7.30 Hillslope Processes and Climate Change

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Glossary

Deep-seated gravitational slope deformation Gravity-induced processes which evolve over a very long time interval and generally affect entire slopes, displacing rock volumes up to hundreds of millions of cubic meters over areas of several square kilometers with thicknesses of several tens of meters.

El Niño Southern Oscillation (ENSO) climatic cycle The ENSO climatic phenomenon consists of slow manifestations of ocean and atmosphere interactions starting in the Pacific Ocean that are the source of interannual climatic variability at a global scale. The ENSO cycle is a system that comprises a warm phase called El Niño, and the opposite phase, cold episodes named La Niña, occurring every few years.

Geomorphological hot spot Goudie has identified as geomorphological hot spot areas where the effects of global warming might be especially serious in highly sensitive landform environments, including tundra terrains, alpine glaciers, desert margins, tropical coastlines, deltas, sabkhas, and sandy beaches.

Abstract

This chapter focuses on the relationships between hillslope processes and climate change. Particular attention is given to the role of climate variations on the temporal and spatial occurrence of landslides (including falls, topples, slides, flows, and spreads). An introduction on the causes and trends of climate change is provided as a basis for a better understanding of the influence of temperature and precipitation changes on gravity-induced processes on hillslopes through time. The links between global and regional climate change and landslide activity (or inactivity) at different temporal scales (from interannual to millennial) are explored, providing information on the major findings on the topic in different parts of the world as well.

Finally, hazard and risk issues related to the possible increase in frequency and magnitude of slope instability processes from global warming and more intense rainfall are discussed, with emphasis on the expected consequences for human activities and on possible mitigation measures.

The chapter makes clear that understanding the relationship between hillslope processes and climate change is of crucial importance in planning a proactive approach to hazard and risk management in a changing environment. Advances in geohazard modeling and prediction, as well as in real-time monitoring technology, enable us to be better prepared for the impacts of climate changes; however, in many countries, there is still an urgent need for effective risk management and informed planning policy to improve the safety and sustainability of communities at risk.

7.30.1 Introduction

This chapter focuses on the relationships between hillslope processes and climate change. Particular attention is given to the role of climate variations on the temporal and spatial occurrence of landslides. The causes and trends of climate change are introduced as a basis for a better understanding of the influence of temperature and precipitation changes on hillslope processes in time and space. The links between global and regional climate change and landslide activity (or inactivity) at different temporal scales (from interannual to millennial) are explored, providing information on the major findings on the topic in different parts of the world as well. Hazard and risk issues related to the possible increase in

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frequency and magnitude of slope instability processes in a changing environment are finally discussed, with emphasis on the expected consequences for human activities and on possible mitigation measures.

7.30.2 Climate Change

For climatologists, the frequently misused expression 'climate change' defines a statistically significant variation either in the mean state of the climate (which is defined by the World Meteorological Organization as the weather averaged over a long period of time, classically at least three decades) or in its variability, persisting for an extended period. The variations can be global or regional and can stretch over timescales ranging from decades to millions of years.

Climate change may be due to natural processes internal to the Earth system (i.e., circulation acting in the oceans or in the atmosphere, volcanic activity releasing aerosols, modifications in land cover, plate tectonics, mountain building, etc.) or to external forcing agents (i.e., orbital parameters, solar activity, etc.). More recently, one of the possible causes of climate change has been the anthropogenic modification of the composition of the atmosphere and/or of land cover (IPCC, 2007).

All these processes are operating at different temporal and spatial scales with interactions, teleconnections, and feedback mechanisms (**Figure 1**). A variety of feedback mechanisms for climate change are known that can either amplify or diminish the initial forcing. Moreover, some components of the climate system, such as the oceans and ice caps, respond relatively slowly to climate forcing, mainly because of their large mass. Therefore, the climate system can take centuries or longer to fully respond to new external forcings.

To understand and interpret present-day climate change, the knowledge of past climates is mandatory. For the reconstructions of paleoclimate, records from ice sheets, tree rings, sediments, corals, and many other proxies are used. These reconstructions show periods of stability as well as periods of rapid change throughout the last 1 billion years (**Figure 2**). In general, interglacial climates tend to be more stable than cooler, glacial climates. For example, the climate during the Holocene and Eemian interglacials has been more stable than the Last Glacial Maximum. This glacial period was characterized by widespread, large, and abrupt climate changes that tend to frequently accompany transitions between glacial and interglacial periods (and vice versa).

Even if the interglacials tend to be relatively stable, a number of pieces of evidence show that, although generally smaller in amplitude than the dramatic shifts of the last glacial cycle, Holocene climate variations have been larger and more frequent than previously recognized (**Figure 3**). Moreover, a series of rapid climate change events have occurred in the last 11 500 cal year BP; and not all sites have shown to respond synchronously or equally during these events, even despite their global extent (Mayewski et al., 2004; Wanner et al., 2008).

As far as recent and present climate is concerned, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) states that the warming of the global and regional climate system is unequivocal. We all have become familiar with the so-called 'hockey stick' temperature trend (**Figure 4**), representing the warming that occurred in the last 30–40 years. The issue of whether the temperature rise of the last 100 years crossed over the warm limit of the boundary defined by the Medieval Climate Anomaly has been a controversial topic in the science community, and discussing the details of the 'battle of the graphs' is not the aim of this chapter. However, at present, the level of confidence is high that the global average temperature during the last few decades was warmer than any comparable period during the last 400 years. In particular, present evidence suggests that temperatures at many, but not all, individual locations were higher during the past 25 years than any period of comparable length since AD 900. However, uncertainties associated with this statement increase substantially backward in time. At the same time, very little confidence can be assigned to the estimates of hemisphere average or global average temperature prior to AD

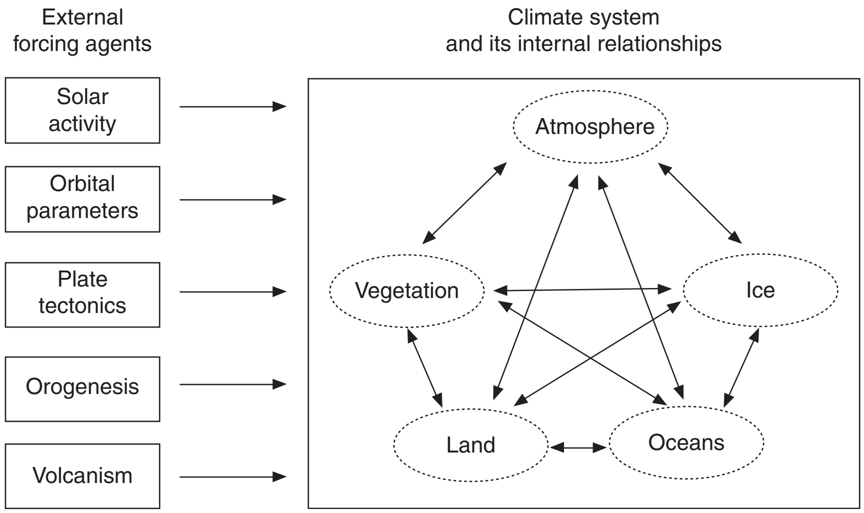

Figure 1 The climate system: relationships between internal components and external forcing agents.

