Understanding the Dynamics of Snow and Glaciers in the Hindu Kush-Himalayan Region

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The Hindu Kush-Himalayan (HKH) region is complex and characterised by intricate biophysical and socioeconomic linkages between the upstream and downstream parts of its predominantly transboundary river basins. The cryosphere, in the form of glaciers, snow, permafrost, and seasonally frozen ground, forms a large natural storage system of fresh water important for sustaining the lives of the more than 1 billion people living downstream. The cryosphere and the climate system are linked in numerous ways. The high albedo (reflection coefficient) of snow and ice surfaces is associated with feedback processes and

Snow and glaciers – source of fresh water

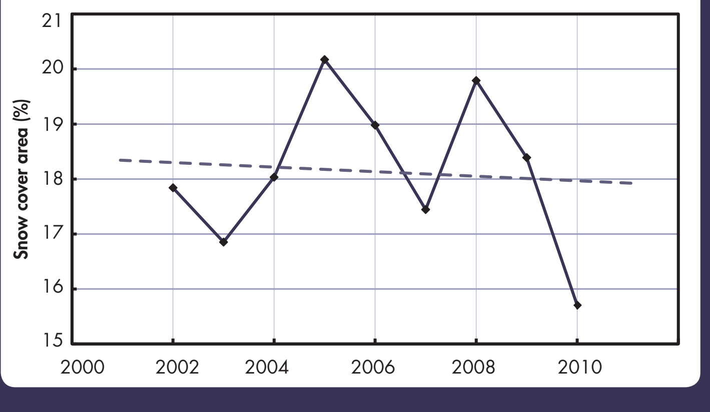
plays a significant role in the global climate. Changes in the cryosphere may have grave consequences for the regional and global climate systems. These changes may have strong social and economic consequences, especially in mountainous regions where economic opportunities such as hydropower, tourism, and agriculture are to a certain degree dependent on the snow and ice melting regimes. The increased melting of snow and glaciers at the headwaters of rivers also increases the risk to infrastructure, particularly when combined with heavy monsoon rainfall.

The cryosphere is thus one of the most important topics in climate science and in climate change impact and adaptation research. The monitoring of all components of the cryosphere is of prime importance in understanding the processes in the cryosphere and the climate system. Without an understanding of the role of the cryosphere, it is not possible to model and predict the variability and future changes of the climate system (Khromova 2010).

Bridging the data gap

To address the data gap pointed out by the Intergovernmental Panel on Climate Change (IPCC 2007), ICIMOD, together with a number of key regional and international partners, undertook a comprehensive study to understand the dynamics of the cryosphere in the HKH region, focusing specifically on two components, snow and glaciers. Remote sensing based observations proved to be critical for the monitoring and assessment of the cryosphere in the HKH region because routine data collection in mountainous regions is often hampered by highly inaccessible terrain and harsh climatic conditions. The study provides a comprehensive account of remote sensing based information, providing homogenous and contiguous datasets at the regional level. A common approach and methodology were used to standardise and harmonise the database in line with international norms, which are a precondition for regional level assessment.

Figure 1: **Average variation in snow cover area in the HKH region, 2002–2010**



Snow

The HKH region has a vast snow-covered area (SCA); the maximum area recorded from 2002 to 2010 was 1.79 million km^2 (42.9% of the total land area). The permanent SCA during this period was 0.18 million km^2 (4.3% of the total land area). The SCA shows strong inter-annual variation (Figure 1). The mean annual SCA ranged from 0.70 million km^2 in 2002 to 0.84 million km^2 in 2005 (Gurung et al. 2011).

A nine-year (2002–2010) analysis of SCA derived from MODIS based standard snow cover products after filtering cloud pixels based on linear regression analysis of annual mean SCA, indicates a positive trend in the western and eastern HKH (Table 1).

Table 1: **Annual snow cover trends in the Hindu Kush-Himalayan region (%)**

Region	Trend
HKH region	-0.05 ± 1.32
Western HKH	+0.02 ± 1.36
Central HKH	-0.40 ± 1.86
Eastern HKH	+0.03 ± 1.55

A map of the spatial trends in SCA shows that this positive trend does not pertain in the central HKH (Figure 2). A seasonal analysis was also performed for the region for the same period. The analysis indicates a consistent negative trend during winter (December to March) across the HKH region. For spring (April to June) and summer (July to September), SCA analysis indicates a negative trend, except in the western HKH region. The trend for autumn (October to November) was negative in the western HKH region while it was positive in the eastern and central HKH (Table 2).

