Europe’s avalanches, landslides and rockfall in a changing climate

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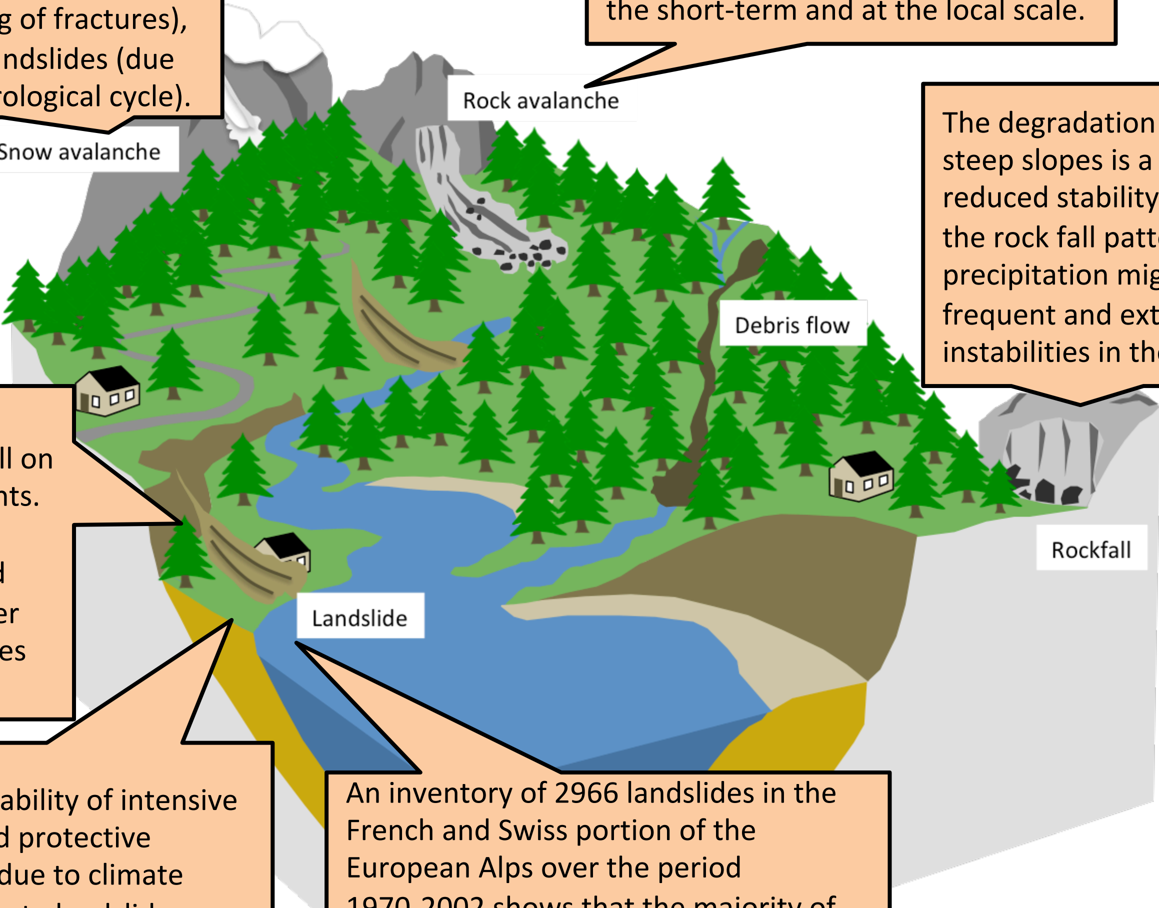
Avalanches, landslides and rockfall

Processes

Changes in the air temperature influence directly ice falls and avalanches, and have an indirect impact on rock falls (due to the formation and opening of fractures), and on deep-seated landslides (due to changes in the hydrological cycle).

Variations in rainfall totals influence mostly rockslides, mud flows and earth flows, at both the local and the regional scale, whereas variations in rainfall intensity affect rock falls and debris flows and debris avalanches, in the short-term and at the local scale.



The degradation of permafrost in steep slopes is a major factor for the reduced stability of rock walls and the rock fall pattern. Increased precipitation might lead to more frequent and extended slope instabilities in the future.

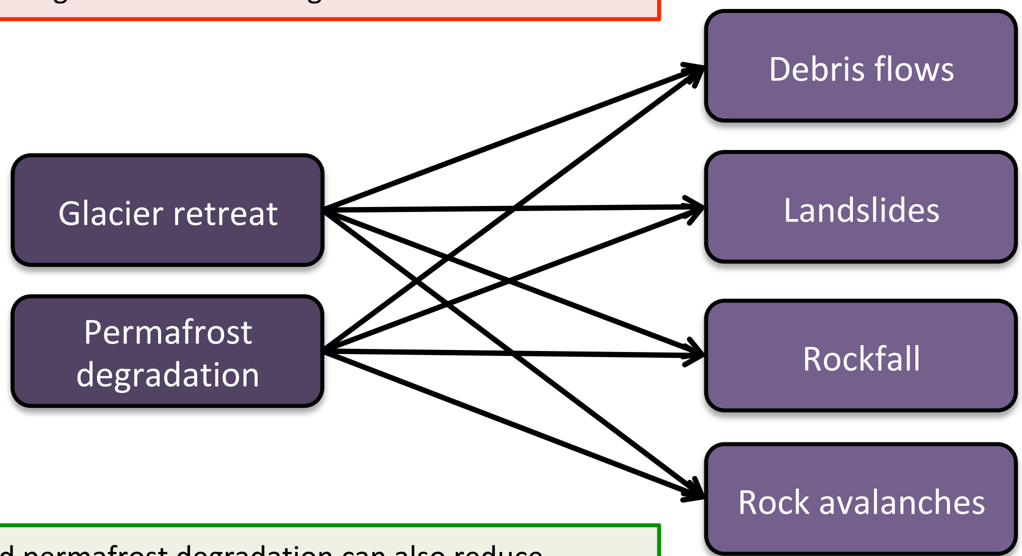
Rainfall itself does not trigger landslides; it's the impact of rainfall on destabilization of the soil that counts. Infiltrating rainfall can significantly increase the soil pore pressure and thus induce slope movement. Other causes of landslides are earthquakes and human activities.