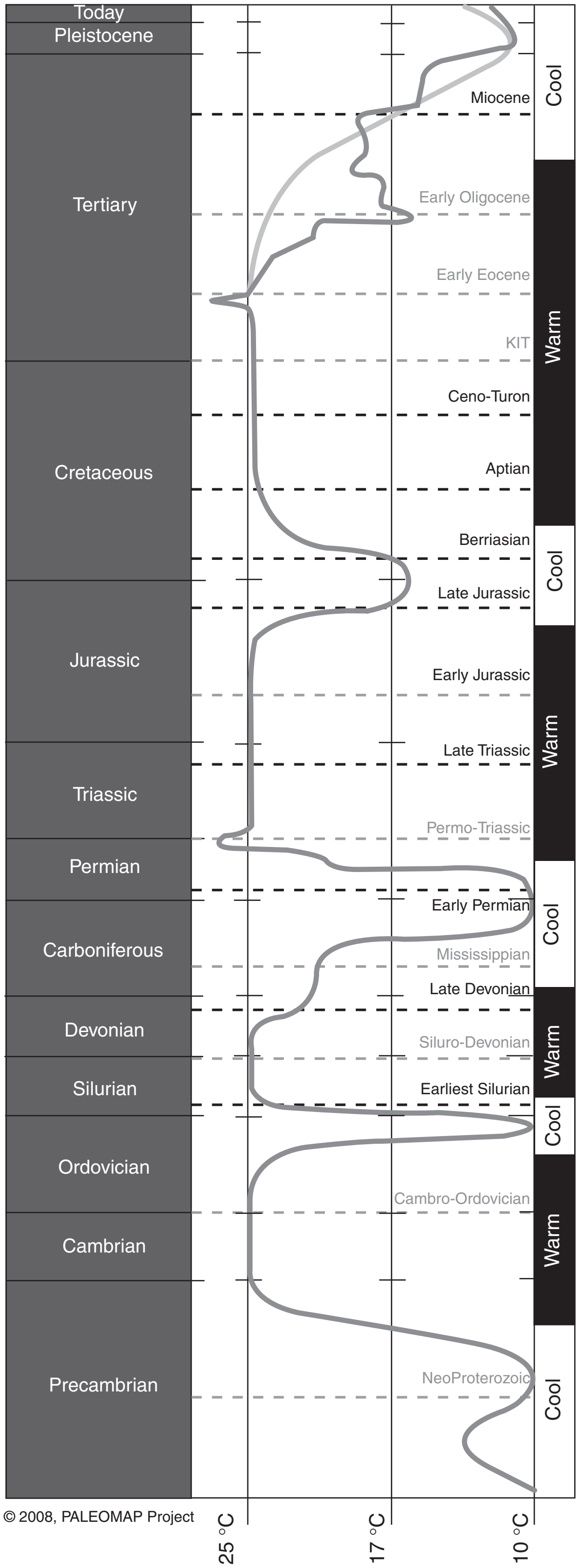

Figure 2 Past climate changes. From Scotese, C.R., 2002. Global Climate History, PALEOMAP Project. http://www.scotese.com (accessed December 2010).

900 because of limited data coverage and challenges in analyzing older data. Since the Industrial Revolution (*c.* 1750), human activities have contributed substantially to the amount of heat-trapping greenhouse gases in the atmosphere. The burning of fossil fuels and biomass has also resulted in emissions of aerosols that absorb and emit heat and that reflect light changing the albedo (together with deforestation). The addition of greenhouse gases and aerosols has changed the composition of the atmosphere (together with agricultural and breeding activities). The changes in the atmosphere have likely influenced temperature, precipitation, storms, and sea level (IPCC, 2007). However, these features of the climate also vary naturally; so, determining what fraction of climate change is due to natural variability versus human activities is challenging nevertheless.

Concerning future climate, a range of greenhouse gas emission scenarios are also presented by the IPCC based on estimates of economic growth, technological development, and results of possible international cooperation. In all scenarios, temperatures will continue to rise worldwide, with global mean temperatures averaging over 2–4 °C by the end of the century. The predicted amount of CO_2 released in the atmosphere and the subsequent rate of warming seem to be faster than ever recorded from historical or proxy records, even if the understanding of the driving forces that are responsible is still not clear. Although changes in average conditions can have serious consequences by themselves, the main impacts of global climate change will be felt because of changes in interannual climate variability and weather extremes. The changes in temperature can have a range of secondary effects on terrestrial and marine ecosystems. Some examples include an increase in the global mean sea level; retreat of glaciers; decrease in snow cover; thawing of permafrost, shifts of plant and animal ranges (generally poleward, and upward in elevation); earlier flowering of plants, bird breeding seasons, and emergence of insects; increased frequency of coral bleaching events, etc.

Although the general trend is toward a warming atmosphere, significant differences between various regions on Earth have to be taken into account. For example, in general, polar regions tend to warm faster than tropical areas, and land areas warm faster than oceans.

As far as precipitation is concerned, the general projection is that the hydrological cycle will become more intensive, which will result in a wetter climate. Additionally, the intensity and frequency of extreme precipitation events are likely to increase over many areas, and the return period of extreme rainfall events is expected to drop (Christensen and Christensen, 2003).

The projections for relatively small-scale atmospheric phenomena, such as storms, are subject to greater uncertainty. Nevertheless, an increase both in storminess (i.e., extra-tropical storms) and in the frequency and intensity of extreme precipitation events, at any time of the year regardless of the season (i.e., rain on snow events during fall), has been observed, and is expected to increase. In all cases, a number of questions remain open concerning the effects at a local scale. Global climate models (GCMs) generally simulate the weather and the climate on large grids (a few degrees latitude and longitude, or a couple of hundreds of kilometers across).

