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IMPACTS OF CLIMATE CHANGE ON DEBRIS FLOW OCCURRENCE IN THE CORDILLERA OF WESTERN CANADA AND THE EUROPEAN ALPS

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ABSTRACT

In spite of a general agreement on present climate trends, actual impacts on terrestrial systems are still very debated. Evidence is mounting that climate change is affecting the stability of slopes, although the full extent, time, and magnitude of the response remain uncertain, in part because climate is only one of the factors contributing to slope instability. Moreover, at the regional and local scale climate change patterns can be very different. Mountain environment seems to respond promptly to climate warming, in part because of the presence of the cryosphere. The present paper contributes to discussions within the scientific community by discussing controls on debris flow occurrence in the Cordillera of western Canada and the European Alps. Several debris flow case studies illustrate how cryosphere degradation can play a significant role in debris flow occurrence in glacial and periglacial margins, both on a short and on a long time span. Processes responsible for debris flow development under a warming climate include rock falls and rockslides induced by glacier debuttressing, thaw of alpine permafrost, sudden draining of glacial lakes, and exposure of unconsolidated, unvegetated, and commonly ice-cored sediments due to glacier recession.

Key words: *debris flow, cryosphere, climate change, Canadian Cordillera, European Alps*

INTRODUCTION

Earth's climate is likely to warm through the remainder of the 21st century (IPCC, 2007), with significant impacts on the amount, intensity, and spatial distribution of precipitation. Evidence is mounting that climate change will affect the stability of slopes, although the full extent, time, and magnitude of the response remain uncertain, in part because climate is only one of the factors contributing to slope instability (Turner & Schuster, 1996). The role played by climate may be difficult to discern, both because of sparse observational data through much of the historic period and because the responses may be delayed or non-linear over time (Viles & Goudie, 2003). Moreover, the effects of climate warming onregional and local precipitation patterns are still uncertain.

In this paper we contribute to discussions within the scientificcommunity of the impacts of climate change on mountainenvironments by discussing controls on debris flow occurrence inthe Cordillera of western Canada and the European Alps. We useseveral debris flow case studies to illustrate these controls.

STUDY AREAS

Our focus is the mountains of western Canada and the European Alps. These two areas share many common features, but also have marked climatic, geologic, and physiographic differences that provide context for a discussion of the processes affecting the world's mountains, the emphasis here being on debris flows.

THE CANADIAN CORDILLERA

The Cordillera of western Canada is part of the great belt of mountains that forms the western margin of the Americas. The population of the region is only 4 million people and most mountain valleys are remote and uninhabited. The Canadian Cordillera is a region of extremely diverse topography, geology, climate, and vegetation. Rugged glacier-clad mountains that receive more than 3000 mm of precipitation per year are within sight of broad semiarid valleys. The general form of the Cordillera resembles that of a great wall flanking Canada's Interior Plains (Bostock, 1948). The high mountains of the Cordillera today support valley glaciers and small ice caps. The total area of glaciers in B.C. and Alberta is about 26,000 km^2 and the number of glaciers is approximately 15,000 (Clague *et alii*, in press). During major Pleistocene glaciations, glaciers covered a great part of the area beneath as much as 2.5 km of ice. These glaciers repeatedly disrupted and rearranged the drainage of the region, sculpted mountains, and left prodigious quantities of sediment in valleys, plateaus, coastal lowlands, and the seafloor (Clague, 1989).

The climate of Canada's western Cordillera is controlled by three main factors: the proximity to the Pacific Ocean, the presence of several mountain ranges trending parallel to the Pacific coastline, ENSO and its linked North Pacific Ocean state, the PDO (Pacific Decadal Oscillation). Permafrost is continuous in northern Yukon Territory and is common, although discontinuous elsewhere in the Yukon (Brown, 1967). In British Columbia, permafrost has a patchy distribution above 1200 m asl in the north and above 2100 m asl in the south (Brown, 1967).

THE EUROPEAN ALPS

The Alps are a complex of mountain ranges that form an arc across western Europe, and are home to about 15 million people The highest peaks are between 4400 and 4800 m asl, and the average elevation is about 2500 m asl. Alpine physiography is strongly controlled by geology, which ranges from folded sedimentary rocks in the low-lying pre-Alps that border the main range everywhere except in northwestern Italy, to the crystalline massifs of the inner Alps, which have the highest peaks. The Alps, like the Canadian Cordillera, were strongly shaped by glaciers during the Pleistocene (Ehlers & Gibbard, 2004). Tongues of ice, some up to 1.6 km thick, filled valleys and flowed out onto the plains north and south of the Alps. Today, glaciers cover about 2000 km^2 of the Alp,s but the glacierized area is rapidly decreasing (Zemp *et alii*, 2007). Permafrost is sporadic at elevations from 2000 up to 3200 m asl, and more continuous at higher elevations, but even at high elevations ground temperatures are close to 0°C (Guglielmin, 2004).