The increased probability of intensive rainfall and reduced protective function of forests due to climate change can exacerbate landslides, muddy flows and torrential floods.

An inventory of 2966 landslides in the French and Swiss portion of the European Alps over the period 1970-2002 shows that the majority of landslides recorded occurred during the spring (29%) and summer (36%), with the lowest numbers recorded during autumn (15%) and winter (20%).

Avalanches, landslides and rockfall

Glacier retreat and permafrost degradation seem to be the two most important processes in the context of global warming and mountaineering. Both provide additional rock material for different kinds of mass movement processes. Unstable material provides new potential starting zones for different kinds of mass movements such as debris flows, landslides, or rockfall. Numerous classical ice climbs in the Eastern Alps have become heavily affected by rockfall and falling stones as well due to rocks melting out at the ice margins.



Natural hazards in the Alpine countries have resulted in economic losses of EUR 57 billion over the 1982-2005 period (insured losses EUR 10,5 billion). This is without counting the large investments made by Alpine countries in protection and prevention measures.

Both glacier retreat and permafrost degradation can also reduce morphodynamics locally, thereby decreasing the occurrence of natural hazards. Hence, it cannot be generally stated that the mountains are becoming more dangerous throughout. There is still little known about the frequency of the mentioned hazard events, and to date there are no time series available to prove that these events have become more frequent in the long run.

Avalanches, landslides and rockfall

Current situation in the Alps

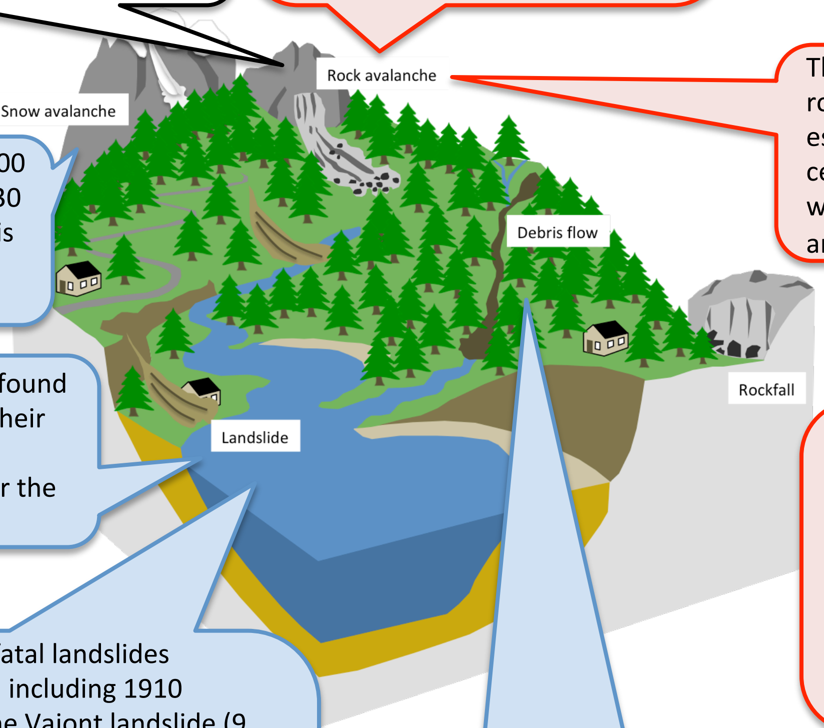
Indications changing hazard

- Reduction
- No indication of change
- Increase

In Austria 74% of all communities are endangered by torrents and avalanches. Most of the torrent events (93.5%) occur from June to August, and more than 20% of them are dangerous debris flows.

Since the mid-1980s there have been five major rock slides of more than 1 million m^3 in the Alps. Four of them affected tourism areas (roads, ski slopes, hiking trails). For three of them the relationship to glaciers and permafrost has been proven.

There has been an apparent increase in large rock slides during the past two decades, and especially during the first years of the 21st century in the European Alps in combination with temperature increases, glacier shrinkage, and permafrost degradation.



Avalanches have claimed an average of 100 victims per year in the Alps over the last 30 years. Victims are primarily skiers. There is no clear trend in the frequency of avalanches.

Significant trends have not been found in the number of landslides and their impacts in the French and Swiss portion of the European Alps over the period 1970-2002.

Permafrost degradation might play a role in the growing number of slope failures at high elevation in the Alps that has been documented since the beginning of the 21st century. A study of 41 rock-slope failures in 1997 - 2013 at high elevation (above 1500 m a.s.l.) in the Italian Alps showed that temperature is a key factor contributing to slope failure occurrence.

In Italy from 1950 to 2015, 661 fatal landslides occurred causing 4105 fatalities, including 1910 estimated fatalities caused by the Vajont landslide (9 October 1963), the most destructive slope failure in Europe in historic time. In this period, the frequency of low magnitude events (with one or two fatalities) has remained unchanged, and the magnitude of the most destructive events has decreased. The reduced magnitude of the most destructive events is related largely to the increased availability of information, and to improved monitoring and warning systems. The largest landslides cost the country 1.2 billion dollars.