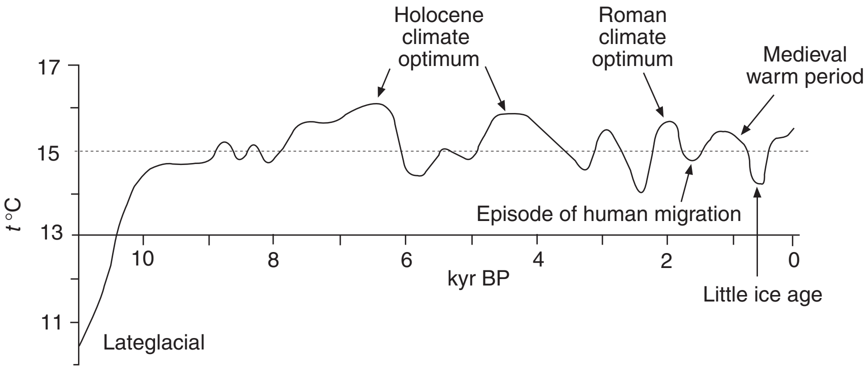

Figure 3 Schematic reconstruction of average temperature variations in the Northern Hemisphere during the Holocene. Adapted with permission from chapter 4, Figure 25 in Schoenwiese, C., 1995. Klimaänderungen: Daten, Analysen, Prognosen. Springer, Berlin, Heidelberg, 224 pp.

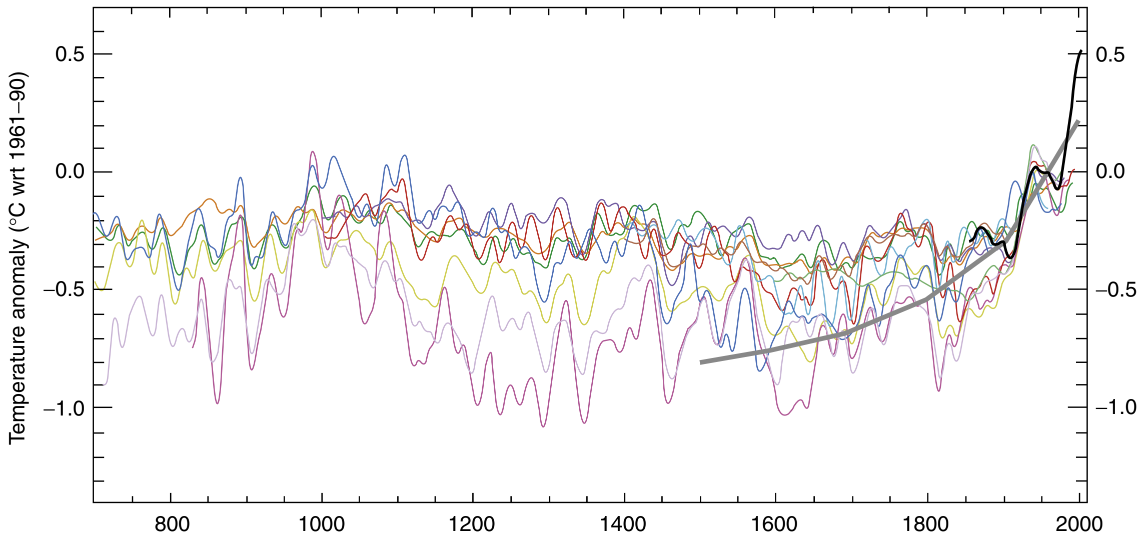

Figure 4 Records of Northern Hemisphere temperature variation during the last 1.3 ky. Curves show the trend of different climate proxy records; instrumental temperature records are reported in black. All temperatures represent anomalies (°C) from the 1961 to 1990 mean. Adapted with permission from chapter 6, Figure 6.10 in IPCC, 2007. Climate change 2007 synthesis report. In: Paschauri, R.K., Reisinger, A. (Eds.), Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, 104 pp.

The models incorporate large-scale features (such as mountain ranges) and perform relatively well in terms of simulating large patterns in the atmosphere, but they do not represent smaller-scale phenomena, such as differences in climate between two flanks of a mountain or a valley. As a consequence, the general patterns obtained from climate models, even if downscaled, always have to be interpreted in the context of the local geography and meteorology or modeled with the recently developed regional climate models (RCMs), which are also able to incorporate smaller-scale features at a local scale.

7.30.3 Landslides and Climate Coupling

Like most geomorphic processes, landslides (*see* Chapter 7.14) are to be considered as natural, multidimensional, and nonlinear dynamical systems, displaying a complex behavior in space and time (Brunsden, 1999). The evolution of the slope system is strictly connected with other geomorphic processes (fluvial among others) and is sensitive to both inherited and present controls. Mass movements are therefore four-dimensional phenomena and display a complex spatial and temporal evolution. In general, landslide initiation and each phase of landslide activity, surge or acceleration, are the near-immediate response to an external trigger that increases the stress in the slope or reduces the strength of the slope material (Wieczorek, 1996). The main landslide triggers are intense or prolonged rainfall events, snow melting, earthquakes, volcanic eruptions, and river and wave erosion (*see* Chapters 7.19, 7.20, 7.21, 7.22, and 7.23). Nevertheless, mass movements may also occur without any evident near-immediate trigger, occurring as the long-term response of the slope system to the combination of predisposing factors, such as lithology, geological structure, gradient, relief, etc. (**Figure 5**).

