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# CLIMATE CHANGE AND GLACIAL RETREAT IN THE HIMALAYA: IMPLICATIONS FOR SOIL AND PLANT DEVELOPMENT

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## ABSTRACT

While there is abundant literature on Himalayan glaciations and glaciers, including glacier retreat, there is limited information on soil development and plant succession in deglaciated Himalayan terrain. This paper reviews current knowledge on soil development and plant succession in deglaciated environments around the world. Implications of plant succession in deglaciated environments, particularly as Himalayan glaciers shrink due to climate change, are discussed. Understanding the effects of climate change on Himalayan soil and vegetation dynamics is crucial for assessing impacts on mountain livelihoods, as well as for implementing effective conservation strategies.

**Keywords**: climate change, deglaciation, Himalaya, plant succession, soil development.

## INTRODUCTION

Glaciers are sensitive and 'high-confident' indicators of climate change [1, 2]. They respond to changes in temperature and snowfall: glacial length change indicates an indirect and delayed response to climate change, while glacier mass balance indicates a direct and un-delayed response to the climate [3]. In the Himalaya, glaciers have been generally retreating since 1850 AD at the end of the Little Ice Age [4]. This has corresponded with an increase in air temperature [5]. In Nepal, between 1975 and 2005, mean annual temperature increased at a rate of 0.04ºC/year with a higher rate of increase at high altitudes [6].

When glaciers retreat, they expose new sites for soil development and plant succession [7]. A retreating glacier presents a temporal sequence (chronosequence) in ecosystem development: the further the distance from the retreating glacier, the older the site and hence the longer the period for plant succession to occur [8]. Thus, retreating glaciers in the Himalayas present new sites for soil development and plant succession to occur. In turn, this is likely to affect conservation ecology, as well as livelihoods of local people.

## HIMALAYA: A HISTORY OF GLACIATION

The Himalayas are the high ranges that stretch 2,400 km between Nanga Parbat (elevation 8,126m) and Namcha Barwa (elevation 7,755m) as its western and eastern boundaries, respectively, with a north-south extent of 180km [9]. According to the geotectonic model of mountain formation, the Himalaya was formed as a result of the collision of India with Eurasia 15-20 million years ago [10]. The actual process occurred over a series of events that formed several overthrusts and faults. The Nepal Himalaya has been inventoried under various classifications (Table 1).

Table 1. Classification of the Nepal Himalaya.

| **Geographic Component** | **Physical Feature** | **Native Term**[11] | **Natural Regions**[10] | **Ecological Units**[12] | **Physiographic Regions**[13] |
|---|---|---|---|---|---|
| Mountain | Trans-Himalaya | *Bhot* | Inner Himalaya | High Himalaya | High Himal |
| | Himalaya | *Himal* | Himalayas | | |
| Hill | High Spurs | *Lekh* | Midlands | Transition Zone | High Mountain |
| | Hills | *Pahar* | | Middle Mountain | Middle Mountain |
| | High Range | *Mahabharat Lekh* | Mahabharat Lekh | | |
| Inner Tarai | Longitudinal Valley | *Bhitri Madhes* | Siwaliks | Siwaliks | Siwaliks |
| | Low Range | *Chure Danda* | | | |
| Tarai | Plain | *Tarai* | Terai | Terai | Terai |

Glacial advances, i.e. glaciations, occur in cycles with interglacial periods when glacial ice retreats due to global warming; the interglacial typically occurs for about 10,000 years before the next glaciation [14]. These cycles recur at approximately 100,000 years due to changes in solar radiation reaching the earth's surface resulting from changes in the earth's rotation, tilt and orbit around the sun [15 in 16]. There have been at least 17 major glaciations in the last 1.6 million years, with the most recent – the Last Glacial Maximum (LGM) – reaching its peak 20,000 to 18,000 years ago and ending about 10,000 years ago [14]. Glacial cycles are interspersed with short periods of glacial advance and retreat caused by localized cooling and warming. During the last interglacial, there was a period of cooling commonly referred to as the Little Ice Age (LIA) which occurred approximately from 1650 to 1850 AD [17].