The Alps are affected by four climate systems (Wanner *et alii*, 1997): mild, moist air masses from the Atlantic Ocean to the west; warm Mediterranean air from the south; cold polar air from the north; and continental air from the east. The range strongly influences its own climate, which ranges from maritime to continental, and from temperate at low elevations to alpine. The exact role of large-scale climate systems on Alpine climate and, in particular, recent climatic trends is still uncertain (Agrawala, 2007).

CLIMATIC FACTORS OF DEBRIS FLOW INITIATION

Climate affects the stability of slopes in a variety of ways and on different time scales. Debris flows, in particular, have a close and immediate relationship with climate and weather; most are triggered by heavy or intense rainfall (Sandersen *et alii*, 1996). Even so, topographic and geologic factors, land-use, and vegetation are important in preconditioning slopes to debris flow activity (Tropeano & Turconi, 2003; Wieczorek & Glade, 2005).

Intense rainstorms and rapid melt of snow and ice are the principal triggers of debris flows. Rapid infiltration of water can saturate soil and elevate porewater pressures, reducing the strength of surficial materials and initiating shallow debris avalanches and slides (Iverson, 2000) that evolve into debris flows. In addition, channelized runoff may entrain sediment and transform into debris flows. The critical rainfall threshold for debris flow initiation is generally expressed as a combination of intensity and duration. It can be used by emergency managers as part of warning systems (Wilson, 2005), although studies have documented important regional differences (Jakob & Weatherley, 2003; Guzzetti *et alii*, 2008).

Antecedent rainfall and snow influence whether debris flows are triggered during a rainstorm, earthquake, or volcanic eruption. Its role in debris flow initiation, however, is still debated. In particular, there is little agreement on the duration of significant antecedent rainfall necessary to trigger debris flows. Antecedent soil moisture can vary significantly with slope morphology and aspect, and the geologic and climatic setting of an area (Wieczorek & Glade, 2005). Yet, several studies have illustrated the importance of soil moisture conditions in initiating debris flows at times of earthquakes and volcanic eruptions (Pierson *et alii*, 1990, Martinez *et alii*, 1999).

Climate also affects geomorphic processes that supply sediment to slopes susceptible to debris flow activity, such as solifluction, freeze-thaw activity, and glaciation. Sediment supply can be a limiting factor in debris flow initiation (Bovis & Jakob, 1999).

Warm and dry weather can also predispose slopes to debris flows. Wildfires under such conditions can lead to fires that remove vegetation and produce surface hydrophobic ashy layers in soils (Cannon, 2001).

CLIMATIC TRENDS IN THE STUDY AREAS AND RELATED CHANGES IN THE CRYOSPHERE

Tree-ring research has provided temperature reconstructions for the Cordillera of western North America for the past millennium. The reconstructions show generally cooler climate during the Little Ice Age and pronounced warming late in the 19th century, between the 1920s and 1940s, and after about 1980 (Bradley & Jones, 1993; Jones & Moberg, 2003; Koch *et alii*, 2009). Surface temperatures rose, on average, 0.6° in the 20th century, but high latitudes experienced higher increases (IPCC, 2007). The most significant warming has occurred since the 1990s: most of the warmest years on record in North America have been in this period, including 1998, the warmest year of the 20th century (IPCC, 2007).

Most glaciers in western North America have fluctuated in tandem with climate on a decadal timescale, with large ice losses in the 20th century. Most glaciers have lost more than 25 percent of their mass in the 20th century, and many small glaciers have shrunk by more than 50 percent (Luckman & Kavanagh, 2000; IPCC, 2007). Over the same period, the lower limit of alpine permafrost has rise on average 100-200 m

Precipitation patterns during the 20th century have been more spatially and seasonally variable than temperature. Much of British Columbia, however, experienced an increase in precipitation during the 20th century. Significant trends in northern British Columbia range from +10.2 to +18.6 percent (Egginton, 2005).