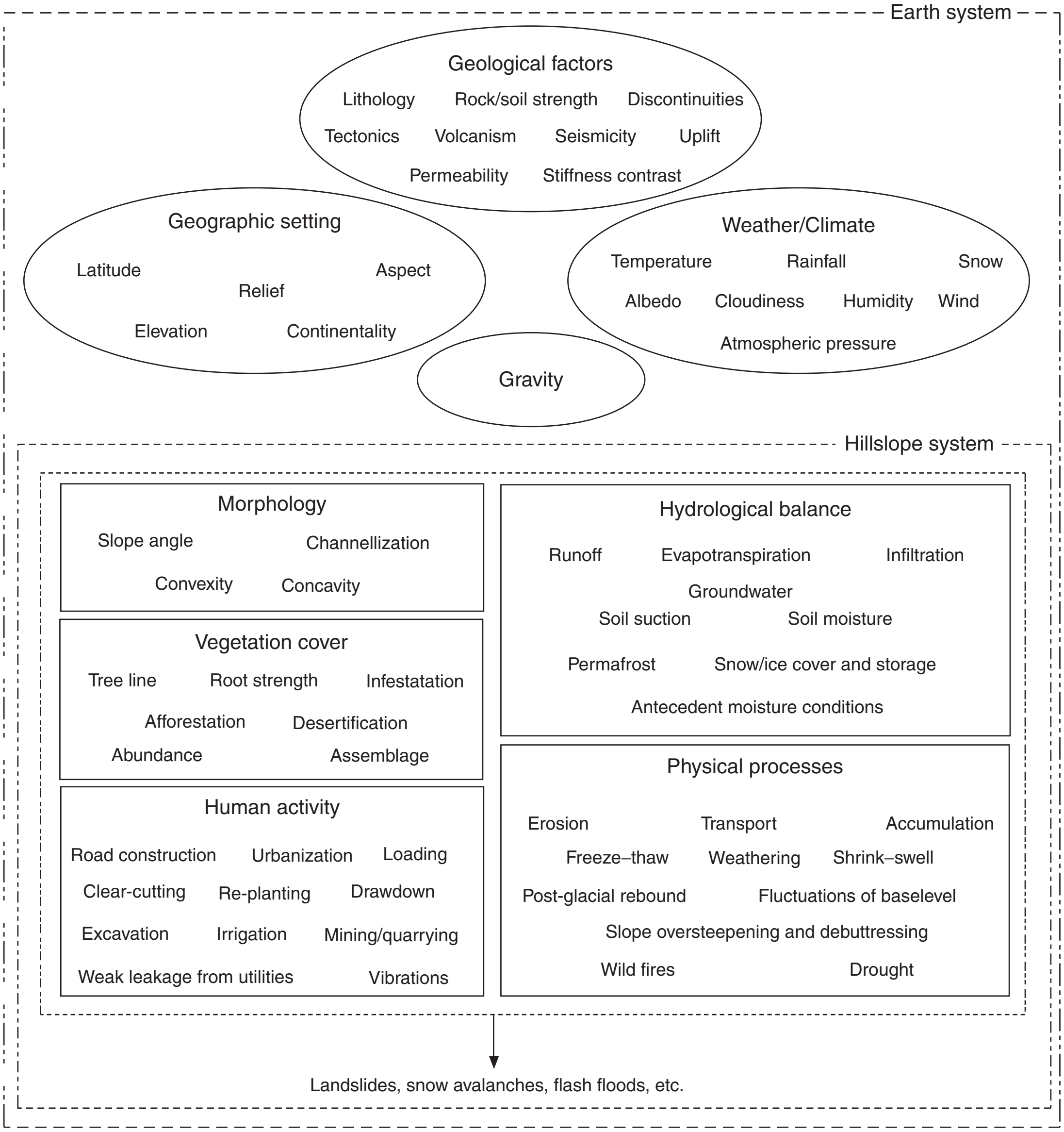

Figure 5 Predisposing and triggering factors of hillslope processes.

Climate is coupled with landslide processes through the highly nonlinear soil–water system, and no unique relationships exist between certain climate conditions and the occurrence of landslides. Nevertheless, we can assume that the connection between climate – in particular, positive (or negative) hydrological balance – and landslide activity (or inactivity) exists at every timescale, from daily to millennial. In particular, moisture changes in the balance, resulting from the temporal distribution of temperature and rainfall, and the resulting evapotranspiration directly influences the hydrological regime of slopes, which in turn governs a number of mass movement features:

- type and style of activity (fall, topple, slide, flow, and spread; complex and composite);
- magnitude (area, volume, depth, velocity, acceleration, runout, and mobility);
- temporal occurrence (single catastrophic event, many small events);
- spatial distribution (single vs. pervasive events);
- temporal evolution (episodic or intermittent behavior, dormancy, and reactivation);
- spatial evolution (retrogressive, advancing, and enlarging).

In general, similar climatic and hydrological conditions can be easily associated with different patterns of landslide distribution (Van Asch et al., 1999) in space and time. Nevertheless, the influence of moisture balance is evident in the triggering of shallow slope failures and debris flows, in the acceleration and surge of active slides and flows, and in the reactivation of dormant phenomena.

Shallow translational slides are generally triggered by water infiltration in unconsolidated slope deposits, which cover near-impermeable rock masses. Increasing soil saturation is responsible for the reduction of the shear strength of the soil, by the temporary rise in pore-water pressure and by the loss of the apparent cohesion of the soil (Wieczorek, 1996). Translational slides, rotational slides, as well as complex and composite slope movements are triggered by a sequence of long-duration rainfall and subsequent modification of the regional groundwater tables and subsequent shear-strength reduction (Van Asch et al., 1999). Such hydrological conditions can occur as a result of cumulative rainfall periods that are 40–90 days long and are also related to antecedent moisture conditions. Slope movements from bank erosion are mostly activated during flood episodes, related to very intense and/or concentrated rainfall, increased stream discharge, incision, and erosion along riverbanks.

At a short timescale, long-duration/high-intensity rainfall events are known to be the most important triggering factors of landslides worldwide (Wieczorek, 1996; Corominas, 2001). Physically based and empirically based models of rainfall-induced landslides have been used to simulate and understand this complex interaction and to derive thresholds for landslide initiation under different boundary conditions (Van Asch and Buma, 1997). A large number of physically based models have been developed (Montgomery and Dietrich, 1994; Iverson, 2000; Crosta and Frattini, 2003), whereas empirically based models statistically relate rainfall parameters such as intensity and duration to recorded landslide events at different spatial scales (i.e., global, national, regional, or local thresholds). Guzzetti et al. (2008) recently compiled a comprehensive review of worldwide thresholds and set minimum rainfall intensity–duration thresholds for the possible initiation of rainfall-induced shallow landslides and debris flows. Concerning deeper landslides or different types of slope processes (complex phenomena such as rock slides–earth flows or rock/debris avalanches), field observations and monitoring of present-day activity show that first-time failures and reactivations of large landslides display a complex hydrological and mechanical behavior (Corominas, 2001).

The coupling between landslide occurrence and climate is also indirect. Slope oversteepening and debuttressing by glacier retreat in recently deglaciated mountains, together with permafrost melting, have proved to be predisposing causes of slope instability in the past (Cossart et al., 2008) and under present warmer climate conditions in high mountain terrains. A number of recent examples of large rockfalls from steep permanently frozen slopes undergoing thawing have been reported (Haeberli et al., 2004; Geertsema et al., 2006; Lipovsky et al., 2008; Chiarle et al., 2007; Huggel, 2009). Permafrost acts at a shorter timescale than physical weathering, chemical alteration, or any change to hillslope inclination, varying the rock mass temperature field together with water availability at high altitudes and runoff. Over longer timescales, permafrost warming may lead to a rise in the lower permafrost boundary, decreasing permafrost thickness by bottom-up thawing and, hence, theoretically also increasing the risk of large, deep-seated landslides. For example, the Brenva Glacier rock avalanche, which occurred in January 1997 (Deline, 2001), may be related to deep-reaching and long-term changes of the subsurface thermal conditions. Thus, the probability of large-scale rockfalls (millions of cubic meters and more) is likely to increase with time in a period of climate warming.

