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149

Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Water Storage Properties under Changing Climate

Oxana S. Savoskul and Vladimir Smakhtin

IWMI International Water Management Institute

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Oxana S. Savoskul and Vladimir Smakhtin

International Water Management Institute (IWMI)
P O Box 2075, Colombo, Sri Lanka

The authors: Oxana S. Savoskul is a Research Associate at the International Water Management Institute (IWMI) in Colombo, Sri Lanka; and Vladimir Smakhtin is Theme Leader - Water Availability and Access at IWMI in Colombo, Sri Lanka.

Savoskul, O. S.; Smakhtin, V. 2013. *Glacier systems and seasonal snow cover in six major Asian river basins: water storage properties under changing climate*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 69p. (IWMI Research Report 149). doi:10.5337/2013.203

/ glaciers / monitoring / seasonality / snow cover / river basins / climate change / impact assessment / remote sensing / water resources / water availability / water storage / hydrological cycle / mountains / surveys / models / institutions / Asia /

ISSN 1026-0862
ISBN 978-92-9090-766-4

Front cover photograph taken in 2010 at the headwaters of the Syr Darya River shows part of the Barkrak Sredniy glacier system *(photo credit:* Maxim Petrov, Institute of Geology, Tashkent, Uzbekistan).

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Acknowledgments

The authors gratefully acknowledge the help of Prasanna Sambandamurthy, Yamuna Udumalagala and Giriraj Amarnath (all of IWMI, Colombo), as well as Samjwal Ji (International Centre for Integrated Mountain Development [ICIMOD], Nepal), Kara Gergely (National Snow and Ice Data Center (NSIDC), USA), Lynn Lay (Goldthwait Polar Library, The Ohio State University, USA) and Elena Shevnina (Saint Petersburg State University, Russia) during the search for published literature and in primary data acquisition, or both. Online resources of NSIDC, World Glacier Monitoring Service (WGMS) and ICIMOD were extensively used, and Graham Cogley (Trent University, Canada) is thanked, in particular, for sharing the World Glacier Inventory - Extended Format (WGI-XF). The assistance of Ameer Rajah and Salman Siddiqui (both of IWMI, Colombo) was essential in downloading and processing data on seasonal snow.

The authors would also like to thank Victor Zagorodnov (Byrd Polar Research Center, The Ohio State University, USA), Tobias Bolch (University of Zurich, Switzerland), Andrey Yakovlev (Tashkent State University, Uzbekistan), Felix Pertziger (URS New Zealand, New Zealand), Kenji Matsuura (University of Delaware, USA), Vladimir Aizen (University of Idaho, USA) and Michael Zemp (WGMS, Switzerland) for many fruitful discussions and valuable advice.

Constructive comments and criticism of two anonymous reviewers and Peter McCornick (IWMI, Colombo) are gratefully acknowledged. The authors are also indebted to the late Mark Dyurgerov (University of Colorado Boulder, USA) for sharing his ideas and general insights years before this study materialized.

Donors

This research study was funded by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

