Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and Their Consequences for Highland and Downstream Regions

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1. Background

Soon after the International Panel on Climate Change (IPCC) released its Fourth Assessment Report (AR4) in 2007 (IPCC, 2007), two statements therein, namely *(a) the high mountains of Asia till then remained a "white spot" and (b) all glaciers in the Himalayas could disappear by 2035*, drew the attention of all concerned and subsequently there seemed to be a surge in the studies and research activities on the dynamics of snow and glacier in the Himalayas as well as on their potential impacts on the runoff of the Himalayan perennial rivers. Meanwhile, the second statement after considerable discourse was altered into a new statement (IPCC, 2010).

Himalaya, the abode of snow (Fig. 1), has the third largest reservoir of snow and ice after Arctic/Greenland and Antarctic regions and is the source of all the major perennial rivers in Asia and provides fresh water to billions of people living in and around the region. In the Himalayan rivers like Indus, Ganges and Brahmaputra, glaciers and snow, for example, contribute important components of flows in the years of poor monsoon and reduce inter-annual and inter-seasonal variability during lean summer and post monsoon months. Global change, however, is likely to alter these flow patterns with adverse impacts on the economy in terms of water availability, food security and hydropower generation. In addition, rising population and the increasing pace of economic development will raise demands for fresh water in the scenario of plummeting availability of this resource. Hence understanding the impacts of global change on snow and ice dynamics in the Himalayas and their hydrological consequences has become urgent and important.

As a modest initiative, this two-year project on *"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and Their Consequences for Highland and Downstream Regions"* (ARCP2008-16NMY-Shrestha) was initiated in the year 2008 with research grant from the APN with the following objectives:

- To assess the impacts of climate change on the dynamics of snow, glaciers and runoff over the Himalayan mountains;

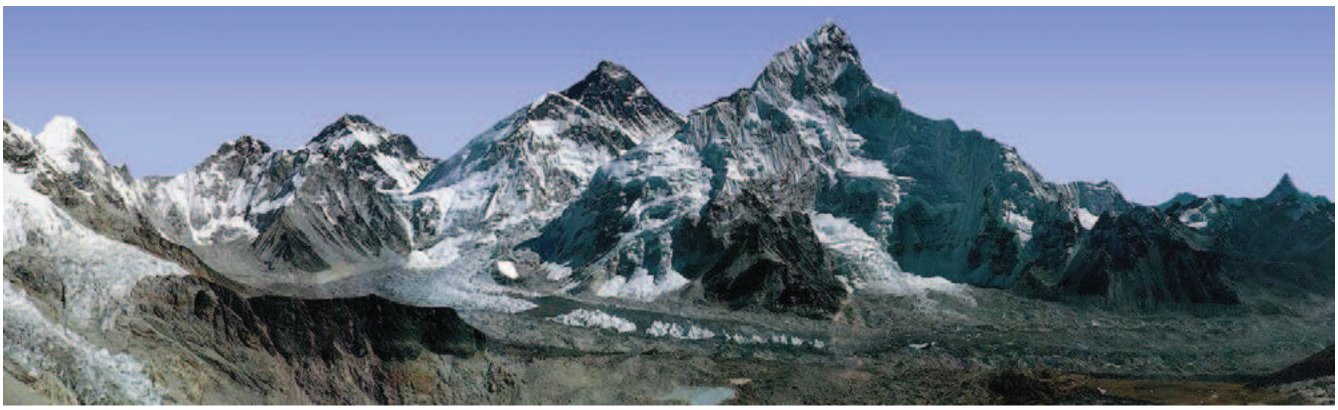

Fig. 1 Asian high mountains with glaciers abound

- To assess the consequences for people's livelihoods and the economies and societies in the upland and downstream regions; and
- To provide scientific information to planners and policy-makers for identifying and implementing adaptation and mitigation strategies for sustainable development of the regions.