7.30.4 Landslides and Climate Change

On the basis of a large number of studies, the evidence of ongoing climate change is unquestionable. Research on climate and related impacts has also addressed the assessment of the effects of climatic variability (Viles and Goudie, 2003) and climate change (Goudie, 1992, 2010) on geomorphic processes and hazards, among which is hillslope processes. Climate change will likely cause a series of impacts on the environment and on the operation of geomorphic processes as a result of changes in temperature, precipitation amount and/or intensity, and, consequently, soil moisture conditions (Goudie, 2010). In this context, as the severity of climate change will vary spatially, its potential impact will vary accordingly. Together with geomorphic processes, induced geomorphic hazards and risks will undergo significant modifications under the changing of climate conditions, and some transitional environments will transform more than others the so-called geomorphic hot spots (Goudie, 1996) that are both susceptible environments and unperturbed landscapes. In general, ice caps and alpine glaciers will melt at a higher rate, permafrost will thaw and retreat, coastal areas will be inundated because of sea-level rise, and floods and droughts will become more frequent.

What about hillslope processes, with particular reference to landslides (*sensu* Cruden and Varnes, 1996; including falls, topples, slides, flows, and spread)? In general, climate change has the potential to modify the processes acting on hillslopes and therefore their stability conditions (Borgatti and Soldati, 2010b). This issue is clearly important and urgent in terms of hazard and risk scenarios and that the debate on what are the actual causes of climate change itself is almost irrelevant in this context.

As stated beforehand, the majority of landslides are caused by at least one or the combination of three main causal factors: precipitation, seismicity, and human activity. Most landslides occur because of saturated soil moisture conditions and by consequent loss in soil or rock strength (Wieczorek, 1996) triggered by climatically controlled processes, such as intense and/or prolonged precipitation events, rapid snowmelt, glacier thinning, permafrost degradation, or river erosion, depending on geomorphic settings. If climate change leads to increased frequency and/or magnitude of these hydrological processes, the frequency and/or magnitude of landslides in a region will be similarly influenced (Crozier and Glade, 1999). Thus, we can expect more instability as a consequence of the increasing number of short, but intense, events, as well as by increasing cumulative rainfall, infiltration, and runoff.

Although the frequency and/or magnitude (mainly in terms of area involved, volume, or runout) of landslides may increase with the foreseen climate change, the regional distribution of landslides is not expected to change significantly as many of the primary factors controlling landslide susceptibility (such as lithology, tectonics, and morphology) are remaining relatively constant. New potentially unstable areas, however, could include slopes presently underlain by degrading permafrost (Harris et al., 2001) at progressively higher altitudes. At the same time, areas hit by weather extremes or by modified tracks of tropical cyclones or intensified monsoons can experience more slope instability. Moreover, the generation of cascading processes may also be expected: increased landslide activity may lead to increased sediment loads and channel instability in rivers (Korup et al., 2004), which in turn may cause more landslides.

It is also worthy to stress the fact that predicted temperature changes could influence the response of some hillslopes through increased evapotranspiration and soil suction, leading to a change in the precipitation thresholds that can trigger instability. Theoretically, this could help counter the impact of changes in precipitation rates and patterns. In this sense, some regions could experience fewer landslides as a consequence of climate change. Another indirect effect of climate change is related to the type and distribution of vegetation, as canopy intercept, evapotranspiration rates, and the root strength and biomass distribution affect hillslope stability in forested terrain. At the same time, in arid regions, wetter conditions can lead to an increase of vegetation cover that could reduce erosion rates and create more stable conditions on the long term, thanks to root structure and biomass.

As far as the magnitude is concerned, the combination of higher rainfall intensity and increasing volumes of unconsolidated sediments from glacier retreat and permafrost wasting could result in higher landslide and debris flow volumes and runout (Stoffel, 2010). Similarly, the combination of long-term temperature increase, heat waves, and high-intensity rainfall events may imply more frequent rock slope failures over a range of volumetric scale (Gruber et al., 2004).

However, the hydrologic response of landslides to climate is very complex (Jakob and Lambert, 2009) and cannot be reduced to a statement that simply associates more rain with more frequent or larger landslides. On the one hand, more annual rainfall may derive from more rainy days in some regions, whereas in other areas, short-term rainfall intensity may increase. On the other hand, antecedent moisture conditions are an important variable in landslide susceptibility. In case of drier and longer summer seasons, antecedent moisture thresholds will occur later into the rainy season. Warmer temperatures may result in a thinner and higher snow accumulation that can control both the timing and the elevation of shallow landslides and debris flows in high mountain terrains (Jakob, 2010), with the starting zone migrating progressively at higher elevations.

Apart from the impact of climate change, in many cases, specific geologic and geomorphic characteristics (lithology, structure, sediment availability, altitude of the triggering zone, slope aspect, etc.) still play a major role in landslide-triggering mechanisms. In the case of debris flows, which are clearly climate controlled, geomorphic features may result in different types of phenomena that do not display a single response to climate change (Jomelli et al., 2007; Stoffel et al., 2008). In this sense, the importance of spatial and temporal overlap of heavy rainfall and an available volume of debris are fundamental to explain the temporal and spatial patterns of events (Pech and Jomelli, 2001). The exceedence of a climatic threshold is necessary but not sufficient to trigger landslides. A number of studies on debris flows have shown that the availability of debris is of primary importance. In this context, weathering-limited and transport-limited basins have to be differentiated (Bovis and Jakob, 1999). Channels in weathering-limited basins typically recharge at rates controlled by rock weathering, whereas transport-limited basins typically contain large volumes of readily available debris. Consequently, transport-limited basins tend to produce debris flows more readily whenever a climatic threshold is exceeded. In weathering-limited catchments, a higher frequency of debris flows may result in a decreased volume per event (Bovis and Jakob, 1999; Jakob et al., 2005). At this point, however, changes in landslide frequency–magnitude relationships as a consequence of climate change are still highly speculative (Jakob and Lambert, 2009).

Finally, the compound effects of climate change and human actions, where humans can act as both co-triggers and element at risk, must be accounted for. In this sense, some studies seem to highlight the fact that climate change is important, but land-use change is even more important in the case of slope instability (Collison et al., 2000; Glade, 2003).

7.30.5 Landslides as Inheritance of Global and Regional Climate Change, at Different Temporal Scales

Climate oscillations have been recognized at different timescales, from intraseasonal to millennial (and more) and at different spatial scales (see Viles and Goudie (2003), for a review from a geomorphic work standpoint). Moreover, these modes of variability were also operating in the past with interactions, teleconnections, and positive- and negative-feedback mechanisms.

We can argue to which spatial and temporal extent climate variability and change are having an impact on slope instability. As the impact can be from global to regional, landslide occurrence in the past seems to have been significantly modulated by climate changes at different temporal scales, from decadal to millennial (**Figure 6**).