The Himalayas have experienced numerous glaciations during the late Quaternary (Table 2) [18, 19]. These glaciations have occurred during different time periods, and as many as eight glacial advances in the Hunza Valley in Pakistan have been identified. The LGM in the Himalayas generally occurred between approximately 25 and 21ka but also occurred as recently as 16-10ka in Zanskar. During the LGM, the glaciers advanced as much as 40km (in the Garhwal Himalaya) from their present extent and could be found occurring at elevations as low as 1,200m (in the Nanga Parbat Himalaya) (Table 2).

Table 2. Glaciations in the Himalaya [18, 19].

| *Direction* | West → | | | | | East |
|---|---|---|---|---|---|---|
| *Location within Himalaya* | Middle Indus Valley & Nanga Parbat Himalaya | Hunza Valley | Zanskar | Garhwal Himalaya | Khumbu Himal | Kangchenjunga Himal |
| *Glacial Stages** | 1. ~23-21ka<br>2. ~15ka | 1. Shanoz<br>2. Yunz (~139ka)<br>3. Borit Jheel (~52-42ka)<br>4. Ghulkin I (~25-21ka)<br>5. Ghulkin II (~18-15ka)<br>6. Batura (~11-9ka)<br>7. Pasu I<br>8. Pasu II | 1. Chandra<br>2. Batal (~78-40ka)<br>3. Kulti (~16-10ka) | 1. Bhagirathi (~63ka)<br>2. Shivling (~5ka)<br>3. Bhujbas (~300-200 yr BP) | 1. Thyangboche<br>2. Pheriche (~25-18ka)<br>3. Thuklha<br>4. Lobuche I-III (~2-1ka) | 1. ~23-22ka<br>2. ~9ka<br>3. ~6ka |
| *LGM (ka)* | ~23-21 | ~25-21 | ~16-10 | ~63 | ~25-18 | ~23-22 |
| *LGM ice limit (km) [relative to present ice margins]* | ~12<br>and >40 | 6 | 10 | 40 | 10 | ~ 10-15 |
| *Lowest elevation (m) that glacier advanced* | 1,270<br>1,200 | 2,450 | 4,140 | 3,000 | 3,500 | 2,730 |

* Glacial stages are not formally named for Middle Indus Valley and Nanga Parbat Himalaya, and Kangchenjunga Himal.
ka = kilo annum
yr BP = years Before Present
LGM = Last Glacial Maximum

## SHRINKING HIMALAYAN GLACIERS

Glaciers in the Himalaya cover an area of 33,050 sq.km. [2]. This represents 28.8% of glaciers in Central Asia and 4.8% of glaciers and ice-caps in the world (Table 3). Present glacier terminus in the Himalaya occurs at approximately 3,500m to 4,500m [1]. Most glaciers in the Himalaya have retreated since the Little Ice Age [4, 2], while many glaciers less than 0.2 sq.km. have already disappeared [20]. The rate of glacier retreat in the Himalaya varies from 10m to 60m per year [20].

Table 3. Summary of world-wide glaciers and ice-caps [2].

| **Region** | **LIA Maximum** | **Current Area** (sq.km.) |
|---|---|---|
| New Guinea | mid-1800s | 3 |
| Africa | late 1800s | 6 |
| New Zealand | end of 1700s | 1,160 |
| Scandinavia | mid-1700s | 2,940 |
| Central Europe | mid-1800s | 3,785 |
| South America | late 1600s to early 1800s | 25,500 |
| Northern Asia | 1550-1850 | 59,600 |
| Antarctica | na | 77,000 |
| Central Asia* | 1600 to mid-1800s | 114,800 |
| North America | early 1700s to late 1800s | 124,000 |
| Arctic Islands | mid-1700s to end 1800s | 275,500 |
| | **Total area** | **684,294** |

* Includes Himalaya, Karakoram, Tien Shan, Kunlun Shan and Pamir mountain ranges.

## SOIL AND PLANT DEVELOPMENT IN DEGLACIATED ENVIRONMENTS

### Pedogenesis

The history of glacial advance and retreat has been well documented in North America (e.g. Glacier Bay in Alaska, USA and Athabasca Glacier in Alberta, Canada), Scandinavia (e.g. Storbreen Glacier in Norway), and the European Alps (e.g. Grand Glacier d'Aletsch in the Swiss Alps) [8]. Moreover, the process of soil development (i.e. pedogenesis) and subsequent plant succession in deglaciated environments has also been well researched in these areas.