Four institutions from four different countries initially committed to work in the project as collaborating institutions (Box A), and three of them, namely **GCISC**, **GBPIHED** and **IDI** cooperated and actively participated in the three selected representative research basins namely, **Hunza** basin, **Upper Bhagirathi** basin and **Koshi** basin.

BOX A

Participating Countries & Institutions

China:	The Institute for Tibetan Plateau Research (TPI)
India:	The G. B. Pant Institute of Himalayan Environment and Development (GBPIHED)
Nepal:	The Institute for Development and Innovation (IDI)
Pakistan:	The Global Change Impact Studies Centre (GCISC)

The details on the research strategies and methodologies adopted to attain the above objective have been published earlier in the Mountain Research Initiative (MRI) Newsletter in 2009 (Shrestha, 2009). This article presents a brief description of key results of the study conducted during year 1 as well as the current activities during the year 2.

2. Project Approaches

As the rugged topography of Himalayas hinders field collection of scientific data in particular at high altitudes and over long periods, significant knowledge and uncertainty exist for proper understanding and assessing the impacts of global change on snow and ice dynamics as well as corresponding hydrology and consequent implications for highland and downstream communities.

In order to address such knowledge gaps and uncertainties, remote sensing and Geographical Information System (GIS) are used to determine the topographical features and to assess the status of snow and glacier dynamics of the region. Likewise, Regional Climate Models (RCMs) at the basin scales are run and used after necessary calibration and validation to provide meteorological conditions for contemporary as well as future periods. The obtained meteorological profiles with necessary bias corrections are then used to run suitable hydrological models to assess the impacts of climate change on the water availability in the selected basins both in space and time. Their consequent implications for highland and downstream communities are next studied using chosen appropriate tools.

3. Project Activities

The project activities focused on the three river basins that are selected as representative ones along the western, middle and eastern regions of the Himalayan range. Their geographical locations are shown in Figure 2. All the three chosen basins are highly glaciated. Glaciers like Hispar, Batura and Passu in the Hunza basin; Gangotri and Dokriani in the Upper Bhagirathi basin; and Khumbu and Imja in the Koshi basin are some of the well studied major glaciers in the region. The Koshi basin, with Mount Everest—the highest mountain on earth—almost at its centre, is the most rugged and the one with highest glaciers. Likewise, the Ganges river originates from the terminus of Gangotri glacier and Hunza river in the Karakoram region constitutes an important tributary to the Indus river originating from the northern side of the Himalayan range in the Tibetan plateau.

Fig. 2 The Selected Basins - Hunza, Upper Bhagirathi and Koshi along the Himalayan Range

3.1 Snow and Glacial Melt Runoff

In the high altitude snow/glacier fed basins of the Himalayan region, the cryospheric melt runoff constitutes an important component in the total runoff. Thus generating better estimates of snow and glacier melt contribution to the Himalayan river flows and the likely change in this component due to global warming are two of the major driving concerns.

Koshi Basin

Fig. 3 Koshi Basin

The Koshi basin broadly consists of seven major sub-basins (Fig. 3). Surface energy balance model in conjunction with comprehensive catchment model was used to assess the total runoff including its snowmelt/glacialmelt component. Shuttle Radar Topography Mission (SRTM) 90m digital elevation data were used to derive the Digital Elevation Model (DEM) of the basins. These together with meteorological data from nearby field stations were used to derive the climate parameters at the different altitudinal bands of the selected basins. Landsat 7 ETM+ images have been used to determine the extent and status of glaciers in the selected basins. The total melt volume comprising of snowmelt over bare ground area, debris-free glacier area, debris-covered glacier area, ice ablation under the debris layer and ice ablation from debris-free glacier for the year 2002 were calculated for all smaller glaciated parts of the basins. The melt volume for seven sub-catchments of Koshi basin is then found out by summing up the ones from the associated respective individual smaller basins and is shown graphically in percentages in Fig. 4.