The SCA depletion curve helps in understanding the snow ablation and accumulation cycle, which is important in assessing the contribution of snow melt to the hydrological regimes of river systems. Intra-annual variations in the SCA for the entire HKH region were studied using mean monthly SCA for 2002–2010. Two peaks were observed: one in February and a subsidiary peak in November/December. Immerzeel et al. (2009) observed a similar pattern in the Yangtze and Yellow river basins. SCA depletion curves were also calculated for different elevation bands (<1,000, 1,000–2,000, 3,000–5,000, 5,000–7,000, and >7,000 m) based on mean monthly values for the hydrological year

Figure 2: **Changes in snow cover area in the HKH region and beyond, 2002–2010 (%)**

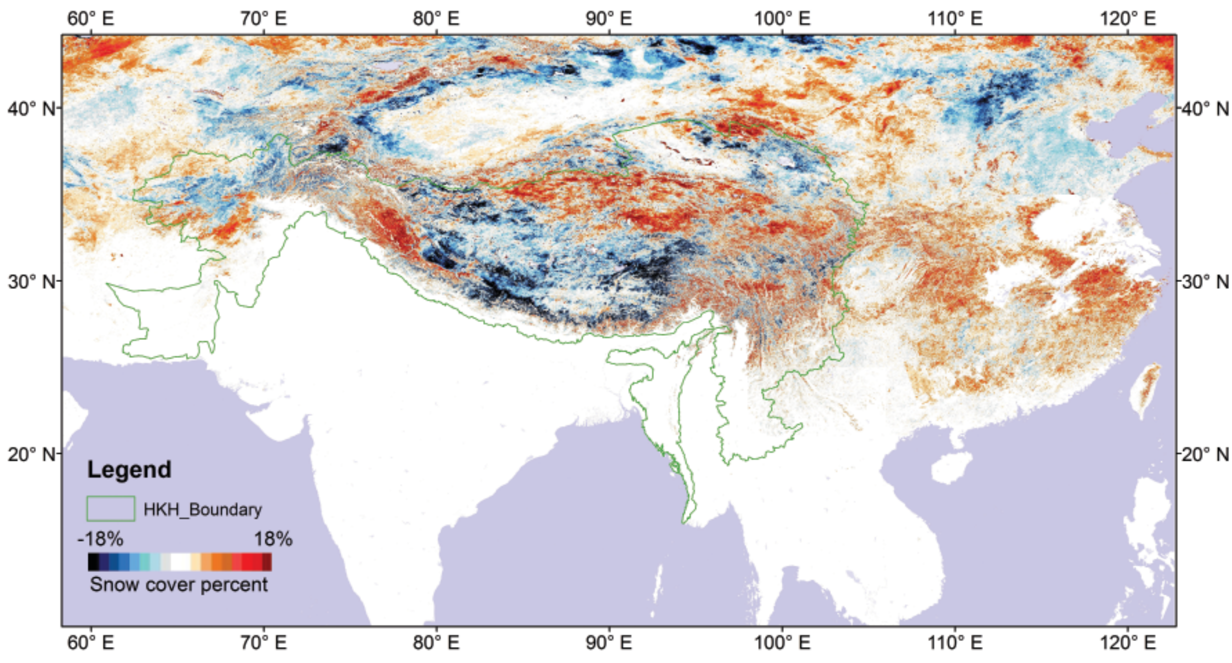


Table 2: **Seasonal snow cover trends in the Hindu Kush-Himalayan region (%)**

Season	HKH region	Western HKH	Central HKH	Eastern HKH
Spring	-0.03 ± 1.28	+0.11 ± 1.83	-0.23 ± 2.46	-0.03 ± 1.06
Summer	-0.01 ± 0.49	+0.16 ± 0.65	-0.20 ± 1.40	-0.04 ± 0.52
Autumn	+0.09 ± 3.97	-0.26 ± 2.81	+0.02 ± 5.74	+0.29 ± 5.32
Winter	-0.16 ± 2.23	-0.02 ± 2.80	-0.84 ± 2.63	-0.01 ± 2.47

2000–2001. The analysis shows delayed snow melt onset with rise in elevation, consistent with observations on the Tibetan Plateau (Pu et al. 2007).