Climate also warmed in the European Alps during the 20th century and the early years of the present century, with accelerated warming since the early 1990s (Casty et al., 2005, 2007). Surface temperatures rose 1.2°C in the 20th century (Auer *et alii*, 2007), almost double the global average of 0.74°C (1906-2005; IPCC, 2007). As a consequence, glacier cover in the Alps has decreased about 50% in the past 150 years (Zemp *et alii*, 2007). The rate of ice loss has increased over the past three decades. Warming of permafrost, although spatially variable, is typically 0.5-2°C at the depth of zero annual change (Brown & Romanovsky, 2008).

Precipitation patterns in the Alps have been more variable than temperature, both spatially and seasonally. In the hydrographic basins of the European Alps, well-defined meteorological configurations of several consecutive days duration give rise to extraordinary rainfall events (Nigrelli *et alii*, 2009). Auer *et alii* (2007), however, reported an increase in precipitation north of the Alps of 9 percent during the 20th century and an equivalent decrease south of the Alps, enhancing the polarity in climate across the orogen. Brunetti *et alii* (2004) found that the decrease in precipitation south of the Alps is the result in fewer wet days – precipitation intensity has increased. This finding is consistent with observed increases in extreme precipitation events, for example 1-in-50 year storms (IPCC, 2007)

INITIATION MECHANISMS RELATED TO CLIMATE CHANGE IN THE STUDY AREAS

Debris flow initiation depends on both debris and water availability (Marchi *et alii*, 2002). Climate change influences both debris abundance and the hydrological cycle, and thus can alter the spatial and temporal distribution of debris flows. The effects of climate change are most evident in glacial and periglacial environments, where geomorphic processes are particularly sensitive to temperature changes.

A consequence of climate warming is that debris availability in proglacial and periglacial areas is increasing: glacier retreat has exposed large quantities of glacial sediment and increased instability of formerly glacier-buttressed rock walls and glacial deposits enhanced. Instability has been excacerbated by thaw of alpine permafrost. Large quantities of unconsolidated, unvegetated, and, in some instances ice-cored debris are available for transportation and can be easily mobilized by heavy rainfall, enhanced snow and ice melt, and outburst floods (Fig. 1; Chiarle *et alii*, 2007)

Climate change is also affecting the hydrological cycle in glacial and periglacial areas. The ratio of rainfall to snowfall is increasing and more water is supplied by melting snow and glacier. Unstable, ephemeral ice-dammed lakes are developing due to glacier retreat and downwasting. Sudden draining of these lakes produce catastrophic floods and debris flows (Clague & Evans, 2000). Melt of massive ground ice in glacial and colluvial deposits can destabilize moraine dams and lateral and terminal moraines, producing unexpected floods and debris flows.

The impacts of climate change in the glacial and periglacial environments of the Canadian Cordillera and European Alps are similar, as temperature is the dominant driving process in both orogens. However, glacier retreat in the Italian Alps has been proportionately greater due to the concurrent reduction of precipitation.

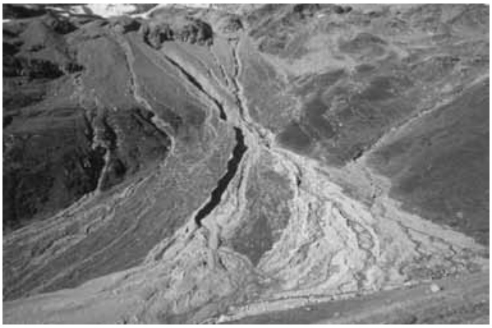

Fig.1 - Heavy rainfalls on 24 July 1996 started a par oxysmal erosion activity on the fore field of the Ormelune Glacier (Aosta Valley, NW Italy). Note the extensive flooding of the distal fan portion and valley bottom

Fig. 2 - Path and deposit of the 2010 Capricorn Creek debris flow. The debris flow travelled down Capricorn Creek (top center) and Meager Creek (mid-center),before coming to a rest in Lillooet River valley (bottom center). (J.J.Clague)

The exact role played by cryosphere degradation in debris flows is poorly known, but recent events from western Canada and Europe, summarized in the following sections show how climate warming contributes to debris flow occurrence.

