complexity and variability of natural systems, as well as the challenges involved in data collection and statistical analysis. Many of our current observations are in agreement with our theoretical understanding, and they clearly underline the impact of climate change on mass movements. If warming continues unabated, snow and ice related hazards will strongly diminish by the end of the century. In the interim, however, the changing and frequently rising intensity of alpine mass movements will increasingly challenge natural hazard management and adaptation. Importantly, the risk posed by these processes is characterized not only by their changing nature, but also by the simultaneous change in exposure and vulnerability, and the fact that they are deeply embedded within the larger challenges, such as

decreasing touristic attractiveness or increasing demands on renewable energy development, faced by mountain regions.

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Author contributions

MJ and SW co-led the development of the manuscript and wrote and edited the whole text, initially supported by AC. MS organized the workshop from which the idea for this review was born. Groups of co-authors contributed input and drafted sections for the different processes, with one person per group taking the lead (L). For the individual groups, these were: SW (L), MarCh, FM, CM, MS (rockfall and rock avalanches); JH (L), AC, RK, MS (debris flows); MJ (L), MarCh, MalCh (ice avalanches) and NE (L), CC, JG, FG, SM, AvH (snow avalanches).

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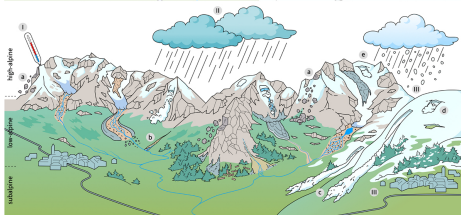
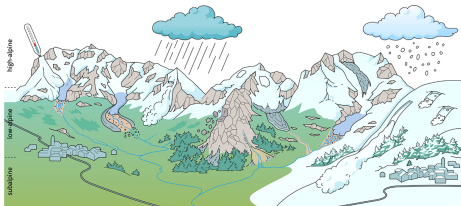
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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Journal Pre-proof