Retreating glaciers expose new sites for soil development through processes of chemical weathering, as well as vegetation and microbial colonization [7]. The pedogenic process in recently deglaciated terrain (generally known as glacier forelands) is a function of various variables including temperature and moisture regimes [21], time since exposure and topography [22].

Pedogenesis affects various soil physical properties including bulk density, texture, and soil depth. In Glacier Bay, Alaska, bulk density decreased in older deglaciated soils and was associated with higher soil organic matter content [23]. Changes in soil texture occur as a result of pervection, and cryogenic and aeolian processes [8]. While recently deglaciated soils in Glacier Bay, Alaska, had higher fractions of sand, older soils had relatively higher fractions of clay and silt [23]. Deeper soil profiles with varied soil horizons were also found in older soils [24].

Soil organic matter is an important component of the soil system. It influences several pedogenic processes including weathering of rocks and minerals, catalyzing reactions to synthesize secondary minerals [25], contributing to flocculation and transport of clay minerals that result in the genesis of argillic horizons [26], and facilitating the podzolization process by chelating with Fe and Al in the soil to form soluble organo-metal complexes that migrate through soil horizons [27, 28]. Soil organic matter also performs numerous functions that determine soil productivity: soil aggregation is promoted by organic matter; decomposition of soil organic matter releases plant nutrients; functional groups in organic acids contribute significantly to soil cation exchange capacity and hence affects nutrient availability; and it enhances the availability of phosphorus in acidic or basic soils by chelating with iron and aluminum in acidic soils or with calcium in basic soils [29].

Soil organic matter in glacier forelands has been measured extensively as either organic carbon, loss-on-ignition, or both [8]. In the Swiss Alps, precipitation determined the organic carbon content in deglaciated soils: organic carbon content increased by six times at the wetter site and by 16 times at the drier site from the youngest to the oldest stratum since glacial retreat [30]. Organic matter concentrations in deglaciated soils have also been correlated with site productivity [31].

**Plant Succession**

A retreating glacier presents a chronosequence for plant succession [8]. Plant succession following deglaciation has been well-documented in Glacier Bay, Alaska-USA starting with the initial work of Cooper [32, 33, 34, 35, 36]. Following glacial retreat, three major vegetation types were recorded at Glacier Bay: pioneer community, willow-alder thicket, and spruce forest. These vegetation changes were linked to soil development which thereby provided the mechanism for plant succession: Sitka alder (*Alnus crispa*) resulted in soil acidification and nitrogen accumulation which then allowed the Sitka spruce (*Picea sitchensis*) to invade.

Plant distribution in deglaciated soils is affected by the availability of nutrients, temperature, topography, and the length of growing season [37]. In a newly deglaciated moraine in East Brøgger Glacier in the high Arctic, scattered patches of bryophytes and vascular plants were found [38], while well developed patterns of vascular plants and some bryophytes were found in an older deglaciated area [39]. In the Alexandra Fiord region of Canada, plant succession included four main stages of dominance in at least 44 years: (1) mosses → (2) graminoid-ford → (3) deciduous shrub-moss → (4) evergreen dwarf-shrub-moss [40].

**Soil Fauna**

An important modification following plant colonization of deglaciated soils is the resulting plant-faunal interactions in the soil. The development of soil microbial communities is inter-related with rhizo-deposits provided by plant roots to the soil, as well as from nutrient leaching and organic matter inputs from aboveground plant litterfall [41]. Soil fauna, particularly soil microbes, play an important role in soil development by accelerating ecosystem development and promoting decomposition and cycling of nutrients, and by facilitating mineral weathering and redox chemistry [42, 43].

## IMPLICATIONS FOR THE HIMALAYA

Research on Himalayan glaciers has largely been limited to glacier retreat and/or mass balance and subsequent impacts on river discharge [44], as well as the potential for glacier lakes outburst floods (GLOFs) [20, 45]. In the Nepal Himalaya, glacier retreat has been well documented in various regions from east to west: Kangchenjunga [46], Khumbu [47, 48, 49, 50, 51], Shorong Himal [51, 52, 53, 54], Langtang [55, 56], and Dhaulagiri [57, 58, 59]. Moreover, a comprehensive report inventorying glaciers, glacial lakes and GLOFs in the Himalaya has been developed by ICIMOD/UNEP [45]. Additional studies on select glacial lakes and GLOFs have also been conducted in the Khumbu region [20, 60, 61]. However, soil and plant research, particularly of glacial forelands, in the Himalaya is sparse.