The contribution of snow and glacier melt discharge to annual flow at the lowermost downstream station 'Chatara' is about 8.46% with a maximum monthly contribution of 22.52% in May and a minimum monthly contribution of 1.86% in January. The snow and glacier melt discharge from Dudh Koshi sub-

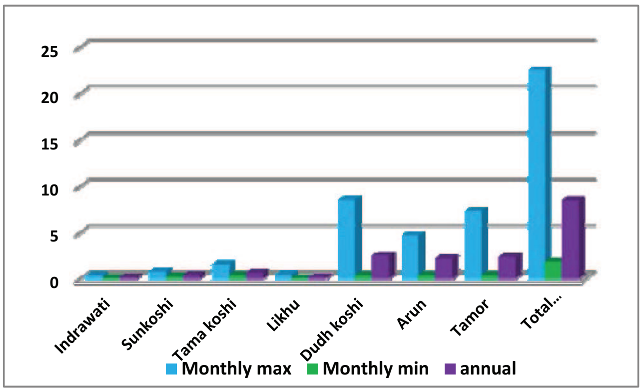

Fig. 4 Maximum and Minimum Percentages of Snow and Ice Melt Contributions in Total Flow at Chatara

basin is found quite significant. It has maximum contribution to annual flow at Chatara (2.51% out of total 8.46%). Whereas glacierized watersheds of Indrawati sub-basin have minimum contribution to annual flow at Chatara (0.15% out of total 8.46%). Dudh Koshi, Arun and Tamor basins are three major tributaries, which share 84% in terms of contribution of snow and glacier melt to the outlet of Koshi basin at Chatara. As almost half of the Arun river basin lies in

		BASE			F1 (2020s)			F2(2050s)			F3 (2080s)		
		Flow	Snow	Glacier	Flow	Snow	Glacier	Flow	Snow	Glacier	Flow	Snow	Glacier
		(Cumecs)			(Cumecs)			(Cumecs)			(Cumecs)		
Annual Average		292.6	6.0	243.7	371.7	6.0	314.5	473.0	6.0	407.9	654.0	4.4	588.3
Seasonal	Spring	62.7	18.3	29.0	83.8	17.9	47.7	148.3	20.0	99.1	195.8	16.9	145.4
	Summer	933.2	5.1	856.4	1162.7	5.6	1065.8	1411.9	3.8	1309.1	1845.9	0.5	1757.6
	Fall	154.5	0.6	89.2	217.0	0.5	144.4	304.3	0.3	223.3	539.9	0.1	449.5
	Winter	20.2	0.0	0.0	23.4	0.0	0.0	27.6	0.0	0.0	34.3	0.1	0.7

Table 1. Control and Scenarios for Base Flow and Projected Flows in Hunza River including the Snow Melt and Glacier Melt Components

Tibet, which is not included in this analysis, its cryospheric melt contribution would obviously be significantly more than indicated here in this analysis.

Hunza Basin

The University of British Columbia (UBC) Watershed Model was applied to study the impact of climate change in the Hunza basin. The DEM (Digital Elevation Model) for the Hunza River basin has been taken from the ASTER global dataset at horizontal resolution of 30 meters. Physio-geographical characteristics such as glaciated area, forest cover, forest canopy density, impermeable area and orientation index along with the land area under each elevation zone have been calculated from the Land Cover and DEM gridded datasets from the US Geological Survey. The base flow and projected flows in Hunza River including the snow melt and glacier melt components for the periods 2020s, 2050s and 2080s as obtained from the control run covering the period 1966–1990 and the scenarios for the chosen periods are shown in Table 1. Assuming the extent and the volume of glaciers in the basin remaining constant, the calculated figures clearly indicates a monotonous rise in the total runoff in the river and turning more than double of the flow during the base period. While the snow melt component is found to be less prominent and it virtually drops to insignificance in the period 2080s, glacier melt is found to be the dominant component in the total flow throughout the period and with its contribution of about 82% in the control period and rising continually to about 90% in the 2080s period. Although the importance of glacier melt in the total runoff is significant, the results need however to be used with caution in view of the limited input data that goes into the UBC model.