Graphics Abstract

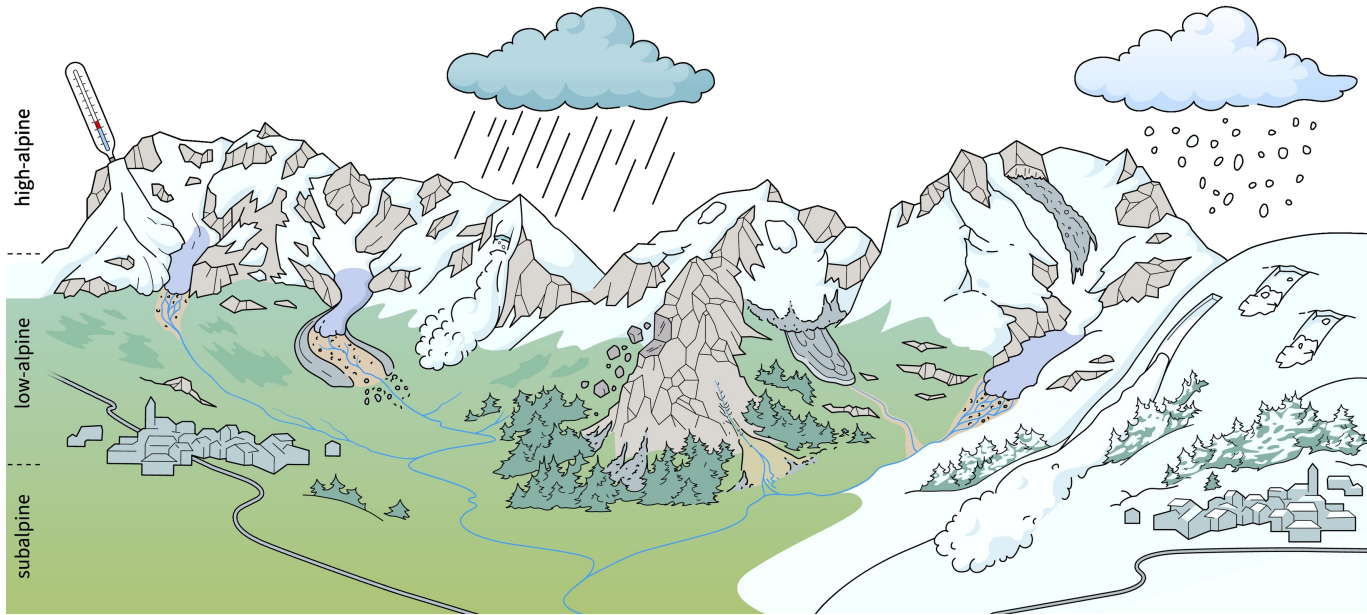


Figure 1

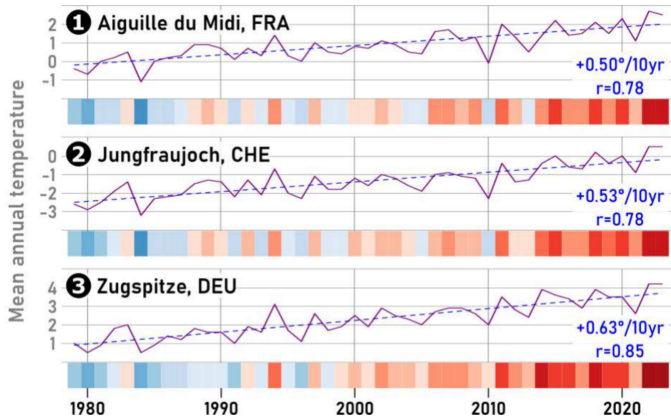
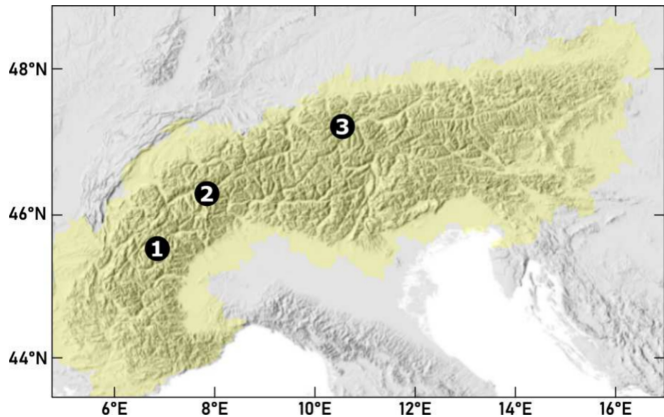
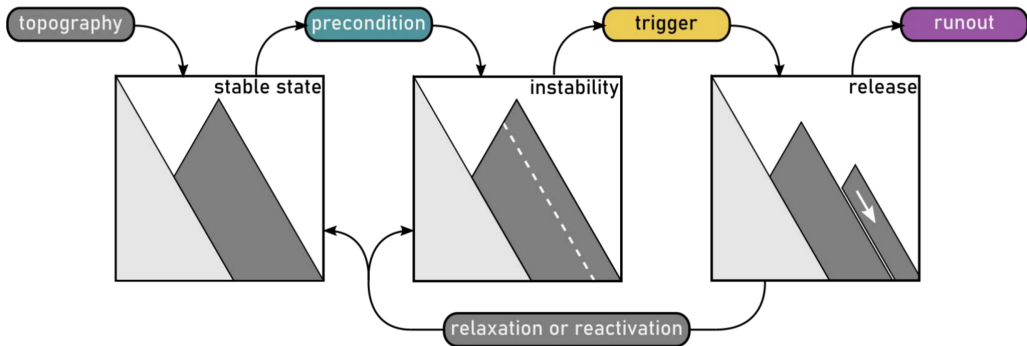


