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HIGH-MOUNTAIN HAZARDS IN A WARMING WORLD

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IMPACT OF CLIMATE CHANGE ON THE CRYOSPHERE

Most alpine glaciers achieved their maximum size of the past 11,000 years in the 18th and 19th centuries, late during what has been termed the "Little Ice Age." Since then, alpine glaciers have thinned and receded, a response to the warming of the past 100 years. This recent warming has been most pronounced at high latitudes and high elevations. As a consequence, glacier cover in most mountain ranges is one-half to two-thirds of what it was in the mid-19th century. Recent climate warming also impacted alpine and northern permafrost. The lower elevation limit of discontinuous permafrost in most mountain ranges has risen, some discontinuous permafrost has disappeared, and active layers have thickened in summer.

FAILING SLOPES

Slope stability is controlled by ground surface steepness, geology, vegetation. and surface and subsurface ice. Steep slopes in high mountains are being destabilized by deglacierization and permafrost thaw. Debuttressing of steep moraine or rock slopes following glacier retreat or downwasting is accompanied by reorientation of stress fields in the affected slopes. Another important effect is the decrease in the strength of rock/ice mixtures in permafrost slopes when subsurface temperatures approach 0^{o}C. These two processes can occur independently of each other or in combination; in a general sense, they increase the probability of rock and ice avalanches on affected slopes. They are especially important in cases where landslides and avalanches might enter existing or newly forming lakes and generate far-reaching flood waves and debris flows.

Recent glacier retreat may be responsible for some landslides in high mountains. Many marginally stable slopes that were buttressed by glaciers during the Little Ice Age failed after they became deglaciated in the 20th century (Figure 1). This effect is most pronounced in mountain ranges with the greatest contemporary ice cover – the Himalayas, St. Elias Mountains, and Coast Mountains – because these are the areas where ice losses in the 20th century have been largest.

Climate change can affect the stability of slopes in other ways. Temperatures in high mountains normally are below freezing. Temperatures rise rapidly above freezing, however, during warm spells. At these times, meltwater infiltrates fractures in marginally stable rock masses. Later when temperatures fall below 0°C, water within the fractures freezes or the fractures may become sealed by freezing at the surface. In either case, pore water pressures rise, dilating an already weak rock mass.

A related process is thawing of permafrost beneath alpine rock slopes. The lowest elevation of alpine permafrost has risen in most or all mountains in the 20th-century due to climate warming. Thawing has lowered the strength of marginally stable rock, because water in fractures in the rock melts.

Another glacier hazard with possible links to climate is ice avalanches. Heavily crevassed snouts of glaciers that terminate on steep slopes are prone to avalanching, especially during warm weather when large amounts of water flow at the base of the glacier. This water can accelerate glacier flow and locally elevate basal pore pressures. July 2007.

OUTBURST FLOODS AND DEBRIS FLOWS

Many glaciers impound lakes that drain suddenly, causing catastrophic downvalley floods termed jökulhlaups. These floods are far larger than normal nival and rainfall-triggered floods. Water bodies may exist on top of, within, beneath, or at the margins of glaciers. Lakes at the margins of glaciers may contain 100,000,000 m^3 of water or more; the largest of these lakes, and commonly the most prone to draining, are in low-gradient trunk

valleys at the toes of glaciers flowing out of tributary valleys, and in a few fiords at the margins of calving tidewater glaciers. Subglacial lakes develop beneath Vatnajökull, an ice cap in Iceland, during eruptions of Grimsvötn and other active volcanoes. These lakes also drain suddenly to produce large jökulhlaups.
During a time of stable climate, when glaciers neither advance or retreat, glacier-dammed lakes are commonly stable and do not empty catastrophically. The situation is very different, however, during periods of pronounced climate change. During the Little Ice Age, for example, new lakes formed when glaciers advanced across streams and blocked drainage (Figure 2). Most of these lakes drained catastrophically in the 20th century when the ice dams weakened due to glacier thinning and retreat. Sudden draining of these lakes typically happened due to rapid enlargement of subglacial channels that served as conduits for outflowing water. Glacier dams may also fail by collapse following surges that block streams. Many Little Ice Age glacier-dammed lakes no longer exist, because the glaciers that dammed them have wasted so much that they no longer impound water. However, lakes have formed at new sites at glacier margins, typically at higher elevations, and pose new risks to downvalley communities and infrastructure.