Glaciers

ICIMOD, together with national partners, has recently completed an inventory of glaciers in Afghanistan, Bhutan, China, India, Nepal, Myanmar, and Pakistan (ICIMOD, in preparation). This is the first time that glaciers from Myanmar have been reported. The study is unique as it comprehensively maps both clean ice and debris-covered glaciers for almost the entire HKH region using a consistent methodology. The only exception is China, for which the inventory was done separately, but following a largely similar methodology. The medium-resolution remote sensing data (Landsat and ASTER) were used in the inventory from a single data source with a short acquisition time interval (2005±3 years), and the properties of each glacier were documented in a standardised internationally accepted form. All of the glaciers in the HKH region with a surface area larger than 0.02 km^2 were mapped (Figure 3). A multi-stage approach using both remote sensing and field data was applied for more accurate results. The inventory revealed about 54,000 individual glaciers with a total area of 60,000 km^2 and an estimated 6,100 km^3 of ice reserves in the entire HKH region (Table 3). The stored water in these ice reserves is about four times the annual precipitation. It was found that the average glacier area in the HKH region is 1.10 km^2 (Bajracharya et al. 2010). The highest concentration of glaciers is in the upper Indus basin, and the lowest in the Irrawaddy basin. The largest glacier in the HKH region is the Siachen Glacier in the Indus basin.

