The effect of Climate Change on Geomorphic Processes and Landslide Occurrences in Himalaya

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Introduction

Climate change has a profound effect on slope stability and landslide as well other mass wasting in high relief regions of the world. The most obvious mass wasting is related to significant glacier ice loss from mountainous areas of the world during the last 100-150 years. The natural processes which pose hazards to people and development in these areas have accelerated as a result of this recent deglaciation. These include glacier avalanches, landslides and slope instability caused by glacier debuttressing, and outburst floods from moraine- and glacier-dammed lakes. In addition, changes in sediment and water supply induced by climatic warming and glacier retreat have altered channel and floodplain patterns of rivers draining high mountain ranges (Evans and Clague, 1994). If climate change proceeds as forecast in mountainous terrain with glaciers, then one of the most apparent results will be a rise in the timberline that will result in a decrease in the extent of the alpine zone, reduced snow and increased rain at elevations close to the present snowline, and increased snowfall on higher and colder mountains. Melting of permafrost and more intense rainfall may initiate or increase the frequency of landslides and debris flows in some areas. Increased sediment input to glacier-fed rivers may lead to increased suspended sediments, channel instability, erosion, and flooding. The hazard zones related to most of these fluvial processes will extend a long way beyond the limits of the alpine zone (Ryder, 1998).

South Asia on its north is bounded by gigantic Himalaya, the highest mountain range and most populated mountain system in the world with an area of 4.3 million sq km (approx.), with largest bodies of ice outside polar caps covering an area of 3735 sq km with eternal ice and snow equivalent of 3250 cubic km fresh water and is therefore very sensitive to climate change. Many of the Himalayan glaciers covering an area of 3 million hectors (17 % of global mountain area) are retreating at an alarming rate ranging from few meters to as high as 75 meters per year. Two well-recognized physical consequences of climate change i.e. increasing global average temperature and extremes in the hydrological cycle have been observed in many parts of Himalaya. In recent times, the Himalaya is confronted with problems of population growth, persistent poverty, natural resource degradation, stress on ecosystem services, climate change, melting glaciers and increasing disaster risks due to frequent and increasing natural hazards such as landslides, flash floods, glacial lake outburst floods (GLOF's) and soil erosion.

Further the surface processes including landslides in Himalaya are greatly influenced by tectonics, that have formed and even influencing present mountain building process as evidenced by active tectonics and GPS observations. Physical interactions between tectonics, surface erosion processes, and climate are manifold and many intricate relationships could be thought of between the tectonic growth of topography, erosional destruction of topography, and climatic influence on erosion rates that have direct bearing on mass wasting phenomena including landslides (Molnar and England, 1990; Willett, et al., 2006; Figure 1).

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Coupling of Climate, Tectonics and Surface Process

Tectonic processes elevate regions of Earth's surface primarily through the isostatic response to crustal thickening. Tectonics also increases relief through faulting and folding. Increased elevation relative to regional base level increases river channel gradients and thus increases rates of erosion by fluvial incision and transport. In addition, topography also tends to increase orographically localized precipitation. This in turn gives rise to increased river discharge and incision. As river channels try to establish equilibrium with local base level, enhanced channel incision leads to increased hill slope failure and sediment supply to channels. Another link between tectonics and erosion is due to the increase in cumulative erosion and sediment yield that occurs as a result of increase in tectonic region or the net basin area, for example, by accretion of new crustal material. As the domain affected by deformation grows, a larger area becomes subjected to high erosion rates and total sediment yield also increases many fold.