ROCK SLOPE INSTABILITY

Glaciers steepen valley walls; when glaciers retreat, valleyside slopes are debuttressed and exposed to weathering and gravitational forces. At the same time, melt of snow and ice increases the input of water to slopes, increasing the possibility of landslide and debris flow inception. This ensemble of processes is well illustrated by the case of recent landslides at Mount Meager, in the southern Coast Mountains of British Columbia

On July 29, 1998, a 550,000 m^3 debris slide released from upper Capricorn Creek basin in the Mount Meager Volcanic Complex, triggering a debris flow which ran 6 km down Capricorn Creek (Bovis & Jakob, 2000). The debris slide that triggered the debris flow originated from a thick blanket of poorly consolidated colluvium on the south flank of Mount Meager volcano. The slide was initiated by accelerated snowmelt during a record-breaking heat wave in late July 1998. Approximately 1.2 × 10^6 m^3 of material were delivered to the Meager Creek confluence, creating a landslide dam. A much larger rock-slope failure occurred at the same site on August 6, 2010, again in fair hot weather (Fig. 2). The failed rock rapidly transformed into a large debris flow that traveled down. Capricorn and Meager creeks into the Lillooet River valley.

Large amounts of water were present with the rock mass that failed, likely due to infiltration of snowmelt and precipitation.

EXPOSURE OF GLACIAL SEDIMENT AND CHANGES IN THE HYDROLOGICAL CYCLE

Glacier retreat is exposing large amounts of loose unvegetated sediment that can potentially feed debris flows. As glaciers thin and retreat, they are less able to retard rainfall-induced runoff. Coincidentally, the elevation marking the transition from rain to snow is rising. An exemplary event illustrating the consequences of these processes occurred on September 7, 2008, in the Castelfranco watershed, at Monte Rosa in the western Italian Alps. During a period of only moderate rainfall (39 mm in 22 hrs), a debris flow initiated at an elevation of 3600 m asl, which is unusually high for the Alps. The debris flow continued as a series of pulses several hours after the end of the rainfall. Upon reaching the margin of Belvedere Glacier, the flows continued in tunnels beneath the ice. Avalanched snow on the stagnant terminus of Castelfranco Glacier played a critical role in the initiation and dynamics of the event, temporarily damming the flow (Fig. 3).

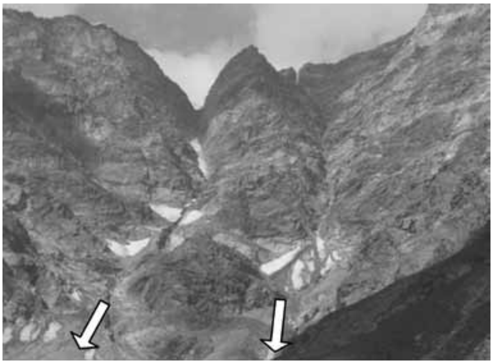

Fig. 3 - Castelfranco catchment (Monte Rosa, Italian Alps). The remnants of the Castelfranco Glacier, along with snow avalanche accumulations, are thought to have played a critical role in the initiation and dynamics of the debris flow started close to the watershed ridge (3600 m a.s.l., see the white stars)

Fig. 4 - Klattasine Creek debris flow. The debris flow was was triggered by the sudden draining of moraine-dammed Klattasine Lake, had a volume of nearly 2 million cubic metres, and temporarily blocked Homathko River. (J.J.Clague)

The deadly debris flow generated by the Kolka-Karmadon rockice avalanche in the Caucasus in 2002 showed the extreme size and travel distance of flows that can result from such combinations of processes (Haeberli *et alii*, 2004).

GLACIAL LAKE OUTBURST FLOODS

Many new glacial lakes are forming in depressions left by glacier retreat or on the surface of downwasting glaciers. Lakes dammed by ice or moraines are susceptible to sudden empting due to failure of their dams. The floods and, in some cases, the debris flows spawned by the escaping waters are a major threat because of the large volumes involved, the long travel distances, and their unpredictability. Klattasine Lake, a moraine-dammed lake in British Columbia, catastrophically drained sometime between June 1971 and September 1973, releasing about 1.7×10^6 m^3 of water (Fig. 4).

The escaping waters trenched the moraine and mobilized large quantities of sediment along the channel and valley margins, and the flood rapidly evolved in a debris flow that travelled 8 km downstream (Clague *et alii*, 1985). Scour of the valley floor by the debris flow locally destabilized adjacent valley slopes, causing secondary slope failures. Two glacial lakes in the European Alps – Roche Melon Glacier lake (French Alps) and the Effimero Lake on Belvedere Glacier (Monte Rosa) – created emergencies when they rapidly expanded due to thermokarst processes. Authorities drained the lakes because of the threat they posed to downvalley villages (Bessans & Macugnaga). An earlier outburst flood from the Locce Lake in 1979 had triggered a debris flood, heightening concerns (Jobard, 2005, Mortara & Tamburini, 2009).