3.2 Regional Climate Models (RCMs)

RCM	Driven by GCM	IPCC SRES	Resolution	Baseline Period	Projected Period	Applied Basin
PRECIS	ERA40	A2	50km x 50km	1961-1990	2020s; 2050s; and 2080s	Hunza
PRECIS	ECHAM 4					
RegCM3	ERA40					
RegCM3	ECHAM 4					
PRECIS	HadAM3H				2071-2100	Upper Bhagirathi
PRECIS	HadAM3P				2020s; 2050s; and 2080s	Koshi
RegCM3	ECHAM 4					Koshi
PRECIS	HadCM3	A1B	25km x 25km	Dec 1969 – Nov 1979	Dec 2039 – Nov 2069	Koshi
WRF	CCSM	A1B	10km x 10km	1970-2009	2051-2060	Dudhkoshi

Fig. 5 RCMs Run and Applied in the Selected Basins

For regional climate change impact studies, properly downscaled regional climate models (RCMs) are required in order to provide fine-resolution climate parameters for driving hydrological models to make future predictions of changes in the hydrological regimes.

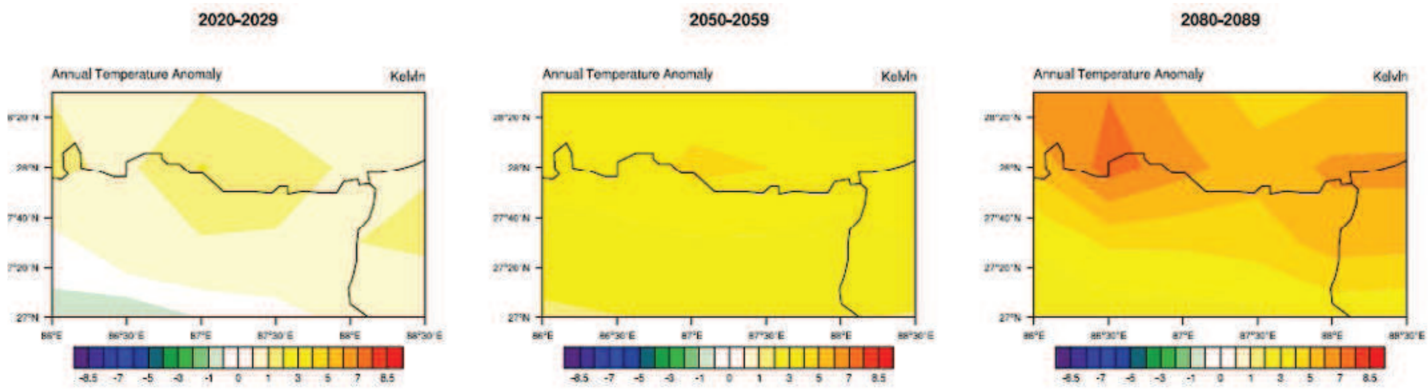