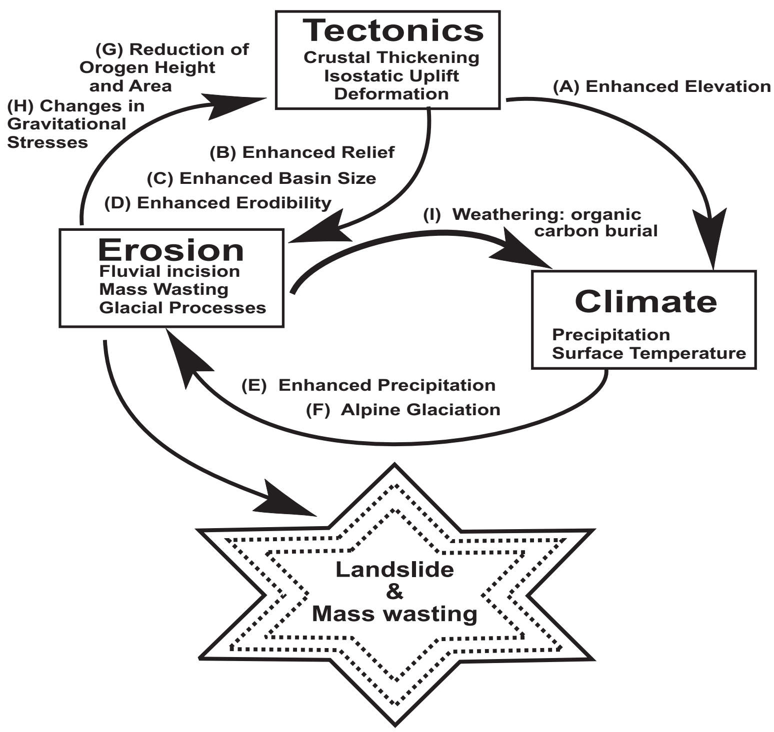

Figure 1. Coupling of climate, tectonics, erosion and landslides (Adopted from Willett et al., 2006)

Apart from climate links on surface uplift and erosion rates through orographic forcing of precipitation, mechanisms also exist for erosion to affect climate on a global scale, through influences on the carbon cycle. Weathering of Mg and Ca silicate rocks provides the essential buffer that balances the introduction of CO2 into the atmosphere and the sequestration of CO2 in carbonate rocks. Erosional refreshing of exposed rock surfaces ensures that chemical weathering can take place. Erosion also promotes drawdown of CO2 by harvesting of life biomass and burial of this material in sedimentary basins, thereby reducing the amount of actively cycling carbon. Together, these two erosion-driven mechanisms are responsible for countering the outgassing of primary CO2 and stabilizing Earth's climate in a narrow range of conditions suitable for the evolution of life.

In mountainous area, much emphasis has been placed on fluvial bedrock incision (Howard et al., 1994; Whipple and Tucker, 1999; Sklar and Dietrich, 2001; Hartshorn et al., 2002). This process is thought to be crucial to landscape evolution because it sets the local base level for hill slope processes, thereby controlling hill slope erosion and occurrences of landslides. Bedrock landsliding has itself gained considerable attention in recent years, as it has become clear that this is the principal hill slope process in tectonically active mountain landscapes (Burbank et al., 1996; Hovius et al., 1997). It is important to note that deformation at the mountain front is very sensitive to small changes in stress that may change by mass redistribution either by erosion or sediment deposition. As a consequence of erosion driven deformation, internal kinematics and stress pattern may change. The change in stress pattern may have an influence on seismic activity in the region. It is interesting to note that epicentres of recent earthquakes of Uttarkashi (1991), Chamoli (1999), Kashmir (2005) and Sichuan (2008) lie very close to prominent river valleys marked by high incision and in close proximity of major faults. It shows coupling of erosion with crustal deformation and rock uplift, which, in turn, leads to landslides and affects erosion rates.

Climate Change and Landslides

Geomorphological processes in response to climate changes, such as warming and increased precipitation, could be catastrophic. A landslide that claimed 60 lives in Yemen was blamed on mountain boulders shifting due to changes in temperature (http://update.unu.edu/issue40_10.htm). Potential effect of global climate change on reactivation of landslides is examined through predicted changes in rainfall pattern on the active landslide at Mam Tor, Derbyshire, UK. For the predicted changes in precipitation, it is shown that the instability threshold could decrease from 4 to 3.5 years by the 2080s for the medium-high climate change scenario (Dixon and Brook, 2007). Clague (2004) presented several examples highlighting small landslides and their relation to short-term climate changes. Similalrly, Perret (2004) described shallow landslides, their link to pore water pressure, and the associated scale of danger. He presented the Leamy Creek landslide (in Canada) suite of five landslides, which occurred simultaneously, most likely triggered by a rapid temperature increase leading to massive snowmelt.

The evidences of climate change in different parts of Himalaya have been reported, although such examples are scanty due to lack of instrumental data. One of the manifestations is increase in rainfall in alpine to sub-alpine zone leading to flooding and landslides as noticed in 2007 in Alkananda valley (a tributary of Ganges) in Uttarakhand (India). Near Mana village, Badrinath, one age old iron bridge was swept away due to flooding in Alkananda (Figure 2).