Figure 3: **Distribution of glaciers in the Hindu Kush-Himalayan region**

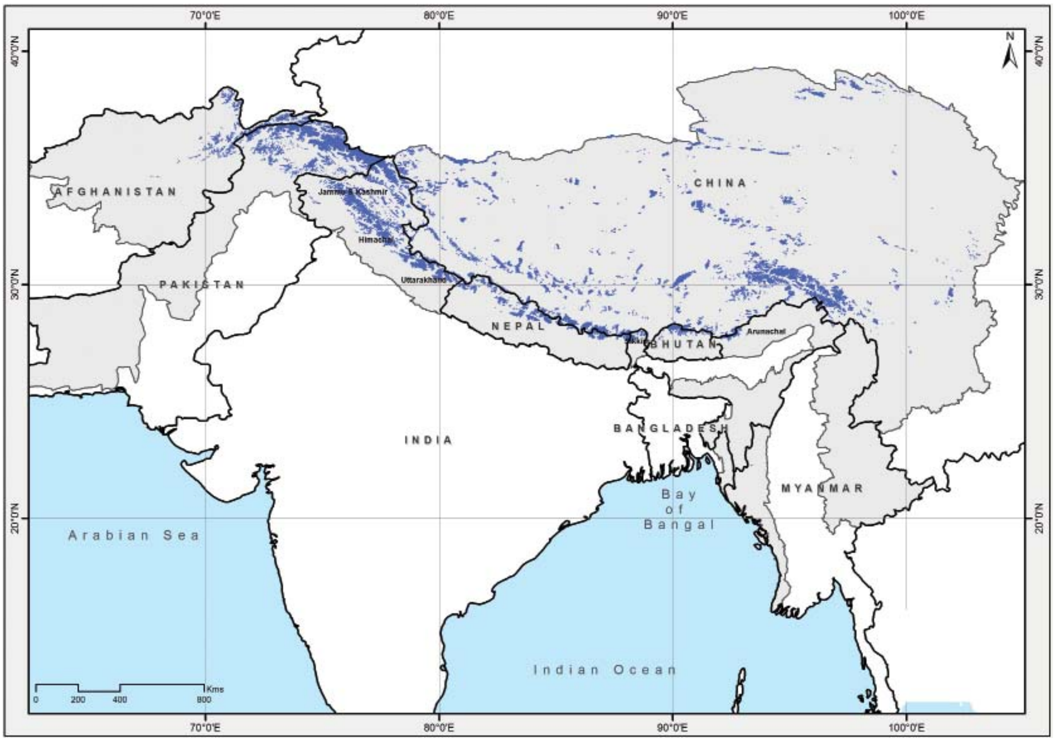


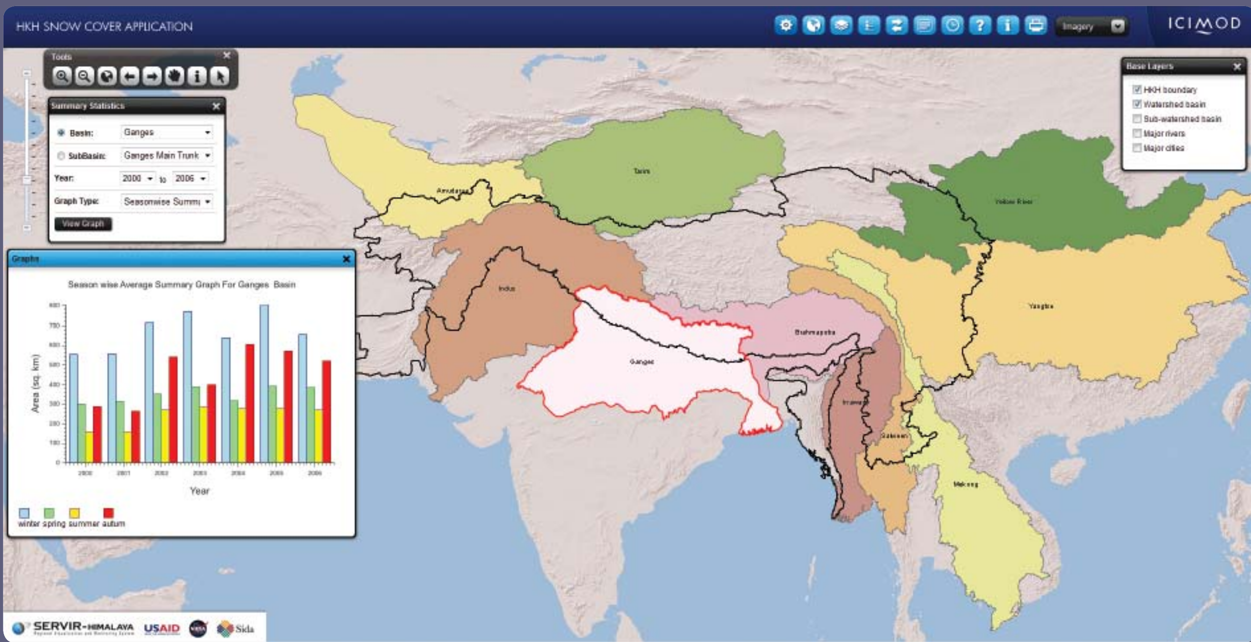
Table 3: **The status of glaciers in Hindu Kush-Himalayan region**

River basin	Number of glaciers	Glacier area (km^2)	Ice reserves (km^3)	Average glacier area (km^2)
Amu Darya	3,277	2,566	162.6	0.8
Indus	18,495	21,193	2696.1	1.2
Ganges	7,963	9,012	793.5	1.1
Brahmaputra	11,497	14,020	1,302.6	1.2
Irrawaddy	133	35	1.3	0.3
Salween	2,113	1,352	87.7	0.6
Mekong	482	235	10.7	0.5
Yangtze	1,661	1,660	121.4	1.0
Yellow	189	137	9.2	0.7
Tarim	1,091	2,310	378.6	2.1
Interior	7,351	7,535	563.1	1.0
HKH total	54,252	60,054	6,126.9	1.1

Cryosphere knowledge hub

The vast amount of data and information collected and the related analyses are disseminated through ICIMOD's Mountain Geoportal (Figure 4). The portal provides essential and unique climate information services on snow and glaciers, as well as information on glacial lakes. The data are accessible to everyone and follow international standards. As a regional knowledge centre, ICIMOD plans to further build this information base on a regular basis by fostering regional cooperation and promoting the sharing and exchange of data and information at the international level.

Figure 4: **Snow cover data in ICIMOD's Mountain Geoportal (www.icimod.org/cryosphere)**



Conclusion

The Himalayan cryosphere, known as the 'water tower of Asia', is under severe threat from global warming, with far-reaching environmental and socioeconomic implications for the region. Understanding of the interplay between climate, the cryosphere, and water availability is at an early stage. Lack of consistent data and information remains a huge challenge in many studies and projects. ICIMOD, together with its regional and international partners, has made a significant leap forward in collecting the necessary baseline information to understand the dynamics of the cryosphere. The information generated will reduce scientific uncertainty and support the formulation of sound policies and programmes at the national and regional levels.

Future work will focus on mapping snow cover and generating glacier inventories at different time intervals. These inventories will make it possible to map changes in glacier areas, to provide continuously updated information on glaciers, and to quantify permafrost areas using climate data and land surface temperature from remote sensing. The final objective is to include all components of the cryosphere.

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