CGIAR RESEARCH PROGRAM ON Climate Change, Agriculture and Food Security CCAFS

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Contents

Summary

The current status, recent and potential future changes of glacier systems and seasonal snow cover in the Indus, Ganges, Brahmaputra, Amu Darya, Syr Darya and Mekong river basins are for the first time systematically analyzed at the basin scale. The baseline (1961-1990) status of each basin's glacier system is evaluated using a comprehensive meta-database for the 48,607 glaciers, which represents a new data product in its own right compiled specifically for this study. The data gaps in existing glacier inventories are identified and filled with expert estimates. The overlaps in glacier inventories are examined to avoid double counting of some data. Uncertainty of estimates of glacier system parameters is critically assessed and shown to be possibly as high as +(50-70)% for ice volume estimates, and around +20% for the glacier area and glacier numbers. The spatial pattern and structure of glacier systems are analyzed using size class frequency distributions of a number of individual glaciers, ice-covered area, ice volume, and where available – the data on variability of equilibrium line altitude, maximum and minimum elevations and elevation intervals. The Indus Basin is shown to have the largest and most diverse glacier system in terms of all parameters examined, while the glacier system in the Mekong Basin is the lowest in terms of size and diversity. It is illustrated that structural diversity of a glacier system determines how it responds to climate change. Recent changes in glacier systems are characterized using estimated annual rates of areal reduction and ice loss derived from data published by the World Glacier Monitoring Service (WGMS) and a compilation of sources based on remote sensing extending from 1960s to 2000s. It is shown that the total glacier area reduction in the study basins in this period is within 14-28% range, and ice volume loss is within 11-40% range. Changes in maximum seasonal snow cover area and maximum seasonal water storage capacity between the periods 1961-1990 and 2001-2010 are assessed using the monthly data from terrestrial water budget data archive of Delaware University, USA. The reduction of maximum seasonal snow cover area was up to 5-15%, while the maximum seasonal water storage capacity decreased by 9-27% in almost all study basins apart from Mekong. Glacier sensitivity to climate change (CC) is examined in terms of the critical warming signal, which would be required for the complete disappearance of glaciers in a basin under the assumption of 3% changes in precipitation per degree of global air temperature rise. It is shown that Syr Darya and Mekong basins are likely to become almost glacier-free under the projected warming temperature of 4-5 °C by the end of the twenty-first century. In Indus, Ganges, Brahmaputra and Amu Darya river basins, glaciers belonging to the large and medium size classes are expected to survive the warming of 4-5 °C, with total basin ice reserves reduced to 20-50% of the baseline 1961-1990.

Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Water Storage Properties under Changing Climate