Figure 2

a Transition of a slope from stable state over instability to release



b Time span of the single transition phases

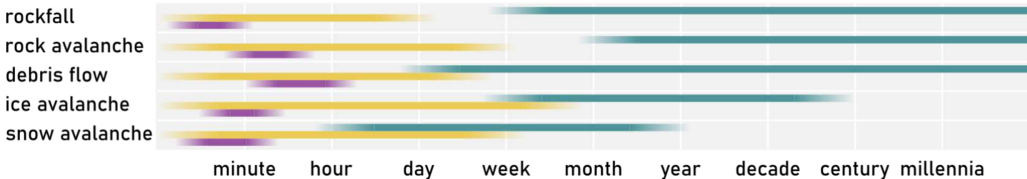


Figure 3

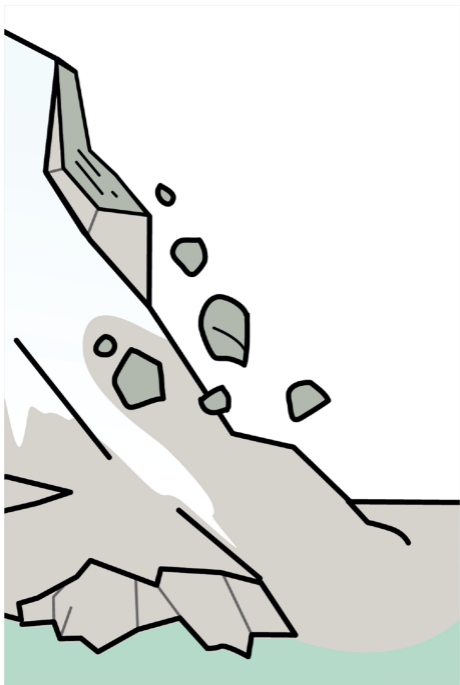


Figure 4

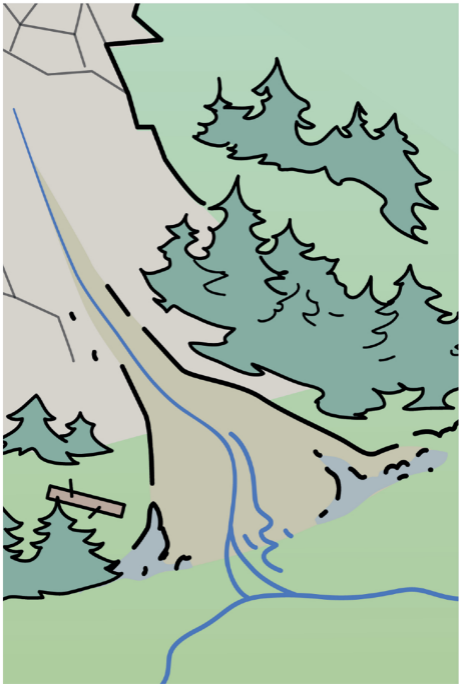


Figure 5



Figure 6