Research has not yet provided any clear indication of a change in the frequency of debris flows due to recent deglaciation. In the French Alps, for instance, no significant change in debris flow frequency has been observed since the 1950s in terrain above elevations of 2,200 m.

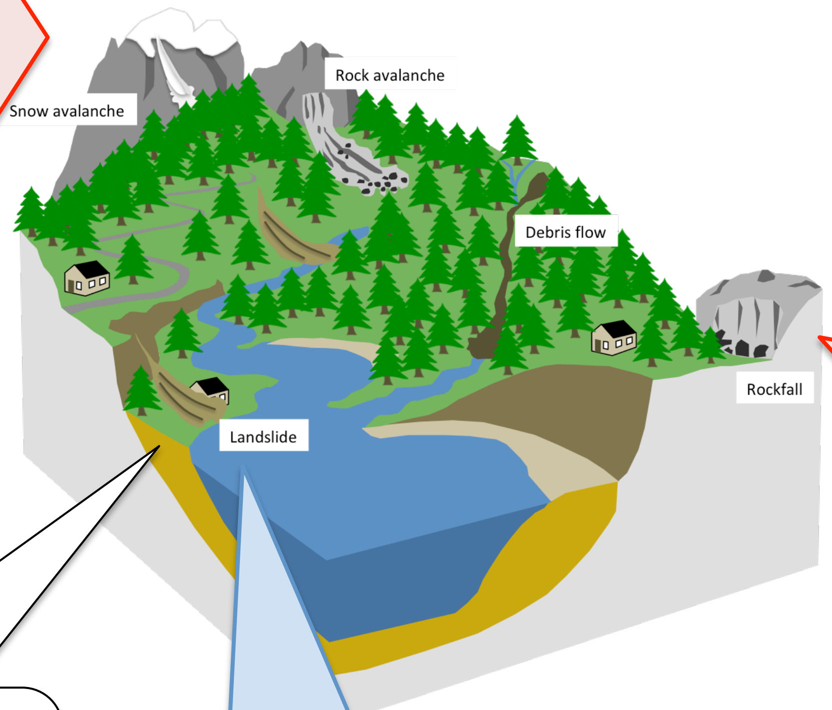
Avalanches, landslides and rockfall

Current situation in Scandinavia

Indications changing hazard

- Reduction
- No indication of change
- Increase

More near-zero events can potentially increase the frequency of snow avalanches in cold areas through their effect on snowpack stability. Infrastructure at higher elevations, such as mountain roads, ski resorts, and cabin communities, might experience more snow avalanches than a few decades ago due to more frequent and intense snowfall in these areas, and possibly also due to more available snow. Another facilitating condition for snow avalanches might be more events of rain on snow, since more winter precipitation comes as rain, and rainfall events seem to be more intense.



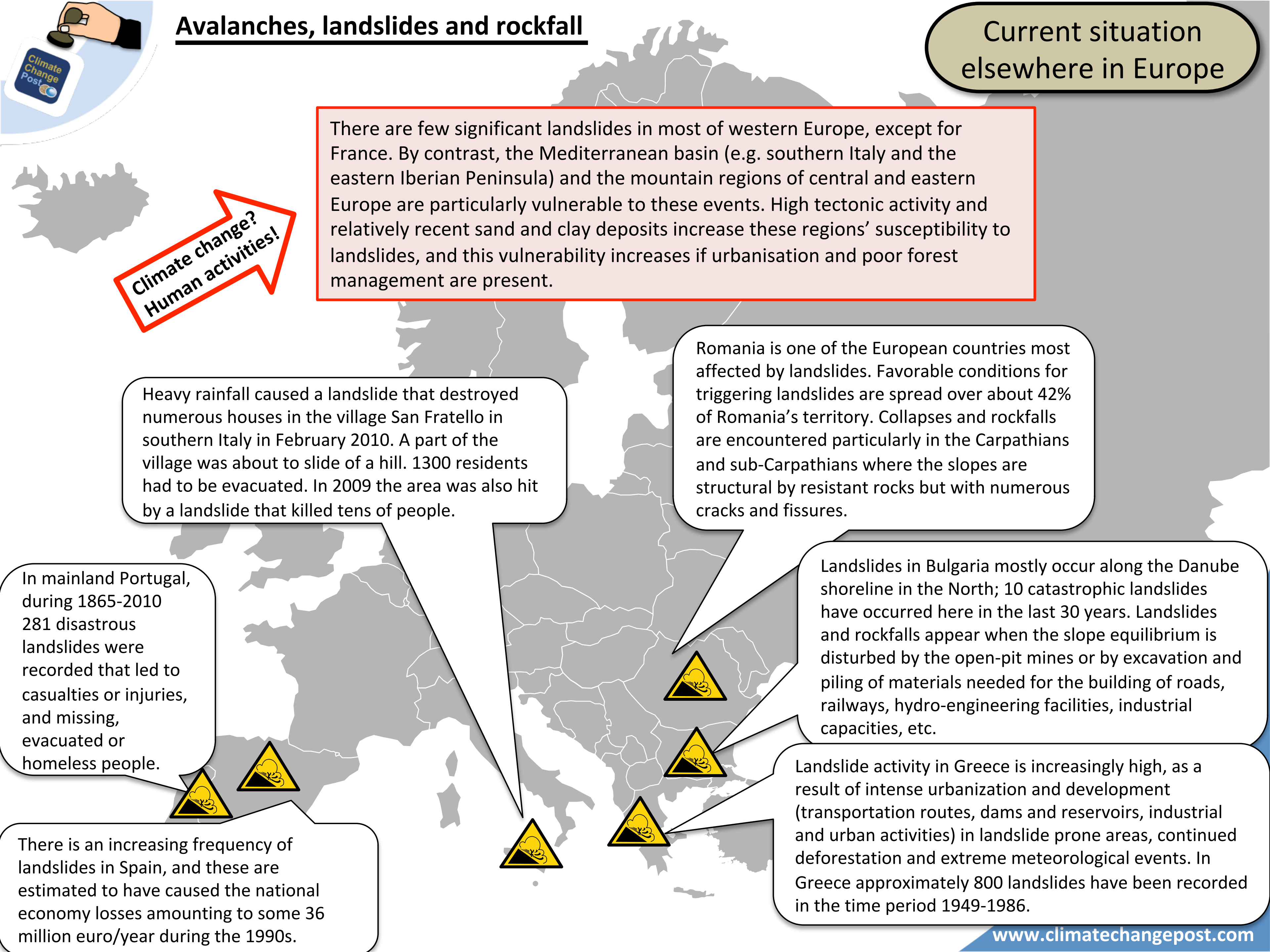
Near-zero (freeze-thaw) events have become more frequent in most non-coastal parts of Norway. Along with more heavy rainfall this might trigger a larger number of rockfalls and rock slides due to decreased rock stability.