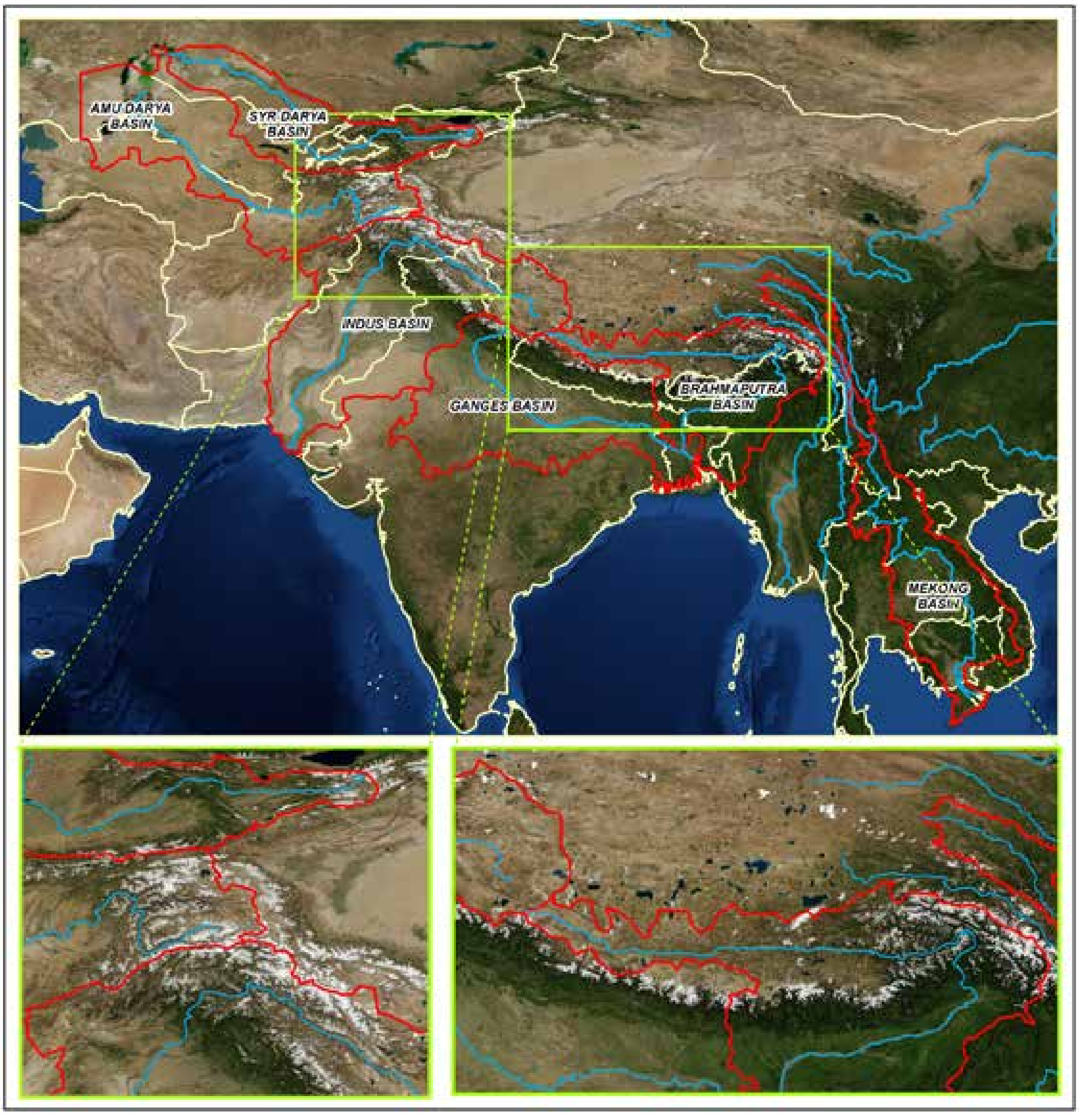
Oxana S. Savoskul and Vladimir Smakhtin

Introduction

Glaciers and seasonal snow are important water resources in basins of the major rivers originating from the Asian mountains – namely Indus, Ganges, Brahmaputra, Mekong, Amu Darya and Syr Darya. These basins (Figure 1) collectively host around 1/6 of the world's population primarily represented by poor rural men and women, whose livelihoods and food security directly depend on basin water resources and their possible changes. Impacts of CC on glaciers and snow in High Asia have recently attracted significant attention (Barry 2005, 2006; WWF 2005, 2009; Rees and Collins 2006; IPCC 2007, 2010; Zhang et al. 2007; Braun et al. 2009; Eriksson et al. 2009; UNEP 2009; Gosain et al. 2010; Malone 2010; Kääb et al. 2012; Cogley 2012; Yao et al. 2012; Committee on Himalaya Glaciers, Hydrology, Climate Change, and Implications for Water Security 2012). However, a lot of controversy remains in the current scientific knowledge of the subject (Bolch et al. 2012; Viviroli et al. 2011).

One major gap is the absence of the assessments of past and current water storage-related properties of glaciers and seasonal snow at the scale of major river basins. Existing large-scale assessments, which were carried out in High Asia typically report total figures on the number of glaciers, glacier-covered area, total ice volume and seasonal snow properties either for large mountain systems such as Himalaya, Karakoram, Tibetan Plateau, Hindukush, Tien Shan and Pamir (Tsarev et al. 1986; Kotlyakov 1997; Dyurgerov and Meier 2005; Yao et al. 2007, 2012; Bajracharya et al. 2008; Dyurgerov 2010; Cogley 2011; Bolch et al. 2012) or for the territories confined by national boundaries (Kravtsova and Tsarev 1997; Mool et al. 2001a, 2001b, 2004, 2005; Karma et al. 2003; Mool and Bajracharya 2003; Bhagat et al. 2004; Sah et al. 2005; Alford et al. 2009; Alford and Armstrong 2010; Ersi et al. 2010). A single summative study carried out at the basin scale in the Hindu Kush-Himalayan (HKH) region (Bajracharya and Shrestha 2011) fills the knowledge gap only partially, since this study covers only four basins fully and presents a snapshot of basins' glacier status only in 2005±3, i.e., does not provide a reference line for analyzing glacier systems' evolution prior to 2000s. For the Aral Sea region, there are detailed basin-scale assessments of glacier status (Lebedeva and Larin 1991; Lebedeva 1997; Dyurgerov et al. 1995; Shetinnikov 1998), but those were published in Russian and, as such, remain largely unknown to the wider research community. Therefore, the first objective of this study is to compile and analyze all available primary and principal secondary data on glaciers and seasonal snow cover for the study basins during the past 50 years, focusing on the 30-year baseline interval of 1961-1990 and the first decade of the new millennium 2001-2010.

FIGURE 1. Map showing the boundaries of the study basins (red line), state borders (light yellow line) and snow-covered high-elevation belts where glaciers are located. At this resolution, individual glaciers cannot be distinguished.