Fig. 6 Projected temperature change in Koshi basin

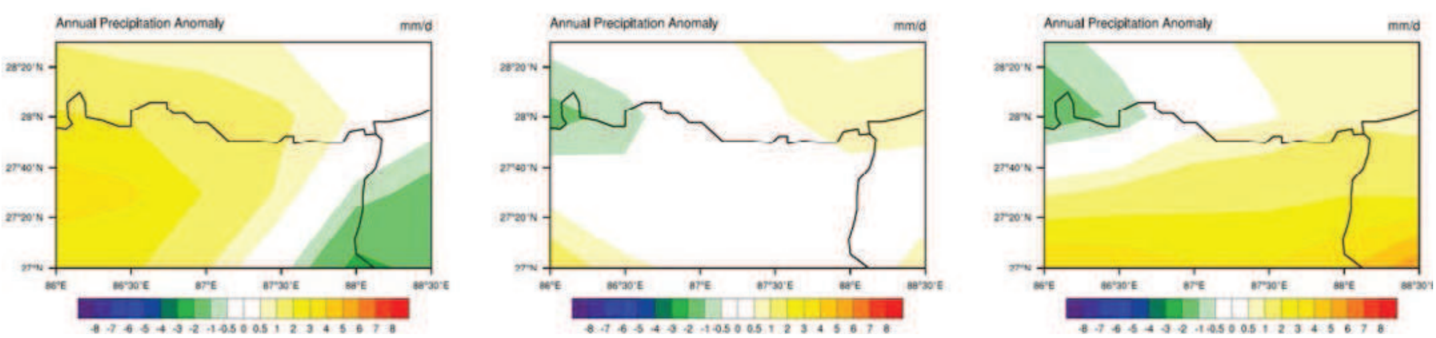

Fig. 7 Projected precipitation change in Koshi basin

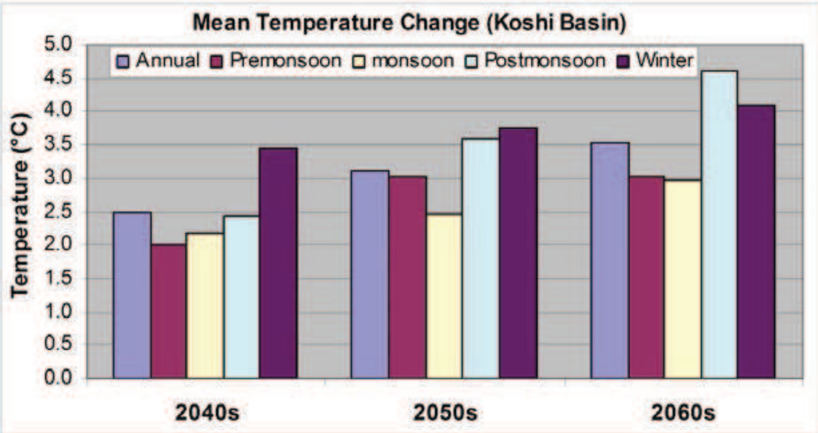

Fig. 8 Projected seasonal mean temperature changes in Koshi basin

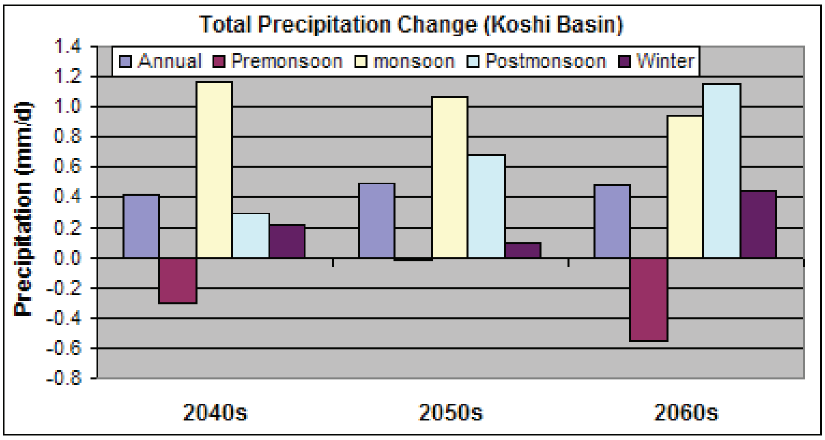

Fig. 9 Projected seasonal total precipitation changes in Koshi basin

The various RCMs downscaling different GCMs for certain IPCC SRES together with their resolutions are shown in Figure 5. Some of them after validation and necessary bias correction have been used to project the changes in the temperature as well as precipitation in the selected basins over chosen periods. The projected variations with spatial distribution for the Koshi basin for 2020s, 2050s and 2080s as obtained by using PRECIS at 50km resolution are presented in Figs. 6 & 7 for temperature and precipitation respectively.