New lakes also developed behind Little Ice Age end moraines during the late 19th and 20th century when glaciers retreated from large moraines they built during the Little Ice Age. Many of these moraine dams are unstable and vulnerable to failure because they are steep-sided and consist of loose coarse sediment. Irreversible rapid incision of moraine dams may be caused by a large overtopping displacement wave produced by an ice avalanche or rockfall (Figure 3). Slow melt of dead glacier ice within the moraine and piping (removal of fine sediment from the dam by groundwater) are other failure mechanisms.

Outburst floods from glacier- and moraine-dammed lakes commonly display an exponential increase in discharge, followed by an abrupt decrease to background levels when the water supply is exhausted. Other outbursts display a near-linear increase in discharge as failure progresses. Peak discharges are controlled by lake volume, dam height and width, the material properties of the dam, failure mechanism, and downstream topography and sediment availability. Floods from glacier-dammed lakes tend to have lower peak discharges than those from moraine-dammed lakes of similar size because enlargement of tunnels in ice is a slower process than overtopping and incision of sediment dams.

Outburst floods from glacier- and moraine-dam lakes may transform into debris flows as they travel down steep valleys. Debris flows can only form and be sustained on slopes greater than 10-15 degrees and only where there is an abundant supply of sediment in the valley below the dam. In general, debris flows are more destructive that floods of the same size.

Outburst floods can erode, transport, and deposit huge amounts of sediment over distances of tens of kilometers (Figure 4). They broaden floodplains and destroy pre-flood channels. The changes can persist for decades, although rivers commonly quickly reestablish their pre-flood grades by incising the flood deposits.
There is a link between climate and the stability of moraine and glacier dams. As mentioned above, most moraine-dammed lakes formed in the last century as glaciers retreated from bulky end moraines constructed during the Little Ice Age. The newly-formed lakes soon began to breach them dams. With continued warming and glacier retreat, the number of moraine-dammed lakes vulnerable to failure will decrease and the threat they pose will diminish. The relation is different for glacier-dammed lakes. Typically, a glacier-dammed lake passes through a period of cyclic or sporadic outburst activity, lasting from years to many decades. The cycle of outburst of floods from the lake ends when the glacier dam weakens to the point that it can no longer trap water behind it. The cycle may recur, however, if the glacier readvances.

Figure 1. A rock avalanche triggered by glacier debuttressing in the southern Alps of New Zealand.

Figure 2. Tide Lake, a glacier- and moraine-dammed lake in the northern Coast Mountains of British Columbia. The lake was dammed when Frank Mackie Glacier advanced across Bowser River and blocked its flow sometime in the 18th or 19 century. This photograph was taken in 1905, when the lake was dammed by a moraine that the glacier had built at its terminus. The lake drained catastrophically through the moraine about 1930. (Canada Department of Energy, Mines and Resources, National Air Photo Library, photograph IBC665.)

Figure 3. Queen Bess Lake in the British Columbia Coast Mountains. This photograph was several years after 6 million m^3 of water flowed out of the lake in 1997. During unusually warm weather in July, 2-3 million m^3 of ice collapsed from the toe of Diadem Glacier (arrow) and plunged into the lake, producing a displacement wave that overtopped and incised the moraine (note moraine breach at 'o'). The upper limit of the displacement wave on the proximal flank of the moraine is delineated by the change in tone from white to pale gray.

Figure 4. Path of a large debris flow triggered by the sudden emptying of moraine-dammed Klattasine Lake in the southern Coast Mountains of British Columbia in the early 1970s. The escaping lake waters entrained several million cubic metres of sediment along its 8-km path.