Another major gap in the current knowledge of the subject is poor understanding of the large-scale processes of glacier and snow evolution under CC (Viviroli et al. 2011; Bolch et al. 2012; Cogley 2012). Numerous publications focusing on this topic vary from research papers to reviews commissioned by nongovernmental organizations (NGOs), development agencies and mass media (Singh and Bengtsson 2003; Hagg and Braun 2006; Ren et al. 2006; Xu et al. 2007; Jowit 2008; Alford et al. 2009; Hasnain 2009; Raina 2009; Schmidt and Nüsser 2009; Absar 2010; Archer et al. 2010; Armstrong 2010; The Economist 2010; Malone 2010; Shekhar et al. 2010; Qiu 2008, 2010; Singh et al. 2011). Yet, actual hard-core research on this subject has been relatively limited. For example, lessons learned from monitoring of recent changes in glacier systems and structural analysis of their spatial organization received very little attention (Xie et al. 2006). Snow evolution, however, is understood somewhat better (Barnett et al. 2005; Immerzeel et al. 2009), but most basin-scale studies either lack a long-term perspective or do not clearly

distinguish between seasonal snow and glaciers. The most detailed study in the HKH region (Gurung et al. 2011, p. vii) reported that, "Decadal (2000-2010) snow cover area figures for the HKH region were insufficient to yield a statistically significant trend…" The second aim of this report is, therefore, to critically review and synthesize all current scientific knowledge on the recent (last 50 years) changes in seasonal snow and glaciers into a coherent and physically plausible picture of the evolution of seasonal snow and glaciers under CC.

The previous studies focused on the assessment of future changes of glaciers and snow under CC impact lack either basin-wide scope or the consistency in the scenarios used (Ye et al. 2003; Singh and Bengtsson 2003, 2004; Rees and Collins 2006). The third objective of this report is to critically overview currently available CC-impact assessments and to infer the most likely future changes in glacier systems and seasonal snow cover in response to CC, which might serve as guidelines for future modeling of various aspects of regional water cycle and water availability in the study basins.

Each of the three principal lines of enquiry (fixed-date snapshots, monitoring of recent changes, and assessment of CC impact on glaciers and snow) has its own section in this report. Each section describes relevant data types and methods, followed by summaries of the data available for the study basins. Particular attention is paid to discussion of the data and methods' accuracy and reliability. Wherever possible, error margins of the most common methods are evaluated. The climatological background of glacier and snow existence has been broached in this report only where it was needed for the clarification of terms and methods.

This report is the first in a series of two. A subsequent second report (Savoskul and Smakhtin 2013) deals with the hydrological role of snow and glaciers in the study basins.

Terms and Definitions

The recent growth in the number of publications on glaciers and snow in Asia is associated with growing confusion with regards to the context of some commonly accepted terms. To overcome this issue, the terms used in this report and major glaciological concepts standing behind these terms are explained below.

'Glacier' is defined here as a natural ice body made out of snow consolidated under its own weight and large enough to flow under force of gravity, either in a spreading pattern from an elevated center towards the edges (dome-shaped ice sheets and ice caps) or downward (mountain glaciers) (Hambrey and Alean 2004; Benn and Evans 2006; Zemp et al. 2009a). Glaciers have a high inter-annual water storage capacity, of which their intra-annual or seasonal water storage capacity makes only a fraction. Part of the atmospheric precipitation accumulated in a glacier annually is released into hydrosphere during the warmer part of the same year, i.e., with a delay of a few months, the other part of annual accumulation melts with a delay of several decades and even centuries (Jansson et al. 2003; Kaser et al. 2005, 2010). The mechanism of water release relies on the ice flow from higher elevations, where it is cold enough for the dominance of multi-annual ice accumulation, to lower elevations, where the air temperature is high enough for 'ablation', i.e., ice loss, to prevail over accumulation. Under a stable climate, these processes are in balance and glaciers are in a steady state, which means that they retain their mass and volume with minor fluctuations due to inter-annual variability in precipitation and air temperature.