The Himalaya are both biologically, as well as socio-economically significant. With 21 vegetation types [62] and 60 ecoregion types [63], the Himalaya is home to an estimated 25,000 species of flora (equivalent to 10% of the world's total), 75,000 species of insects (10% of world's total), and 1,200 species of birds (13% of world's total) [63, 64]. Known numbers of floral and faunal diversity found in the Himalaya are presented in Table 4. The Himalaya also has high endemism: in the Chinese Himalaya, there are 40 angiosperm genera and 28 fish genera endemic to Yunnan [65]; at least 3,165 species of flowering plants, 27 species of birds and 17 species of mammals are reportedly endemic to the Indian Himalaya [66]; at least 500 plant species are endemic to Nepal and 750 to Bhutan [67].

Table 4. Floral and faunal diversity in the Himalaya [64].

| Country | Area | | Flowering Plants & Ferns | Birds | Mammals | Reptiles | Amphibians | Fish |
|---|---|---|---|---|---|---|---|---|
| | sq.km. | % | | | | | | |
| Bhutan | 46,500 | 0.3 | 5,000 | 800 | 160 | - | - | 197 |
| China | 9,596,960 | 70.3 | 29,700 | 572 | 499 | 1,186 | 380 | 279 |
| India | 2,387,590 | 17.5 | 17,000 | 1,200 | 350 | 453 | 182 | - |
| Myanmar | 676,577 | 5.0 | 7,766 | 967 | 300 | 241 | 75 | - |
| Nepal | 147,181 | 1.1 | 5,568 | 844 | 181 | 100 | 43 | 185 |

The Himalaya is the most populated mountain chain in the world and is home to nearly 124 million people [68]. They implement various livelihood strategies including subsistence agriculture, transhumance and pastoralism. Transhumance is a system of grazing livestock away from home and is generally followed by communities living in extreme environments that are too cold and dry to support agriculture [19].

High mountain regions are extremely sensitive to climate change [69, 70, 71]. It has been estimated that temperatures in the Himalaya will rise by 0.04ºC–0.09ºC/year [63]. In response to the rising temperatures, it is likely that ecological zones, species ranges, and ecotones will also shift upwards [63]. Plants found in high mountain regions are generally long-lived species, but long-term changes in the climate are likely to affect their distribution and survival [71]. Thus, the formation of glacier forelands, along with increase in temperatures, present new scenarios for soil development and plant succession in the Himalaya. In turn, this is likely to affect the livelihoods of mountain people who are highly dependent on natural resources for food, medicine, fiber, timber, fodder and fuel among others [63].

## CONCLUSIONS

While the effects of climate change on glacial retreat and its associated hazards (e.g. GLOFs) have been well assessed, there is paucity of information on its effects on Himalayan vegetation, as well as plant succession on recently deglaciated soils. Mountain communities are highly dependent on natural resources for the ecosystem services that they perform: provisioning services (genetic resources, food, fiber, fresh water, etc.); regulating services (regulation of climate, water and human diseases); supporting services (productivity, soil fertility and nutrient cycling); and cultural services (spiritual enrichment, recreation, aesthetics, etc.) (ICIMOD 2009). Therefore, understanding the effects of climate change on Himalayan soil and vegetation dynamics is important for assessing impacts on mountain livelihoods, as well as for implementing effective conservation strategies.

## REFERENCES

[1] Armstrong R L, *The Glaciers of the Hindu Kush-Himalayan Region: A Summary of the Science Regarding Glacier Melt/Retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan Mountain Ranges*, ICIMOD, Kathmandu (2010).

[2] Zemp M, Roer I, Kääb A, Hoelzle M, Paul F & Haeberli W, *Global Glacier Changes: Facts and Figures*, UNEP, Geneva and World Glacier Monitoring Service (WGMS), Zurich (2008).

[3] Haeberli W & Hoelzle M, Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps, *Annals of glaciology*, 21 (1995) 206.

[4] Mayewski P A & Jeschke P A, Himalayan and trans-himalayan glacier fluctuations since AD 1812, *Arctic and alpine research*, 11(1979) 267.

[5] Sharma E, Chettri N, Tse-ring K, Shrestha A B, Fang J, Mool P & Eriksson M, *Climate Change Impacts and Vulnerability in the Eastern Himalayas*, ICIMOD, Kathmandu (2009).