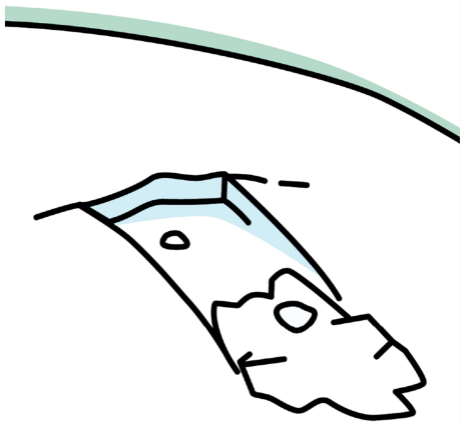


Figure 7

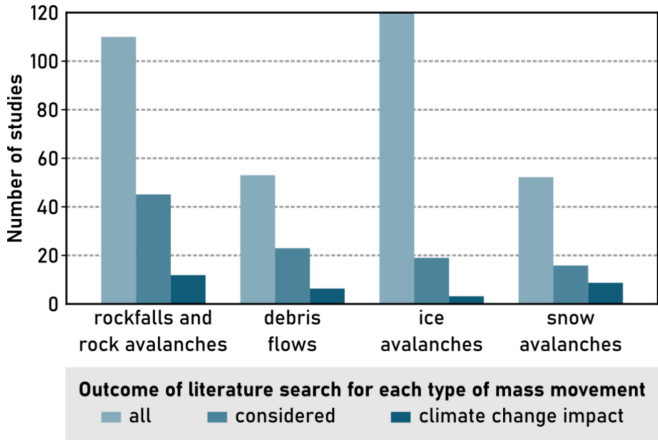


Figure 8

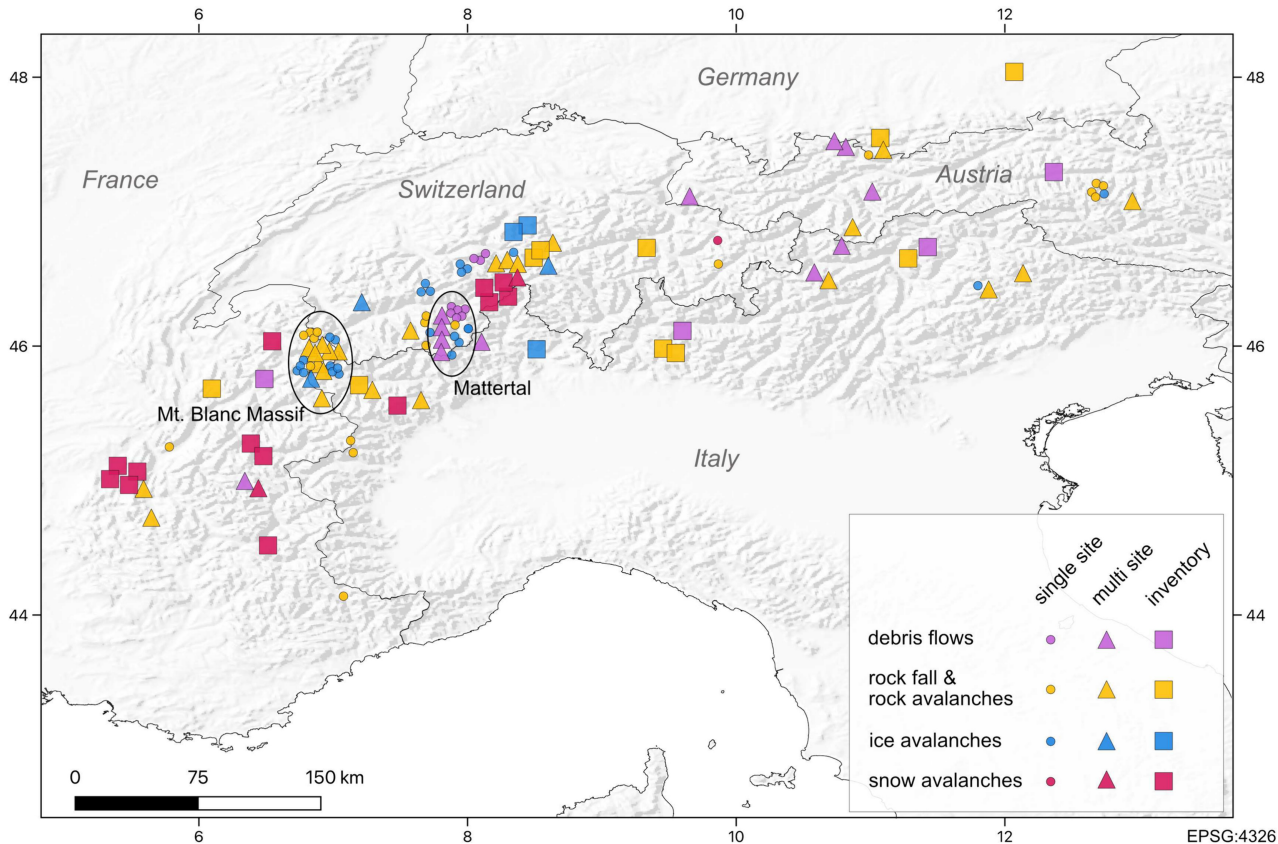


Figure 9