Outbursts of water from cavities within glaciers can be insidious because the water pockets are difficult to detect. An englacial water pocket with a volume of 65,000 m^3 was recently identified with Tête-Rousse Glacier on Mont Blanc. Local authorities, concerned about the threat an outburst posed to several villages in the valley below, decided to drain the water through vertical holes drilled into the glacier. Such a disaster happened in the area in 1892, when a water pocket of about 200,000 m^3 drained, triggering an 800,000 m^3 debris flow. The flow, which devastated the village of Saint Gervais and killed 175 people, is one of the worst glacier-caused disasters in Europe (Vincent *et alii*, 2010).

MELTING OF GROUND ICE

Ground ice and buried dead glacier ice are common in high mountains in western Canada and Europe. Such ice may persist, even though it is no longer in equilibrium with climate, due to the insulating effect of the debris cover and to the low permeability of some glacial deposits. In a warming climate, the ice slowly melts, contributing water to already wet sediments, in some cases leading to debris flows. The flows may be triggered by rainfall, but some occur in fair warm weather, simply due to melting of the ice. Icerich debris and ice lenses have been observed in many debris flow initiation scars (Chiarle *et alii*, 2007), but the exact role played by ground ice is uncertain in most cases. The role played by the melt of ground ice is illustrated by a debris flow on July 29, 2005, in Val di Fosse in the eastern Italian Alps. Melt of a buried ice mass, exposed in a 20-m-long detachment zone at 3000 m asl, triggered her a debris flow (15,000 m^3) that travelled downslope for over 1 hour, cutting off a popular hiking trail (Fig. 5).

Melt of ground ice is expected to significantly decrease the stability of sediments in proglacial and periglacial areas in coming years, although the main effects may be delayed because of the complex interplay of factors and the lack of direct contact of the ice with the atmosphere (Kääb *et alii*, 2007).

CONCLUDING REMARKS

Debris flows, like other natural hazards, represent disequilibria in the natural landscape. Climate change, by altering important factors governing geomorphic evolution, introduces new instability in the Earth system. Mountain environments are being affected by climate change for several reasons: a) geomorphic processes in mountains operate at a high rate because of the high relief; b) processes in high mountains are intimately linked to the cryosphere, which is sensitive to climate change; and c) climate is warming faster in mountains than in midlatitude lowlands. A consequence of these amplified effects is that debris flows are likely to increase in frequency as climate continues to warm.

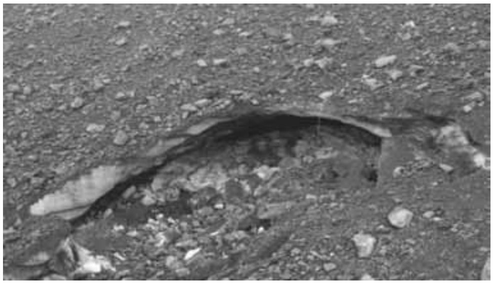

Fig. 5 - Val di Fosse (Eastern Italian Alps). A buried ice mass, exposed in a 20-m long detachment zone at 3000 m a.s.l. was responsible for the trigger of an unexpected debris flow (Photo courtesy of Public Works Service, Bolzano Province)

Yet few statistical studies of debris flow activity have been carried out in recent years in western Canada and the European Alps, and to date no clear trend of increasing activity has emerged in either region. The lack of a clear cause-and-effect outcome may partly be explained by local differences in climate trends, especially for precipitation patterns. Moreover, the factors that predispose slopes to debris flows, and those that trigger debris flows, vary across the landscape.

At present, in our warming world, cryosphere degradation is the dominant driver of instability in high mountains. Debris flows are occurring in response to the greater availability of water and debris caused by glacier melt and permafrost thaw, to slope instability caused glacier debuttressing and permafrost thaw, and to outbursts of water from glacier- and moraine-dammed lakes.

At lower elevations in mountains, changes in seasonal frost activity and snow melt, and rain-on-snow events can change the frequency of debris flows. Changes in total annual rainfall and rainfall intensity can either increase or decrease debris flow occurrence at these lower elevations. Hazard assessment procedures for debris flows in glacial and periglacial environments during a time of rapid climate warming cannot be based entirely on experience gained in ice-free environments. Our study also demonstrates the necessity of integrating observations and data from different areas of the world with a variety of climatic and physiographic settings. Only in this way will it be possible to paint a reliable picture of impacts of climate change on debris flow initiation and development, and to accurately predict other impacts of climate change.

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