Over 55 large landslides, with a spread of at least one hectare, have occurred in Sweden over the past 100 years. The landslides caused immense damage primarily to buildings, but also to infrastructure.

Analyses indicate that the number of recorded landslide events in Norway has increased exponentially since 1960. It is impossible to conclude whether this increase is partly due to climate change.

Avalanches, landslides and rockfall

Current situation elsewhere in Europe



Climate change?
Human activities!

There are few significant landslides in most of western Europe, except for France. By contrast, the Mediterranean basin (e.g. southern Italy and the eastern Iberian Peninsula) and the mountain regions of central and eastern Europe are particularly vulnerable to these events. High tectonic activity and relatively recent sand and clay deposits increase these regions' susceptibility to landslides, and this vulnerability increases if urbanisation and poor forest management are present.

Heavy rainfall caused a landslide that destroyed numerous houses in the village San Fratello in southern Italy in February 2010. A part of the village was about to slide of a hill. 1300 residents had to be evacuated. In 2009 the area was also hit by a landslide that killed tens of people.

Romania is one of the European countries most affected by landslides. Favorable conditions for triggering landslides are spread over about 42% of Romania's territory. Collapses and rockfalls are encountered particularly in the Carpathians and sub-Carpathians where the slopes are structural by resistant rocks but with numerous cracks and fissures.

In mainland Portugal, during 1865-2010 281 disastrous landslides were recorded that led to casualties or injuries, and missing, evacuated or homeless people.

Landslides in Bulgaria mostly occur along the Danube shoreline in the North; 10 catastrophic landslides have occurred here in the last 30 years. Landslides and rockfalls appear when the slope equilibrium is disturbed by the open-pit mines or by excavation and piling of materials needed for the building of roads, railways, hydro-engineering facilities, industrial capacities, etc.

Landslide activity in Greece is increasingly high, as a result of intense urbanization and development (transportation routes, dams and reservoirs, industrial and urban activities) in landslide prone areas, continued deforestation and extreme meteorological events. In Greece approximately 800 landslides have been recorded in the time period 1949-1986.

There is an increasing frequency of landslides in Spain, and these are estimated to have caused the national economy losses amounting to some 36 million euro/year during the 1990s.

The impact of higher temperatures

Summer of 2003

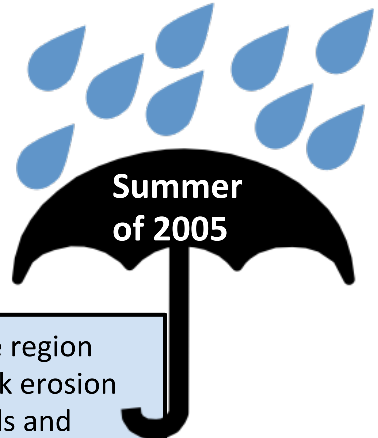
The summer of 2003 was characterized by the hottest temperatures in the last 500 years in Central Europe and the warmest summer in a 1250 year long record for the European Alps. In 2003 the thaw depth in permafrost on bedrock slopes was twice the average of previous years. Permafrost degradation set into action by this warming was reflected in increased rock-fall activity throughout the Alps during summer 2003.

In northern slopes, the depth of thaw is mainly controlled by the influence of air temperature on surface temperatures. Southern slopes additionally receive high amounts of sunshine. As a consequence, the inter-annual variability of thaw depth was already large for southern slopes, and the extent of perennially frozen slopes smaller. The impact of the summer of 2003, therefore, was smaller for southern slopes.

The degradation of mountain permafrost due to persistently high temperatures can lead to slope instabilities which threaten settlements and communication routes. In many mountainous regions, tourist resorts such as those in the Alps have spread into high-risk areas, and these will be increasingly endangered by slope instability.

Avalanches, landslides and rockfall

The impact of heavy downpour



In August 2005, Central Europe and especially the Alpine region was affected by severe floods accompanied by river-bank erosion and sediment transport, as well as debris flows, rock falls and landslides in the smaller catchments. These events caused the most catastrophic flood damage in the last 100 years with respect to loss of life and damage to infrastructure, communication routes and agriculture.

In Switzerland, the August 2005 event caused one quarter of all damage by floods, debris flows, landslides and rock falls recorded since 1972.

In Austria alone, 115 debris flows and 111 other landslides were recorded. Changes to channel courses, enhanced bank overtopping and sediment deposition outside the main channels led to substantial flood damage on inhabited areas and infrastructure along the river channels. Total losses across Austria were up to 555 million Euro.