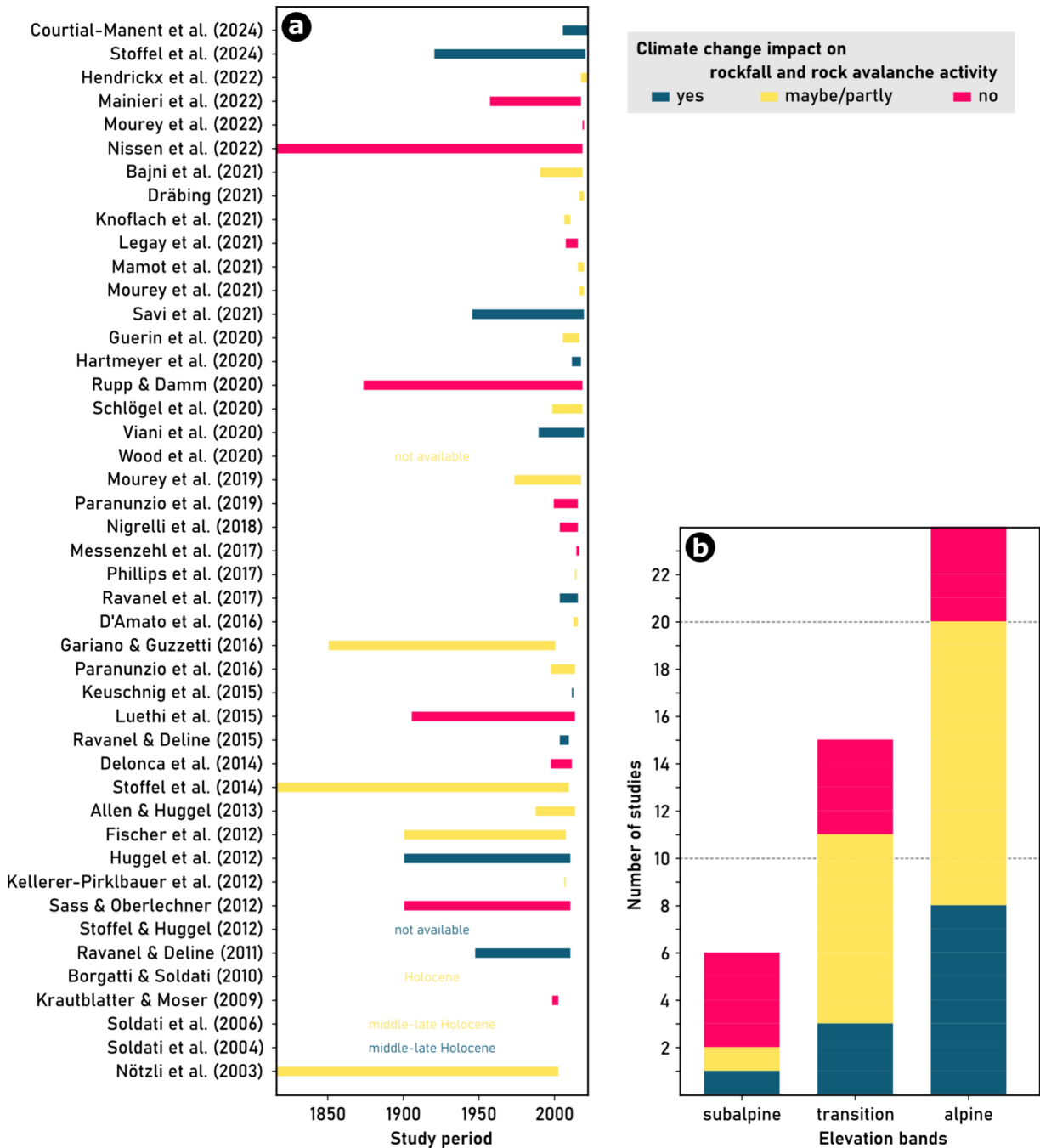


Figure 10

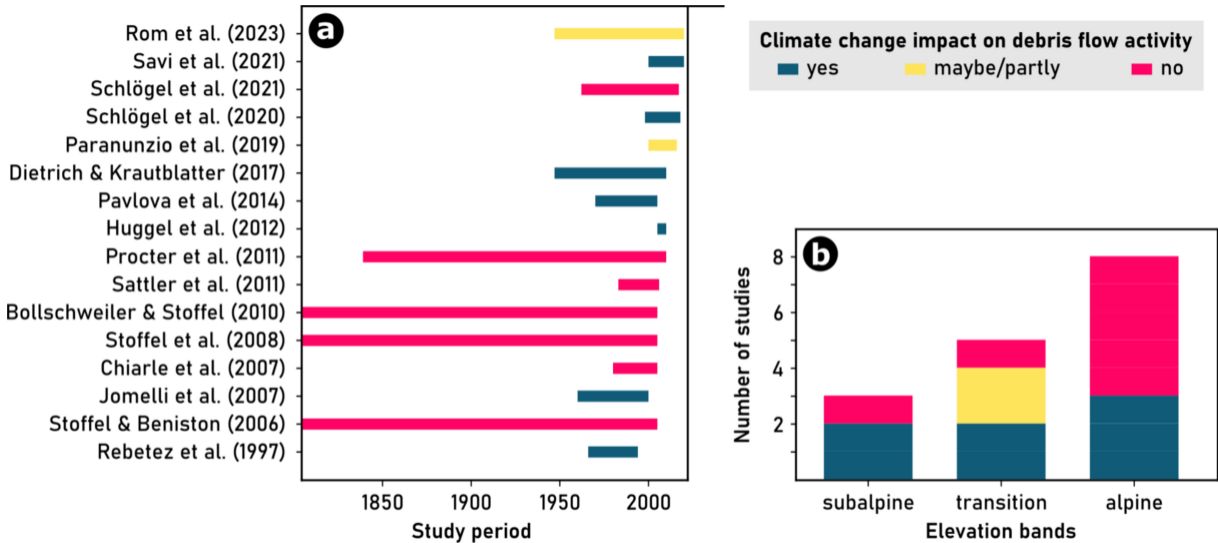


Figure 11

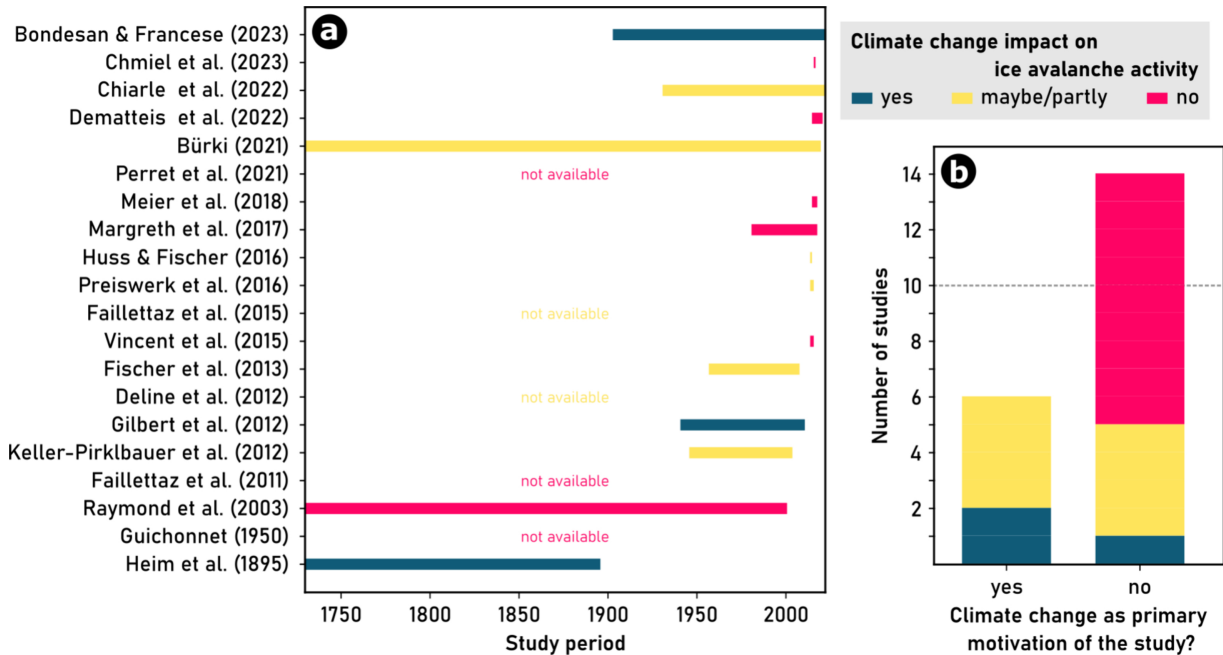


Figure 12