Whereas climate experts need to look at past climates to validate models, geomorphologists have to look at archives that can be both historical and natural in retrospective studies. To read the effects of climate change in the geological and historical records, the temporal and spatial scales of climate change and the related slope instability phenomena have to be taken into account with different methodologies that can tackle time resolution, landform persistence in the landscape, dating constraints, and the inherent discontinuity of landslide records.

Establishing links between past climate and past hillslope activity is indeed very difficult. This is primarily due to the limited number of dating of gravity-induced landforms (e.g., imprecise ages, incomplete databases concerning location and description of the events, and lack of records) related to the last century, to the Little Ice Age (LIA), and to the Holocene. Effects of past climate changes on formative events on slopes have been assessed by means of field evidence and dendrochronology (Corominas and Moya, 2010; Stoffel et al., 2010) or physical dating (Gutiérrez et al., 2010) as well as through physically based models (Brooks, 1997). These links have been estimated tentatively, especially for landslides in the Alps (e.g., Matthews et al., 1997; Soldati et al., 2004).

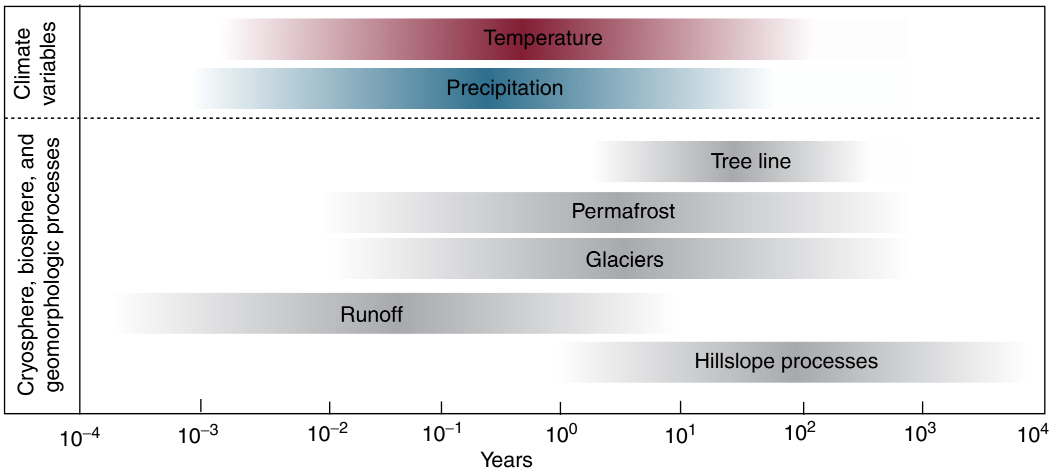

Figure 6 Climate variables, components of the hillslope cryosphere and biosphere, and geomorphological processes.

Landslide occurrence has been exploited as a climate proxy itself (Matthews et al., 1997; Borgatti et al., 2007; Borgatti and Soldati, 2010b). This approach is hindered by a number of biases because of the complexity of climate–landslide coupling, which is much more complicated at a long temporal scale (Crozier, 1997).

At a long temporal scale (i.e., the entire Holocene), the relationship between landslide activity and triggering mechanisms can be established from the temporal clustering of dated landslides. In order to discriminate between the climatic and nonclimatic factors, a multidisciplinary approach directed to the appraisal of the paleoenvironmental conditions at the time of the landslides must be adopted. Therefore, besides the development of a landslide events record, other proxies have to be considered in order to disentangle the possible interactions between the slope system, climate, and humans (Borgatti et al., 2007).

7.30.6 Landslides and Long-Term Climate Changes

Based on the distinct imprint of millennial-scale climate change on surface processes and landscape evolution, previous investigations have clearly shown that at least from the Late Glacial to the present, climate has influenced slope evolution (either directly or indirectly), and that (among others) slope processes may also be considered geomorphic indicators of climate changes (Goudie, 1992; Borgatti and Soldati, 2010b).

Concentration in time of ancient landslide events has in fact been reported from both Southern and Northern Europe (Starkel, 1991; Frenzel et al., 1993; González Díez et al., 1996; Panizza et al., 1996; Ibsen and Brunsden, 1997; Lateltin et al., 1997; Schoeneich et al., 1997; Alexandrowicz and Alexandrowicz, 1999; Dikau and Schrott, 1999; Dapples et al., 2002; Schmidt and Dikau, 2004; Soldati et al., 2004; Bigot-Cormier et al., 2005; Margielewski, 2006; Borgatti and Soldati, 2010b) (**Figure 7**). Apart from landslides, debris flow records are also considered to reflect the increased occurrence of heavy rainstorms during the Holocene (Sletten et al., 2003; Stoffel et al., 2008).

Recently, evidence of slope instability from climate change has been found in Africa (Busche, 2001; Thomas, 1999), northern and southern America (Bovis and Jones, 1992; Smith, 2001), and Asia (Sidle et al., 2004). Post-LIA glacial retreat is one of many factors influencing landslide activity in British Columbia (Holm et al., 2004). Time-series analysis reveals periods of more humid and more variable climates at the time of a clustering of landslide events in the Andes (Trauth et al., 2003).

Some studies have focused on the understanding of these relationships, relating them to relatively known, also proxy-derived, past climate series exploited for projections of future unknown climates (Schmidt and Dikau, 2004). The modeling of groundwater-controlled landslides shows that the highest slope instability occurs at the transition from the more humid LIA to the drier recent climate. The intensity of this impact, however, varies with the sensitivity of the geomorphic system (i.e., local landforms and lithology), and cannot be related to a specific hillslope (Schmidt and Dikau, 2004).

Concerning the inheritance of past climate changes and related indirect effects, a number of recent studies indicate that the largest landslides in the Alps did not occur during deglaciation or immediately after, as the concept of paraglacial crisis (Ballantyne, 2002) might indicate, but during the Holocene. For example, the estimated time lag from deglaciation and failure is about 3000 years for the la Clapière landslide (French western Alps; Bigot-Cormier et al., 2005), about 2500 years for the Flims rock slide (Swiss central Alps; Ivy-Ochs et al., 2009), about 4000 years for the Val Viola rock slide (Italian central Alps; Hormes et al., 2008), about 2000 years for the Fernpass rock slide (Austrian eastern Alps; Prager et al., 2009), and about 5400 years for the Séchilienne landslide (western Alps, France; Le Roux et al., 2009). Considering these data, Ivy-Ochs et al. (2009) suggested that the initiation phase and failure did not occur during deglaciation but during mid-Holocene time when climate became markedly warmer and wetter. These results suggest that temperature and precipitation changes at that period had a significant effect in triggering or accelerating movement rates on landslide-prone slopes.