Austria uses design events with a 100 year recurrence interval for floods and 150 years for debris flows. The 2005 event was far beyond these design events, meaning that the record of past events is no longer sufficient for hazard assessment.

More heavy precipitation events will probably increase the number of landslides in parts of Europe that are susceptible to landslides because of their steep hills and geological subsoil. This is especially the case for a number of regions along the north side of the Alps: the Jura Mountains, the Vosges, the Black Forest, the Swabian Jura, the Bavarian Pre-alps, the foothills of the Austrian Alps and the Bohemian Forest. These regions are also important transport corridors for Europe's road and rail network. More landslides may disrupt these corridors and cause a lot of damage.

Avalanches, landslides and rockfall

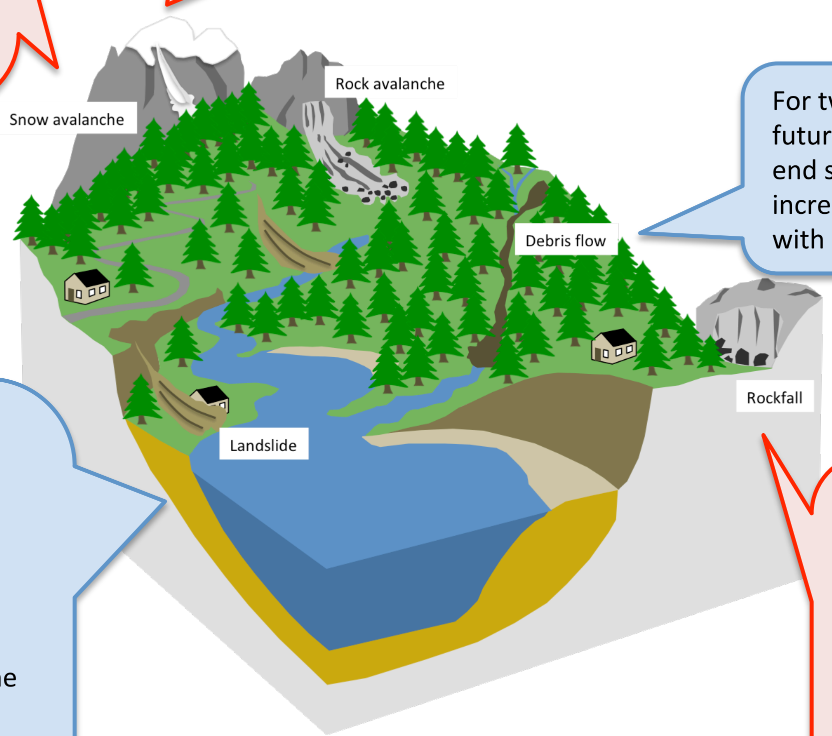
Future situation in the Alps

Indications changing hazard

- Reduction
- No indication of change
- Increase

Ice volume reduction of retreating glaciers leads to debuttressing of over steepened valley flanks, causing landslides and catastrophic rock falls. Failure of such landslides poses significant risks to surrounding settlements and critical infrastructure, because of the formation, and possible breakout of landslide dams, as well as enhanced sediment production, which can lead to debris and mud flows.

The projected glacier retreat in the 21st century may form new potentially unstable lakes. Probable sites of new lakes have been identified for some alpine glaciers. Rock slope and moraine failures may trigger damaging surge waves and outburst floods from these lakes.