Climate change impact on snow avalanche activity

yes maybe/partly no

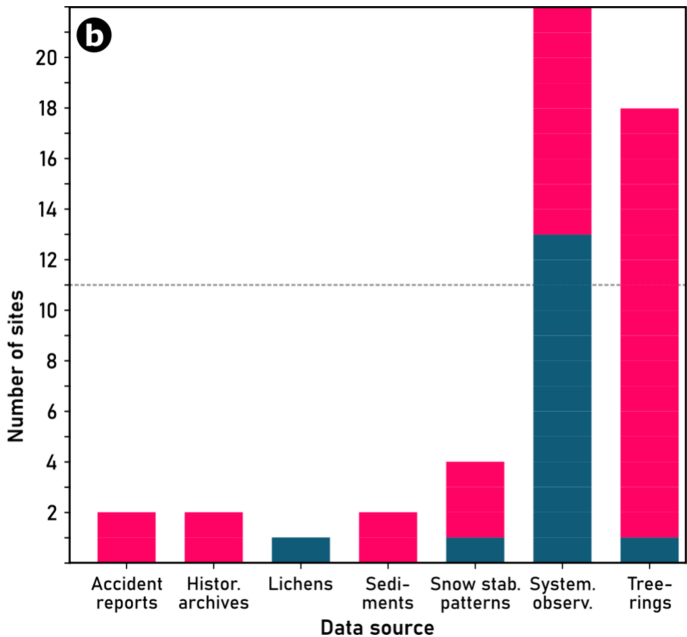
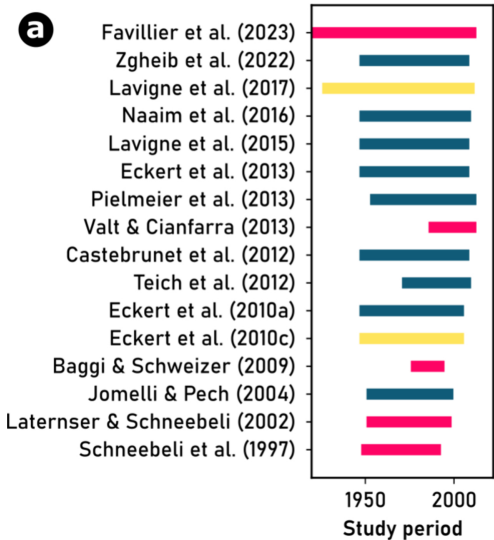