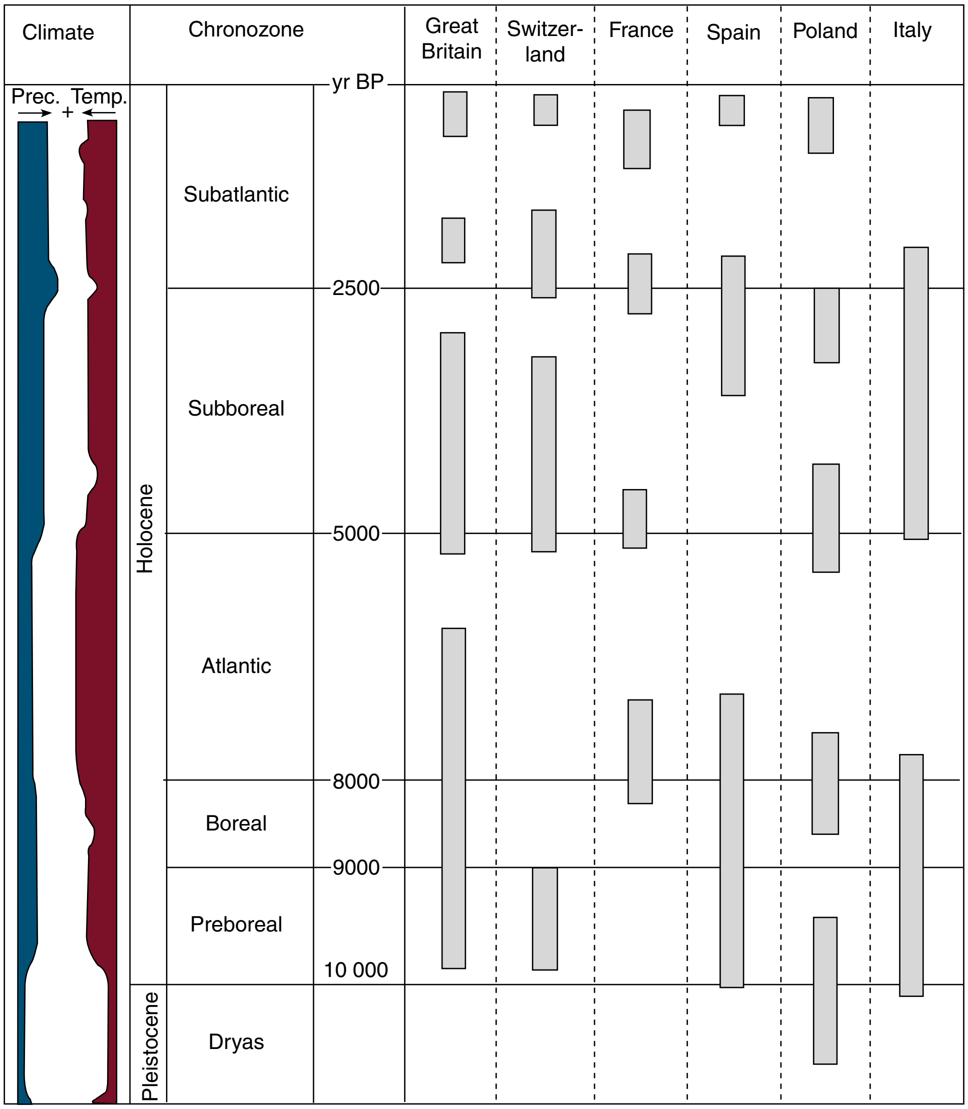

Figure 7 Landslides and climate in Europe during the Holocene. The rectangles represent periods of enhanced landslide activity.

The effects of deglaciation on the onset of deep-seated gravitational slope deformation (DGSD) were also recently assessed in the Italian Alps by means of geomorphic evidence and radiocarbon dating (Pasuto et al., 1997; Agliardi et al., 2009). Slope deformation started during the Late Glacial, soon after deglaciation, and ceased in the early Holocene (beginning of the Boreal chronozone) when the area had already been forested.

7.30.7 Landslides and Short-Term Climate Variability

Climate variability on Earth can occur on a very large spectrum of time and spatial scales. In particular, the variability can span from intraseasonal (20–90 days), to interannual (2–7 years), to decadal timescales.

The relationship between interannual atmospheric and oceanic circulation oscillations (North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) (Walker, 1923; Philander, 1999), among many others), controlling precipitation regime, and landslide activity has been observed in many areas of the world. Several studies have established links between the NAO phase and precipitation in Western Europe and the Mediterranean Basin. In particular, Trigo et al. (2005) and then Marques et al. (2008) showed that the influence of the NAO phases is extensive for the timing and frequency of major rainfall seasonal and monthly episodes and the associated landslide activity in Portugal.

The ENSO climatic phenomenon has been widely referred to around the world because of its impact on economies and human activities, such as agriculture and fishing, in developing countries. El Niño events had a major impact on California and coastal Central America, but the teleconnections were global with effects in Europe, the Atlantic area, and Asia. Furthermore, El Niño has been associated with greater landslide occurrences around the world (Ellen and Wieczorek, 1988; Wieczorek et al., 1989; Cayan and Webb, 1992;

Glantz, 1995; Godt et al., 1997; Reynolds et al., 1997; Coe et al., 1998; Ngecu and Mathu, 1999). In southern America, the temporal distribution and frequency of landslides triggered by precipitation seem to be strictly conditioned by the ENSO climatic cycle (Moreiras, 2005) and also at longer timescales (Trauth et al., 2003).

Intensified Asian summer-monsoon circulation phases, caused by warming, can induce enhanced precipitation, leading to an increase in pore-water pressure in soils, lateral scouring of rivers, and oversteepening of hillslopes, eventually resulting in failures and exceptionally large mass movements (Bookhagen et al., 2005). In some regions, also extratropical, an increasing number of cyclones, hurricanes, and extreme storm events have also been recorded, triggering a large number of shallow landslides.

Concerning recent climate warming and its effect at high altitudes in the Alps, the extremely hot summer of 2003 was associated with increased rockfall activity within the permafrost zone (Gruber et al., 2004). In addition to permafrost-related effects, hillslope instability conditions may also arise from glacier–permafrost interactions. Rapid decay of glacier ice on steep bedrock slopes may lead to ice falls, complex geothermal conditions in bedrock may trigger unforeseen rockfall events, and decay of buried ground ice may cause catastrophic proglacial lake drainage (Harris et al., 2009).