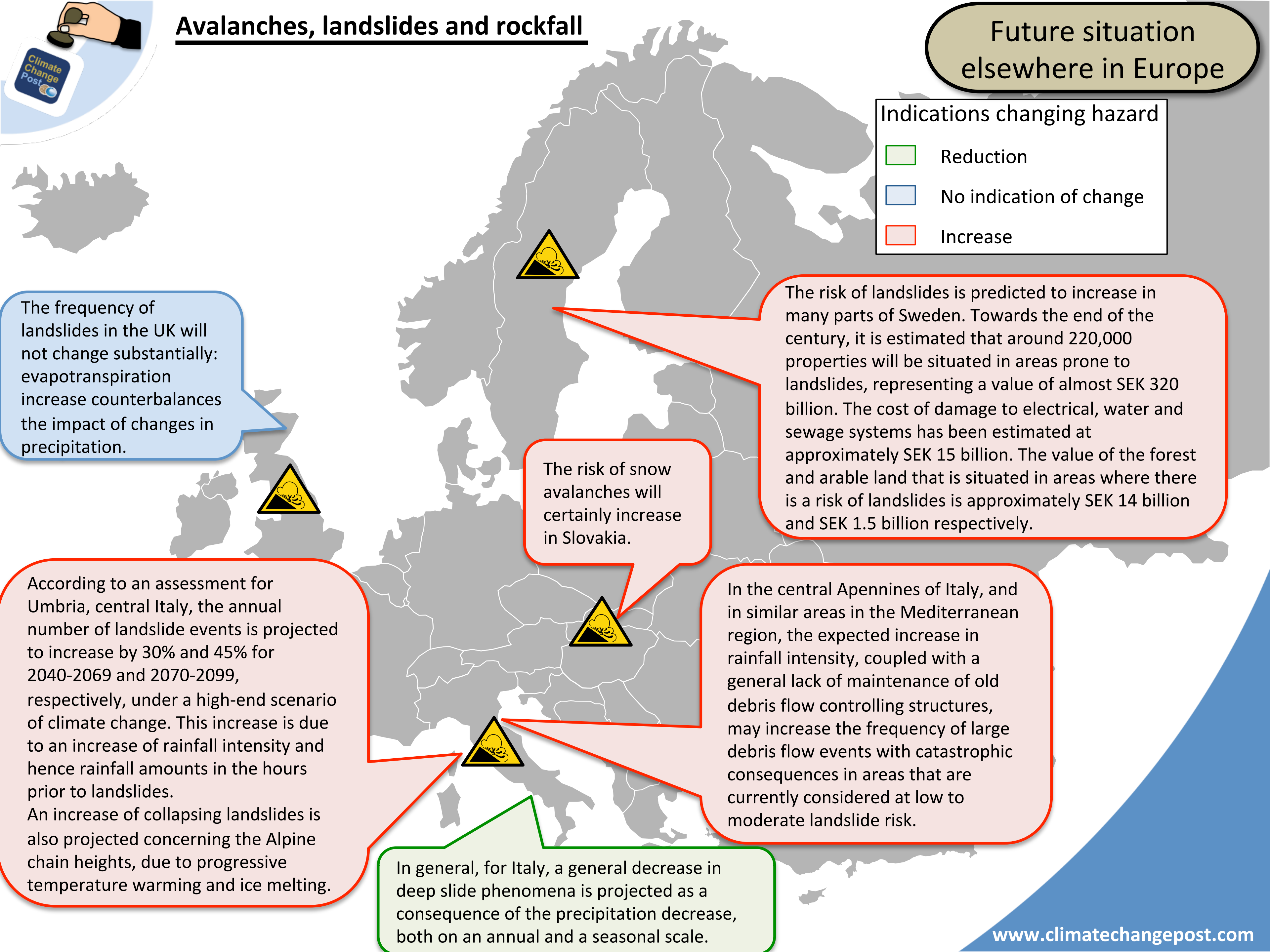


For two Alpine catchments in France and Italy, future projections for an intermediate and high-end scenario of climate change show either an increase or little change in the number of days with debris flows between now and 2100.

The impacts of climate change on avalanches and landslides remain uncertain.

The changes of intense precipitation could impact the shallow landslides (through the surface water runoff and stream actions), while the changes of long-term precipitation could impact the deep landslides (through underground water action). On the other hand, the possible future decrease of summer precipitation may have a positive effect by reducing the deep and shallow landslides activity.

The zone of warm permafrost (mean annual rock temperature approximately -2 to 0°C), which is more susceptible to slope failures than cold permafrost, may rise in elevation a few hundred meters during the next 100 years. This in turn may shift the zone of enhanced instability and landslide initiation toward higher-elevation slopes that in many regions are steeper, and therefore predisposed to failure.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Indications changing hazard
Reduction
No indication of change
Increase
The frequency of landslides in the UK will not change substantially: evapotranspiration increase counterbalances the impact of changes in precipitation.
The risk of landslides is predicted to increase in many parts of Sweden. Towards the end of the century, it is estimated that around 220,000 properties will be situated in areas prone to landslides, representing a value of almost SEK 320 billion. The cost of damage to electrical, water and sewage systems has been estimated at approximately SEK 15 billion. The value of the forest and arable land that is situated in areas where there is a risk of landslides is approximately SEK 14 billion and SEK 1.5 billion respectively.
The risk of snow avalanches will certainly increase in Slovakia.
According to an assessment for Umbria, central Italy, the annual number of landslide events is projected to increase by 30% and 45% for 2040-2069 and 2070-2099, respectively, under a high-end scenario of climate change. This increase is due to an increase of rainfall intensity and hence rainfall amounts in the hours prior to landslides. An increase of collapsing landslides is also projected concerning the Alpine chain heights, due to progressive temperature warming and ice melting.
In the central Apennines of Italy, and in similar areas in the Mediterranean region, the expected increase in rainfall intensity, coupled with a general lack of maintenance of old debris flow controlling structures, may increase the frequency of large debris flow events with catastrophic consequences in areas that are currently considered at low to moderate landslide risk.
In general, for Italy, a general decrease in deep slide phenomena is projected as a consequence of the precipitation decrease, both on an annual and a seasonal scale.
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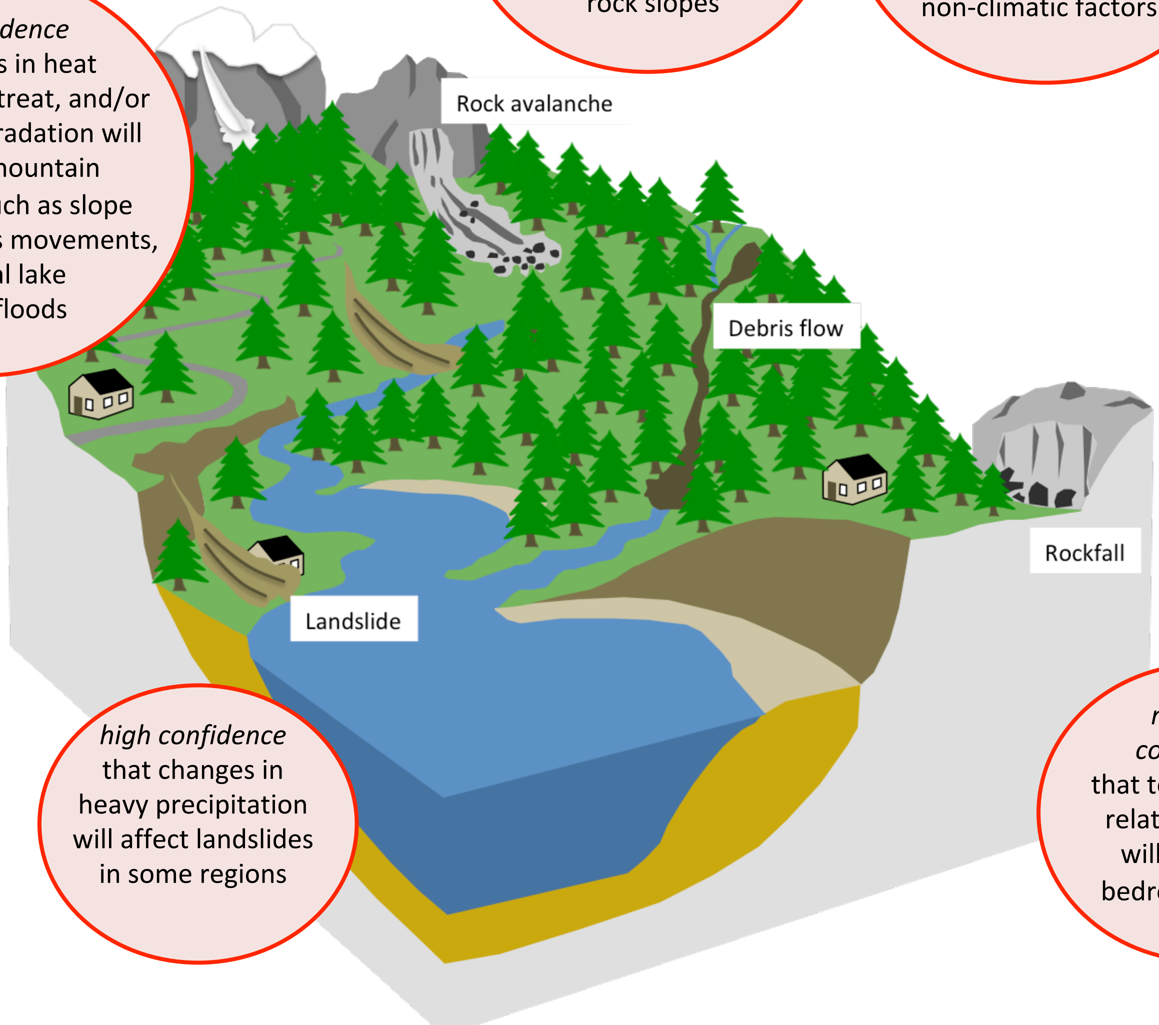
Conclusions IPCC (2012)