Figure 13

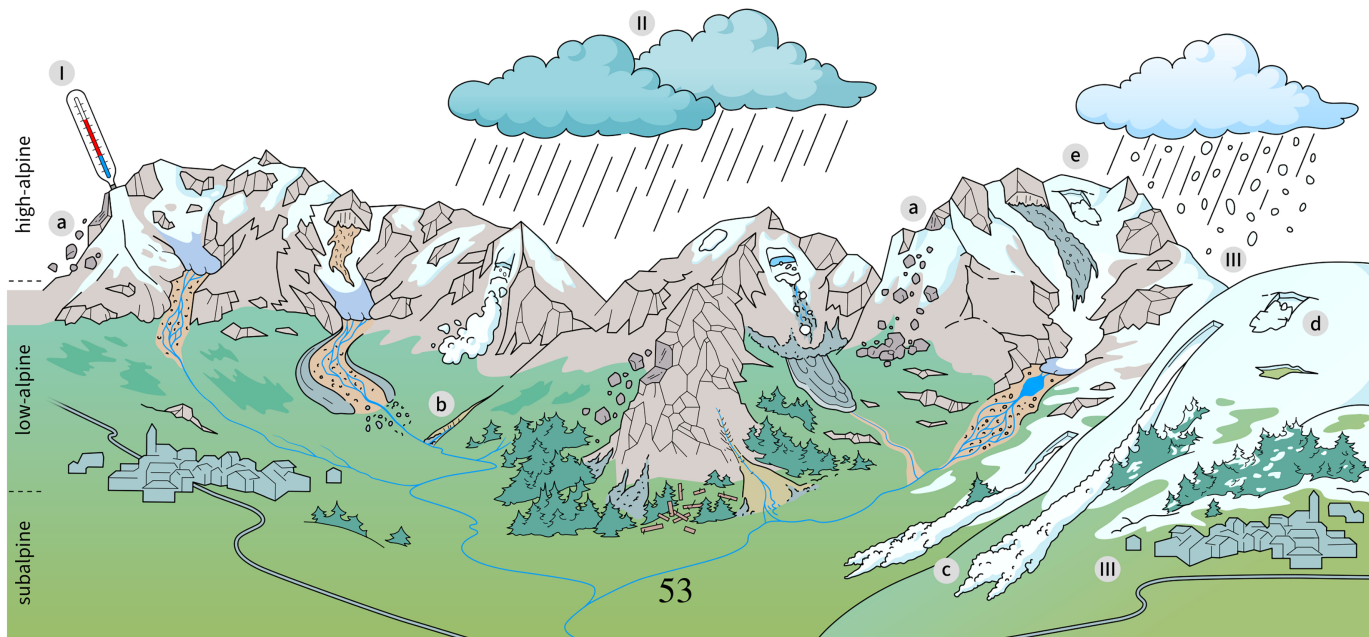
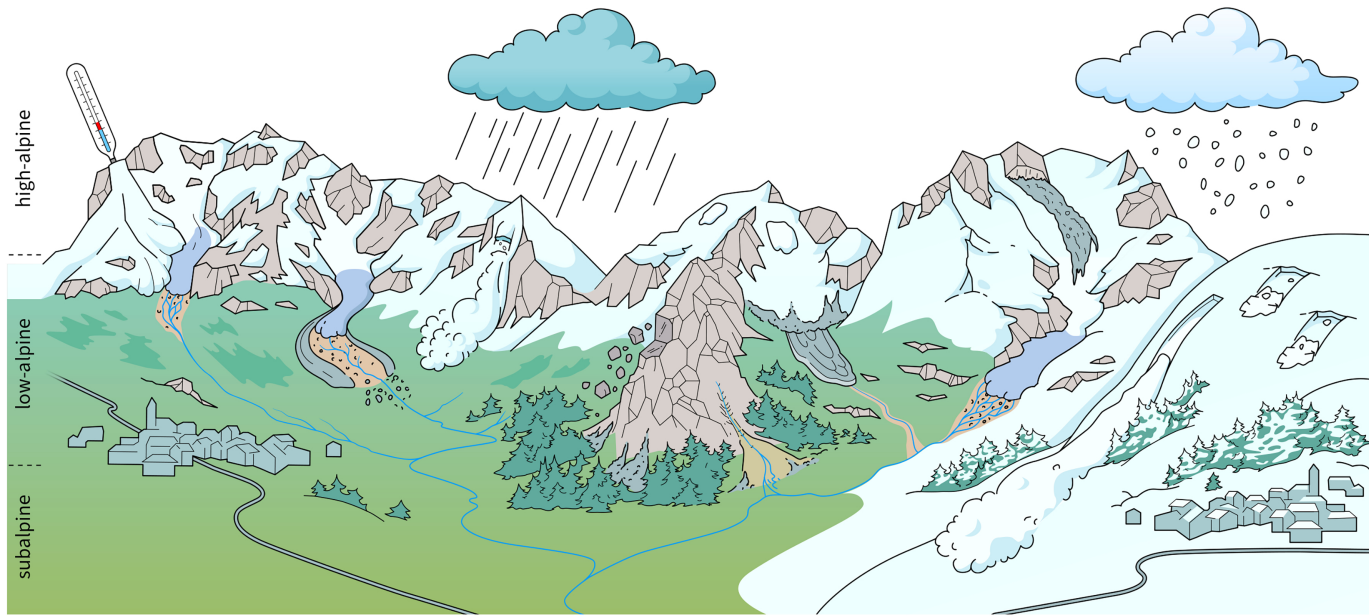


Figure 14