[6] Baidya S K, Regmi R K & Shrestha M L, *Climate Profile and Observed Climate Change and Climate Variability in Nepal*, Department of Hydrology and Meteorology, Kathmandu (2007).

[7] Haugland J E, Short-term periglacial processes, vegetation succession, and soil development within sorted patterned ground: Jotunheimen, Norway, *Arctic, Antarctic, and alpine research*, 38 (2006) 82.

[8] Matthews J A, *The Ecology of Recently-Deglaciated Terrain*, Cambridge University Press (1992).

[9] Gurung H, *Mountain Reflections: Pattern and Development*, Mandala Publications, Kathmandu, Nepal (2004).

[10] Hagen T, *Nepal: Kingdom in the Himalaya*, Berne: Kummerly & Frey (1961).

[11] Gurung H, Landscape pattern of Nepal, *Himalayan Review* IV (1971) 1.

[12] Nelson D, Laban P, Shrestha B D & Kandel G P, *A Reconnaissance Inventory of the Major Ecological Land Units and their Watershed Condition in Nepal*, Department of Soil Conservation, FAO/UNDP, Kathmandu, Nepal (1980).

[13] Kenting Earth Sciences, *Land Resource Mapping Project*, Kenting Earth Science Limited, Canada (1986).

[14] Goudie A, *Environmental Change*, Second Edition, Clarendon Press, Oxford (1983).

[15] Milankovitch M, *Canon of Insolation and the Ice-Age Problem* (in German), Special Publications of the Royal Serbian Academy, Vol. 132, Israel Program for Scientific Translations (1941).

[16] Bradley R S, Quaternary Paleoclimatology: Methods of Paleoclimatic Reconstruction, Unwin Hyman, Boston (1985).

[17] Yamada T, Monitoring of glacier lake and its outburst floods in Nepal Himalaya, *Japanese Society of Snow and Ice*, Monograph No. 1 (1998).

[18] Owen L A, Finkel R C & Cafee M W, A note on the extent of glaciation throughout the Himalaya during the global Last Glacial Maximum, *Quaternary Science Reviews*, 21 (2002) 147.

[19] Richards B W, Owen L A & Rhodes E J, Timing of late Quaternary glaciations in the Himalayas of northern Pakistan, *Journal of Quaternary Science*, 15 (2000) 283.

[20] Bajracharya S R, Mool P K & Shrestha B R, *Impact of Climate Change on Himalayan Glaciers and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan*, ICIMOD, Kathmandu (2007).

[21] Hall K J & Walton D W H, Rock weathering, soil development and colonization under a changing climate, Philosophical Transactions: Biological Sciences, *Antarctic and Environmental Change*, 338 (1992) 269.

[22] Darmody R G, Allen C E & Thorn C E, Soil topochronosequences at Storbreen, Jotunheimen, Norway, *SSSA Journal*, 69 (2005) 1275.

[23] Chapin F S, Walker L R, Fastie C L & Sharman L C, Mechanisms of primary succession following deglaciation at Glacier Bay, Alaska, *Ecological Monographs*, 64 (1994) 149.

[24] Egli M, Fitze P & Mirabella A, Weathering and evolution of soils formed on granitic, glacial deposits: results from chronosequences of Swiss alpine environments, *Catena* 45 (2001) 19.

[25] Tan K H, 1986, Degradation of soil minerals by organic acids, in Huang P M & Schnitzer M, editors, *Interactions of Soil Minerals with Natural Organics and Microbes*, Soil Sci. Soc. Am. Special Publication Number 17 (1986) 1.

[26] Van Cleve K & Powers R F, Soil carbon, soil formation, and ecosystem development, in McFee W W & Kelly J M, editors, *Carbon Forms and Functions in Forest Soils*, SSSA Inc, Madison, WI (1995) 155.

[27] Browne, B A, Toward a new theory of podzolization, in McFee W W & Kelly J M, editors, *Carbon Forms and Functions in Forest Soils*, SSSA Inc, Madison, WI (1995) 253.

[28] Lundström, U.S. 1994. Significance of organic acids for weathering and the podzolization process. Environment International 20:21-30.

[29] Stevenson F J, *Humus Chemistry: Chemistry, Composition, Reactions*,. 2nd edition, John Wiley & Sons, New York (1994).