7.30.8 Hazard Issues in a Changing Environment

If climate change predictions are accurate, together with global warming, more intense and extreme rainfall is expected that can drastically increase landslide hazard and (coupled with population growth) risk and (in particular) landslide-associated casualties. In developing countries, the risk is higher where both population and agriculture pressure on land resources often lead to exploitation of unstable slopes (i.e., villages at high altitudes and infrastructures at high altitudes and/or latitudes). In developed countries, the risk is associated not only with the value of exposed element, but also with the exploitation of landslide-prone area for recreation and tourism purposes. Besides changes in precipitation regimes, climate change may trigger landslides in other ways as well. In high mountain environments, landslides and glacier-related processes (outbursts from moraine and glacier-dammed lakes, glacier avalanches, and landslides/debris flows in the glacier environment) may have impacts reaching much farther downstream than ever previously experienced, in the context of dramatic retreat of glaciers in response to climate change (e.g., September 2002 Kolka Glacier event in Caucasus; Haeberli et al., 2004; Evans et al., 2009).

Understanding the relationship between landslides and climate change is therefore crucially important in planning a proactive approach to hazard and risk management in a changing environment. Advances in geohazard modeling and prediction, as well as in real-time monitoring technology, enable us to be better prepared for the impacts of climate changes; however, in many countries, especially in geomorphological hot spots (Goudie, 2010), effective risk management and informed planning policy are needed to improve the safety and sustainability of communities at risk.

Besides the intrinsic complexity of slope-instability phenomena, many factors may produce changes in both frequency and magnitude of landslide events at different spatial and temporal scales. Mass-wasting processes are primarily controlled by steady or quasi-steady geological and structural predisposing factors, but the effects of different climate-related environmental changes (temperature, rainfall, vegetation, etc.) and human impact have to be taken into account altogether.

At a long timescale (i.e., millennia), a number of inherent difficulties arise in correlating proxy records of climate changes and prehistorical landslide records with the aim of understanding the relationships between climate and slope processes in the past as a key to the present and to future scenarios. Commonly, the spatial scales of paleoclimate and landslide records are different, and prehistoric and even historic records are sparse. Time resolution can also be very different in the two types of records, and several dating constraints may affect both. Nevertheless, some remarkable indications on past climate and past landslide activity are apparent. Landslides have proved to be modulated by climate at a range of temporal and spatial scales, being geomorphic proxies of climate change themselves. The periods of past enhanced slope instability display a correlation with indicators of humid climates, suggesting that these activity phases could have been climatically driven and, that, in particular, a positive moisture balance could have played a major role in conditioning landslide activity at the 100–1000 years' timescale. This is also noted by the periods of lower landslide activity associated with arid periods (Borgatti and Soldati, 2010a).

At a centennial timescale, the post-LIA glacial retreat has increased (1) the spatial frequency of superficial failures within the Neoglacial limit, (2) rockfall occurrence along glacial trimlines, and (3) the likelihood of catastrophic failures in weak rock and in preexisting gravitational slope deformation. A significant spatial association exists between the occurrence of recent catastrophic failures and the slopes that were oversteepened and then debuttressed by glacial erosion (Holm et al., 2004).

At a decadal timescale, the relationship between magnitude of the NAO- and ENSO-induced precipitation and mass wasting is clear and allows for the development of models to be used for both landslide risk assessment and water-resource management. At the same time, in sensitive high mountain terrains and in glaciated mountain belts, the effects of deglaciation and permafrost thawing and retreat that occurred during the Holocene may even have been enforced by present-day changes. Over longer timescales, permafrost warming may have led to a rise in the lower permafrost boundary, decreasing permafrost thickness by bottom-upward thawing and, hence, increasing the probability of large, deep-seated landslides. In the Alps, the rapid increase in permafrost active layer thickness has been associated with greatly increased rockfall activity within the permafrost zone (Stoffel et al., 2005).

Concerning future climate, techniques have been developed for downscaling a large-scale model output to the hillslope scale. Hydrological models and slope stability models have been created for areas in the Italian and French Alps, in southeast Spain, and in south England (Brooks, 1997; Buma and Dehn, 2000; Collison et al., 2000; Dehn et al., 2000;

Van Beek, 2002; Malet et al., 2005; Dixon and Brook, 2007). Nevertheless, it has to be underlined that landslides are localized phenomena, commonly occurring in upland areas where rainfall patterns are complex. GCMs work at larger spatial scales, and the outputs are difficult to be scaled at the slope scale. Improved GCMs and the recently developed RCMs can more accurately represent spatial variations of climate forcing such as topography, lakes, land–sea contrast, giving the possibility to model future landslide activity based on future precipitation scenarios, and past landslide archives.

As recent examples, the effect of global warming on the relative frequency of landslides along the British Columbia coast has been studied by examining the monthly mean simulations of precipitation from a number of climate models using three IPCC climate-change scenarios. Because the antecedent precipitation and the short-term precipitation contribute to the occurrence of landslides, the results of this study support the prediction of increased debris-flow frequency during the twenty-first century (Jakob and Lambert, 2009).

Currently, not only climate is changing, but also all the environmental variables that are climate related. The rate of change is unprecedented, or at least not witnessed, with strong positive- and negative-feedback mechanisms. At the same time, society is changing with growing needs and vulnerability, and also with the capability of access to more education and information resources. In this sense, the phrase 'global change' embraces this overall situation more than 'climate change'. In fact, in this global context, strong and even opposite regional implications are becoming evident. In general, observable evidence from the far and near past suggests an increase in landslide activity under the changing climate conditions, but any generalization is not possible so far. For sure, we have the means to assess which areas will be affected; therefore, adaptation and avoidance strategies are possible, exploiting models that discriminate between and incorporate human and climate effects. Analysis of sources of uncertainty in the models has also been used to establish the factors that contribute to the predicted changes in slope instability. Assessment of these factors can provide an indication of the potential impact of climate change on landslides in different failure-prone areas, where susceptible features occur, such as weak rocks, areas close to sea level, and climatically sensitive areas at high latitudes and high altitudes. It should also be considered that slope instability may be triggered by climate change initially, but that it may subsequently deteriorate independent of climate (Fischer et al., 2006).

At present, in some of these susceptible areas, where the best practice in landslide risk mitigation is established, the design and management of infrastructure and urban assets affected by natural slope instability are performed with reference to specified standards and guidelines that assume static or quasi-static environmental conditions. However, the rate of dominant input parameters (i.e., precipitation and temperature) is now clearly changing. Therefore, a review of this approach is demanded as the assumption of a steady climate state can be at least misleading (see, e.g., Jaedicke et al., 2008).

The main gaps in knowledge are the lack of site-specific scenarios providing the probability of occurrence of various meteorological conditions (temperature, precipitation, wind, snow and sea-ice thickness and extent, waves, etc.). Monitoring and climate sensitivity analyses are necessary. It is also important to combine geological and engineering knowledge with socioeconomic-development scenarios and environmental-impact assessments to evaluate how projected climate change may affect human lives in mountain environments in the near future.

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