medium confidence that continued mountain permafrost degradation and glacier retreat will further decrease the stability of rock slopes

low confidence regarding future locations and timing of large rock avalanches, as these depend on local geological conditions and other non-climatic factors

high confidence that changes in heat waves, glacial retreat, and/or permafrost degradation will affect high mountain phenomena such as slope instabilities, mass movements, and glacial lake outburst floods



high confidence that changes in heavy precipitation will affect landslides in some regions

medium confidence that temperature-related changes will influence bedrock stability

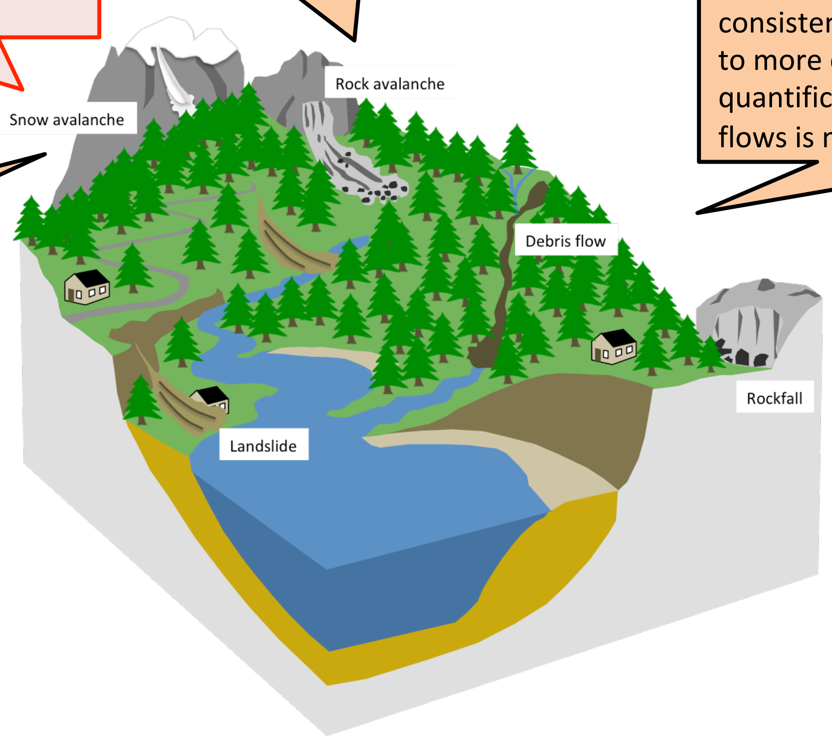
Avalanches, landslides and rockfall

Future situation avalanches and rockfall in general

Higher temperatures might lead to changes in the frequency and intensity of snow and ice avalanches. In general, it is assumed that the possible change would follow the snow cover evolution. A decrease in avalanche hazards is likely at low and medium altitudes.

In high mountain areas, not only small-sized rock falls and ice falls, but also large rock slides and rock avalanches may become more abundant.

For the Alps, the main trigger of debris flows is high intensity, short duration rainfall. Under future climate change, it is likely that increases in extreme rainfall will alter debris flow frequency. Results from climate change impact studies are not consistent, however, varying from less debris flows to more debris flows, or concluding that accurate quantification of changes in the number of debris flows is not possible.