[30] Conen F, Yakutin M V, Zumbrunn T & Leifeld J, Organic carbon and microbial biomass in two soil development chronosequences following glacial retreat, *European Journal of Soil Science*, 58 (2006) 758.

[31] Bormann B T & Sidle R C, Changes in productivity and distribution of nutrients in a chronosequence at Glacier Bay National Park, Alaska, *Journal of Ecology*, 78 (1990) 561.

[32] Cooper W S, The recent ecological history of Glacier Bay, Alaska: I. The interglacial forests of Glacier Bay, *Ecology*, 4 (1923) 93.

[33] Cooper W S, The recent ecological history of Glacier Bay, Alaska: II. The present vegetation cycle, *Ecology*, 4 (1923) 223.

[34] Cooper W S, The recent ecological history of Glacier Bay, Alaska: III. Permanent quadrats at Glacier Bay: An initial report upon a long-period study, *Ecology*, 4 (1923) 355.

[35] Cooper W S, A third expedition to Glacier Bay, Alaska, *Ecology*, 12 (1931) 61.

[36] Cooper W S, A fourth expedition to Glacier Bay, Alaska, *Ecology*, 20 (1939) 130.

[37] Kleiden A & Mooney H A, A global distribution of biodiversity inferred from climate constraints: results from a process-based modeling study, *Global Change Biology*, 6 (2000) 507.

[38] Minami Y, Kanda H & Masuzawa T, The relationship between distribution of bryophytes and soil conditions on deglaciated arctic terrain in Ny-Ålesund, *Polar Biology*, 9 (1996) 307.

[39] Cannone N, Guglielmin M & Gerdol R, Relationships between vegetation patterns and peri-glacial landforms in northwestern Svalbard, *Polar Biology*, 27 (2004) 562.

[40] Jones G A & Henry G H R, Primary plant succession on recently deglaciated terrain in the Canadian High Arctic, *Journal of Biogeography*, 30 (2003) 277.

[41] Bardgett R D & Walker L R, Impact of colonizer plant species on the development of decomposer microbial communities following deglaciation, *Soil Biology & Biochemistry*, 36 (2004) 555.

[42] Ehrlich H L, Geomicrobiology: its significance for geology, *Earth-Science Reviews*, 45 (1998) 45.

[43] Nealson K H & Stahl D A, Microorganisms and biogeochemical cycles: what can we learn from layered microbial communities? in Nealson K H and Banfield J F, editors, *Geomicrobiology: Interactions between Microbes and Minerals*, Vol. 35, Mineralogical Society of America, Washington, D.C. (1997) 5.

[44] Shrestha K L, Shrestha M L, Shakya N M, Ghimire M L & Sapkota B K, Climate change and water resources of Nepal. In: Muhammed A (editor), *Climate Change and Water Resources in South Asia*, Asianics Agro Development International, Kathmandu (2003).

[45] ICIMOD/UNEP, *Inventory of Glaciers, Glacial Lakes, and Glacial Lake Outburst Floods, Monitoring and Early Warning System in the Hindu Kush-Himalayan Region*, Kathmandu, Nepal (2001).

[46] Asahi K & Watanabe T, Past and recent glacier fluctuation in Kangchenjunga Himal, Nepal, *Journal of Nepal Geological Society*, 22 (2000) 481.

[47] Byers A C, An assessment of contemporary glacier fluctuations in Nepal's Khumbu Himal using repeat photography, *Himalayan Journal of Sciences*, 4 (2007) 21.

[48] Kadota K, Seko K, Aoki T, Iwata S & Yamaguchi S, Shrinkage of Khumbu Glacier, east Nepal from 1978 to 1995, *IAHS Publication No. 264* (2000) 235.

[49] Naito N, Nakawo M, Kadota T & Raymond C F, Numerical Simulation of Recent Shrinkage of Khumbu Glacier, Nepal Himalayas, in International Association of Hydrological Sciences Publication 264, *Proceedings of a Symposium on Debris Covered Glaciers*, Seattle, 2000.

[50] Seko K, Yabuki H, Nakawo M, Sakai A, Kadota T & Yamada Y, Changing surface features of Khumbu Glacier, Nepal Himalayas revealed by SPOT images, *Bulletin of Glacier Research* 16 (1998) 33.