Local population has reported increase in rainfall compared to snow fall in recent years and as a result, in 2007 potato crop was badly damaged in Mana and Gastoli region in the upper reaches of Alkananda cachment. Increase in sediment yield in various rivers in Himalaya can be attributed to soil erosion and landslides in upper reach due to increase in rainfall. Some of the power projects in Sutlej and Alkananda valley could not operate in peak discharge period due to high silt content in waters of Himalayan river. In areas close to "Valley of flowers", near Hemkund Sahib and upper reaches, evidences of woody plants have been observed by researchers of HNB Garhwal University, Srinagar, Uttarakhand (personal communication from Dr. M.P.S. Bisht) in places where only grassland used to exist few years back. Therefore, the evidence of landslides, floods, high rate of erosion, higher concentration of suspended particles in river water, and change in phenology as well as plant species indicate towards changing environment in Himalayan region. Similar evidences have also been reported from Nepal Himalaya (www.kmtnc.org.np) such as:

- less cold and frosty winters;
- less snowfall in winter;
- increased rain and snowfall after winter and unusually intense summer rainfall;
- increased frequency of avalanches, flash floods, windstorms and hailstorms; and
- rise in the altitude of the tree line.

Increasing rainfall intensities and frequencies attributed to climate change, coupled with population growth can drastically increase landslide-associated casualties, especially in countries of Hindu-Kush Himalayan region, where pressure on land resources often lead to slope cultivations which are very much prone to landslide disasters. The change in the land-use often leads to over saturation of sub-soil either due to irrigation in agriculture areas or waste water disposal in new human settlements. It has been observed that new urban centres in hilly areas or increase in population further aggravate the situation by adding more water to the already vulnerable pore water condition. The subtle change in the hydrological regime can disturb the equilibrium on hill slope and finally it results in slow creeping and subsidences leading to large landslides. One of the prominent sub-urban centre in Uttarakhand, Joshimath is experiencing numerous such land subsidence and massive landslides (Figure 3). As landslides are retrogressive in space and transgressive in time, it is imperative that such early signs are taken up aptly at the initial stage for timely remedial measures.

The subtle difference of climate and tectonics often shows its effect on smaller landslides and drainage basins as observed in many parts of world. For example, the talus and debris cone that is produced as result of glacier action often remain as unconsolidated mass at a relatively steeper angle of repose. However, with minor change in the hydrological regime i.e. with change towards more wet condition, the water action becomes more prevalent and as a result the unconsolidated talus and debris cone becomes unstable and fails in storm condition. Secondly, various types of moraine material deposited along the earlier glacial path as unconsolidated deposits when drained by excess flow due to heavy precipitation develop bank erosion and failures. Such failures have been observed in downstream of Raphstreng lake in Bhutan Himalaya, wherein, due to high discharge of the melt water and high gradients, streams erode the loose morainic sediments with rapid pace and cause unstable valley slopes which give rise to active slides (Joshi, 2001). Such failures generally start with small scars during a storm event and after successive years develop into large landslides of considerable thickness depending on the bedrock depth, length of the slope and dimension of the under cutting or toe removal. The important point is that they start with small debris failures (Figure 4); therefore, it is important to map and monitor such signatures of changing slope condition in response to changing hydrological regime as a manifestation of climate change. As a surrogate measure, as has been carried out by researchers in Nepal Himalaya, the stream discharge and sediment load can also be taken as a major of mass wasting in inaccessible terrain.

Although it is a foregone conclusion that climate change has influenced local weather, surface processes and environment to a great extent in Himalaya, its influence spatially varies and in order to establish the direct correlation between different weather parameters and their effect on surface process, it is imperative that weather data is collected at critical places to appraise this interlinking in a more plausible manner. In one such attempt, Indian Institute of Remote Sensing has installed several automated weather stations (AWS) at different elevations along the Alkananda valley to establish the minimum rainfall threshold for initiation of landslides and decipher on spatial variation of precipitation in different geological conditions (Figure 5).

Conclusion

The Himalayan ecosystems are complex, fragile, and unique in geomorphology and react to climate change in a manner different from other mountain system due to the fact that Himalayan orogeny is even active today and tectonics play an important role in earth surface processes and landform development. Therefore, coupling and decoupling of climate and tectonics plays an important role in deciphering the influence and interaction of each component in slope stability and mass wasting in the region. This fact is more pronounced across vast stretches of Himalaya evidenced by numerous occurrences of landslides and high sediment yield. Catastrophic geomorphic processes in Himalaya are heavily influenced by climatic factors. As a result, the occurrence of these processes, which include landslides and outburst floods, is very sensitive to climate change. In Himalayas, the analysis of historical data and a limited number of cases, suggest that under conditions of possible increased precipitation in future, the frequency of debris flows and landslides will increase. Therefore, any sustainable development planning in the region must address the adaptation issues related to climatic effects in terms of landslides, flash floods, GLOF, glacial retreat and erosion.