Likewise, the projected annual and seasonal mean temperature and precipitation change for the Koshi basin in three decades as indicated by PRECIS run at 25 km resolution is presented in Figs. 8 & 9.

The higher trend of mean temperature changes in the high mountains in the north (Fig. 6) and during the post monsoon and winter periods (Fig. 8) are in particular notable. Similarly, the reduction in total precipitation in the high mountains in the north (Fig. 7) and during pre-monsoon period and enhanced total precipitation during monsoon and post-monsoon periods (Fig. 9) are also noteworthy. Model performance is also evaluated by comparing the computed and observed values averaged over the whole domain and model bias worked out.

Likewise, annual as well as seasonal analysis of temperature and precipitation change over Hunza basin for the various projection periods as obtained under PRECIS climate projections for A2 are shown in Table 2. Over the Hunza Basin, the annual temperature rise is 5.48°C by the end of the current century which is far more than the projected temperature increase for A2 globally i.e. 4.0ºC. In the case of precipitation, about 10% increase has been observed by the end of the current century. The seasonal analysis of temperature shows higher temperature increase in autumn and winter than spring and summer temperatures. In the case of precipitation, increase has been observed for spring and winter seasons throughout the century but greater increase is

Table 2. PRECIS Climate Projection for A2 over Hunza basin

		Δ Temperature °C			Δ Precipitation %		
		2020s	2050s	2080s	2020s	2050s	2080s
Annual		1.58	3.21	5.48	4.25	9.34	9.94
Seasonal	Spring (MAM)	1.39	2.97	4.25	10.22	12.37	17.15
	Summer (JJA)	1.48	2.93	5.58	-9.42	-22.76	-26.46
	Autumn (SON)	1.66	3.17	6.37	-12.21	3.47	-14.70
	Winter (DJF)	1.78	3.75	5.72	13.65	23.06	33.97

Box B

Consultative Meeting and Workshops

❖ Initial Meeting	13 – 14 November 2008
❖ Joint Workshop	17 – 19 February 2010
❖ International Workshop	13 – 15 September 2010
❖ Scoping Workshop	21 – 22 February 2011
❖ Country Workshop-India	27 – 28 February 2012
❖ Country Workshop-Nepal	10 April 2012

observed in winter than spring (i.e. 34% with respect to base period). However, precipitation in summer and autumn are found to be decreasing by up to 26% and 15% respectively by the end of present century.

3.3 Consultations and Disseminations

A number of workshops and seminars have been held at different time with the objectives of consultations and exchange of knowledge and experience among key researchers, stakeholders and project partners (Box B). The country workshops held recently in India and Nepal were attended by almost all the active key actors in the respective countries in the field of climate change impacts on Himalayan Cryosphere. Hence the country workshops were found particularly helpful in updating the research strategy in the context of new research studies carried out during the gap period between the year 1 and year 2 of this two year project.

4. Way Forward

Water being an essential resource for all forms of life on our planet, variations in hydrologic regimes often have serious consequences and, thus, are a potential threat for society. Contemporary global and regional climate and other environmental changes pose immense challenge to Himalayan water resources management due to high spatial and temporal variation of resource endowment, and upstream-downstream linkages as a result of high degree of interrelationship among water uses and users as well as their transboundary nature. It is therefore necessary to provide best possible information regarding future changes in the hydrological cycle in such a way as to enable responsible decision makers to find possible strategies to mitigate or adapt to global change.

Hydrological models forced by climate parameters from the RCMs are being applied to make future predictions of changes in the hydrological regimes. The consequences of the projected changes in the hydrological regimes in terms of food security, hydropower development and upstream-downstream linkages are being studied. Policy implications of the envisaged changes are also being explored.

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