[51] Yamada T, Shiraiwa T, Kadota T, Watanabe T, Rana B, Ageta Y & Fushimi H, Fluctuation of the glaciers from the 1970s to 1989 in the Khumbu, Shorong and Langtang regions, Nepal Himalayas, *Bulletin of Glacier Research*, 10 (1992) 11.

[52] Fujita K, Kadota T, Rana B, Shrestha R B & Ageta Y, Shrinkage of Glacier AX010 in Shorong region, Nepal Himalayas in the 1990s, *Bulletin of Glaciological Research*, 18 (2001) 51.

[53] Kadota T, Fujita K, Seko K, Kayastha R B & Ageta Y, Monitoring and prediction of shrinkage of a small glacier in Nepal Himalaya, *Annals of Glaciology*, 24 (1997) 90.

[54] Kayastha R B, Ageta Y & Nakawo M, Positive degree-day factors for ablation on glaciers in the Nepal Himalaya: case study on Glacier AX010 in Shorong Himal, Nepal, *Bulletin of Glaciological Research*, 17 (2000) 1.

[55] Ageta Y, Lida H & Watanabe O, Glaciological studies on Yala Glacier in Langtang Himal, Data Center for Glacier Research, Japanese Society of Snow and Ice (1984).

[56] Fujita K, Takeuchi N & Seko K, Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalayas 1994 and 1996, *Bulletin of Glacier Research*, 16 (1998) 75.

[57] Fujita K, Nakawo M, Fujii Y & Paudyal P, Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas from 1974 to 1994, *Journal of Glaciology*, 43 (1997) 583.

[58] Fujita K, Nakazawa F & Rana B, Glaciological observations on Rikha Samba Glacier in Hidden Valley, Nepal Himalayas, 1998 and 1999, *Bulletin of Glaciology Research*, 18 (2001) 31.

[59] Nakawo M, Fujii Y & Shrestha M L, Flow of glaciers in Hidden Valley, Mukut Himal, *Seppyo*, 38 (1976) 39.

[60] Fujita K, Sakai A, Nuimura T, Yamaguchi S & Sharma R R, Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in-situ surveys and multi-temporal ASTER imagery, *Environment Research Letters*, 4 (2009) 045205.

[61] Watanabe T, Lamsal D & Ives J D, Evaluating the growth characteristics of a glacial lake and its degree of danger: Imja Glacier, Khumbu Himal, Nepal, *Norwegian Journal of Geography*, 63 (2009) 255.

[62] Schweinfurth U, Die horizontale and vertikale Verbreitung der vegetation in Himalaya, *Bonner Geographische Abhl*. 20 (1957).

[63] ICIMOD, *Mountain Biodiversity and Climate Change*, ICIMOD, Kathmandu (2009).

[64] Pei S, editor, *Banking on Biodiversity*, Report on the Regional Consultation on Biodiversity Assessment in the Hindu Kush-Himalayas, ICIMOD, Kathmandu (1996).

[65] Hong D & Li Z Y, Biodiversity and its conservation and management in the Hindu Kush-Himalayan region of China. In Sheng P, editor, *Banking on Biodiversity*, ICIMOD, Kathmandu (1996).

[66] Khoshoo TN, Biodiversity in the Indian Himalayas: conservation and utilization. In Sheng P, editor, *Banking on Biodiversity*, ICIMOD, Kathmandu (1996).

[67] Chalise S R, Sustainability of mountain natural resources and biodiversity in the Hindu Kush-Himalayas, *Global Environmental Research*, 10 (2006) 73.

[68] Bhatia A, Pelinck E & Rastogi A, Community-focused approach to biodiversity conservation. In *Ecoregional Co-operation for Biodiversity Conservation in the*

*Himalaya*, Report on the International Meeting on Himalaya Ecoregional Co-operation. UNDP (1998).

[69] Hasnain S I, *Status of the Glacier Research in the HKH Region*, ICIMOD, Kathmandu (2000).

[70] IPCC, *Climate Change 2001: The Scientific Basis*. Houghton J T, Ding Y, Griggs D J, Noguer M, van der Linden P J, Dai X, Maskell K and Johnson C A, editors, Houghton Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (2001).

[71] Pauli H, Gottfried M, Hohenwallner D, Reiter K, Casale R & Grabherr G (editors), *The GLORIA (Global Observation Research Initiative in Alpine Environments) Field Manual – Multi-Summit Approach*, Directorate-General for Research, European Commission (2004).