The projected glacier retreat in the 21st century may form new potentially unstable lakes. Probable sites of new lakes have been identified for some alpine glaciers. Rock slope and moraine failures may trigger damaging surge waves and outburst floods from these lakes.

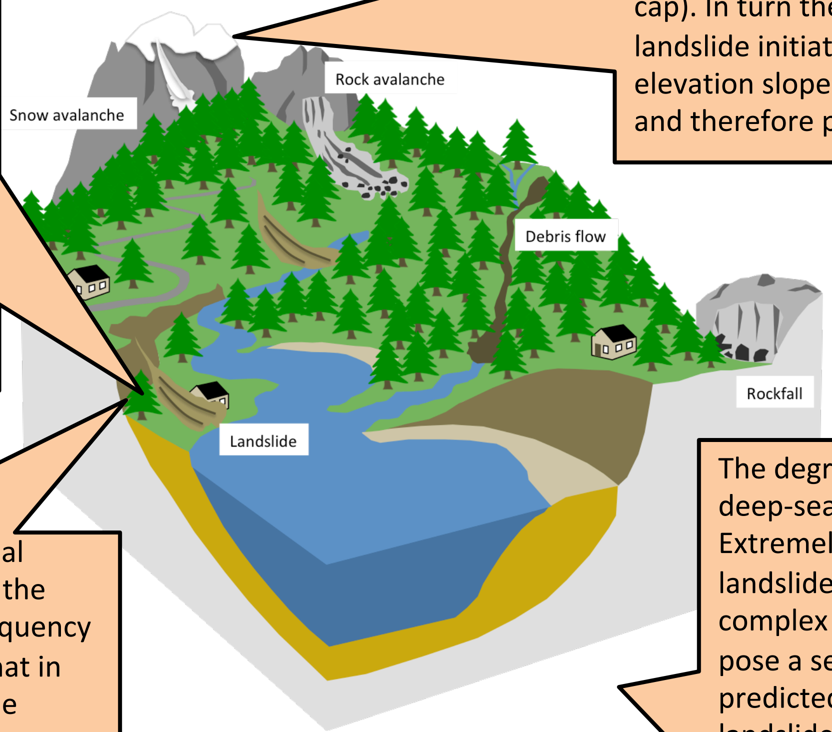
Rising temperatures and melting permafrost will destabilise mountain walls and increase the frequency of rock falls, threatening mountain valleys.

Avalanches, landslides and rockfall

Future situation shallow and deep-seated landslides in general

In Switzerland, the seasonal freezing level (altitude, where surface air temperature is 0°C) has risen by about 200 m per degree of warming from approximately 600 m in the 1960s to approximately 900 m in the 1990s. This level will further rise by about 180 to 680 m until 2050 in case of moderate to strong warming, respectively. The freezing level roughly corresponds to the height of the snow line (the lower limit of the snow cap). In turn the zone of enhanced instability and landslide initiation may shift toward higher-elevation slopes that in many regions are steeper, and therefore predisposed to failure.

It is hard to determine if and where landslide risk, and particularly risk to the population may increase (or decrease) in direct or indirect response to climate change. Whether areas are subject to (an increasing) landslide risk not only depends on temperature and rainfall, but on local geological conditions and non-climatic factors (including land use/cover, agriculture and forest practices) as well.



Given the fact that in some areas global warming is expected to increase both the intensity of rainfall events and the frequency of these events, it is to be expected that in these areas the total number of people exposed to landslide risk will increase. In Europe these areas include the Alps and the Carpathians in Eastern Europe.

The degree of activity and the occurrences of new deep-seated landslides are expected to decrease. Extremely to moderately slow deep-seated landslides (including earthflows, mudflows, complex and compound slides) generally do not pose a serious threat to human life. Hence, their predicted reduced activity will not decrease landslide risk to the population significantly, but it is expected to contribute to reducing landslide impact and the related economic damage.

Avalanches, landslides and rockfall

Adaptation strategies: "soft measures"

Forests provide natural protection against torrential flooding, avalanches and erosion. Around 20% of all forests in Austria has some form or protective function.

- Improve public preparedness and personal responsibility by encouraging participation in emergency planning. To properly inform the public, risk management plans must address both *emergency preparedness* and *early warning systems*.
- Incorporate climate change adaptation into spatial planning, for example by establishing hazard zones, setting appropriate construction standards of buildings and infrastructure in risk areas, and keeping endangered spaces free of development.
- Increase the size of flood plains, floodwater conduits and basins.
- Manage the land and harvest the forests sustainably. In southern Europe the risk of landslides is reduced through revegetation on scree slopes, which enhances cohesion and slope stability coupled with improved hazard mitigation.
- Think of flood risk management in terms of an entire river basin to find solutions that are sustainable.
- When planning for natural hazard risks consider all the environmental risks within a defined area. Natural hazards—floods, droughts, landslides—generate risks that are interrelated and so should be addressed jointly.

Avalanches, landslides and rockfall

Adaptation strategies: "hard measures"

The Swiss town Pontresina is a pioneer in responding to climate change. The town was originally built in two parts: the central part served as a channel for avalanches. But the expansion of the town led to the development of the central part of the city, thus increasing the exposure to avalanche threats. The town sits right below a mass of warming permafrost, increasing the risk of debris flows. Pontresina has taken a proactive approach to protect itself against the effects of climate change. Four years ago a dam was built, estimated to stop 100,000 cubic meters of stone or 250,000 cubic meters of snow.

Existing defensive structures may require modifications to adapt to the new, predicted climate conditions. Defensive structures may have been designed for a specific type of failure and as a result of a change in climate a different type of landslide may be triggered. It is recommend that all structural slope defensive measures be checked to evaluate their efficacy in the new or predicted climate conditions.

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