The progressive CC disrupts the balance. Long-term mass loss or gain leads to glacier areal ‘reduction’ or ‘expansion’, respectively, and either retreat or advance of its frontal part. The time of a glacier’s response to a CC signal, i.e., the period needed for attaining a new steady state varies from a few years to several decades depending on the glacier’s size and climatic conditions (Barry 2006; Benn and Evans 2006).

Although glacier accumulation and ablation in the mountains occur within overlapping elevation belts, a glacier can be subdivided into upper and lower parts termed ‘accumulation area’ and ‘ablation area’, respectively. The former is the part of a glacier where the net annual accumulation is higher than the net annual ablation. The latter is the part where ablation prevails over accumulation in the annual cycle. The border between accumulation and ablation areas is termed ‘the equilibrium line’. The equilibrium line altitude (ELA) is defined as an altitude where net mass balance, i.e., the difference between mass loss and gain, equals zero.

Mountain glaciers are highly diverse in size and morphology (Figure 2). The area of an individual glacier may vary from less than 0.1 km^2 to over 1,000 km^2. The morphological type of a glacier depends mostly on its size and the shape of underlying terrain. Small glaciers hang on the slopes being nested in all suitable hollows, such as niches, shelves, recessions and large crevices. The medium-sized glaciers are situated in cirques and in the upper parts of trough valleys. The large glaciers are typically composed of a number of glaciers originating from side valleys, which adjoin a major glacier body located in the main valley. High-elevated table-top summits are crowned with spreading glaciers of ice-cap type with one or more outlet flows. In the morphological classification, the principal types are distinguished, respectively, as ’hanging’, ‘cirque’, ‘valley’, ‘compound valley’ and ‘table-top summit’ glaciers. Glaciers are dispersed across wide areas and are generally aligned with high elevations (Figures 1 and 2). A group of glaciers located within a large territory, i.e., a mountain range or a major river basin, is termed ‘glacier system’ (Kotlyakov 1997).

FIGURE 2. Left: Google Earth view of scattered small glaciers of hanging (h), cirque (c) and valley (v) type in the Pskem sub-catchment of the Syr Darya Basin, Uzbekistan. Right: An intensively glaciated area in the Indian State of Jammu and Kashmir, Upper Indus Basin, where large compound valley (cv) glaciers and medium-sized simple valley glaciers (v) dominate the landscape. Scale in both images is the same.

Seasonal snow in the mountains is another important component of the regional water cycle. It has a high water storage capacity due to its large areal extent, significantly exceeding that of glaciers. Contrary to glaciers, seasonal snow accumulates and discharges water mainly within one annual cycle. Snow that falls on a glacier surface should be considered as part of the glacier, since it gets involved in the glacier water cycle. The snow that lasts over years on an ice-free terrain forms 'perennial snow fields' or 'snowpacks'. These are normally of small thickness in the order of the first few meters or less. Areal extent and water storage capacity of perennial snowpacks is insignificant compared to glaciers and seasonal snow. Alpine 'permafrost', i.e., a ground being frozen for more than two consecutive years, might contain, in some instances, considerable amounts of frozen water (Bolch and Marchenko 2009; Gorbunov 2009). Nonetheless, since perennial snow and permafrost participate in annual accumulation–ablation cycle only marginally, their role in the regional water cycle is minor too. Perennial snow and permafrost, however, are not considered in this report.

In this report, water storage properties of glacier systems and seasonal snow cover are understood as properties essential for both water storage and release, which depend a lot on the spatial properties of the systems. Therefore, apart from basin total volume of water accumulated in the systems, other principal water storage-related characteristics are areal extent (and in the case of glacier systems, number of glaciers). Elevation-related characteristics of glacier systems are considered too, since those are crucial for understanding structure and evolution of glacier systems, i.e., seeing water storage properties of the system in a broader time and space perspective.

Water Storage Properties of Glacier Systems in the Study Basins

Compilation of Meta-database of Primary Data for Glacier Systems

Compiling a single data bank of statistically reliable information on individual glaciers in the study basins is a challenging task, because none of the existing sources of readily available statistical data covers the entire glaciated area of the study basins. Glacier inventories of the first generation (e.g., ICIMOD 2007; WGMS and NSIDC 2009) are based on topographic and airborne imagery-based surveys of individual glaciers conducted mainly between 1960s and 1980s. The inventories of this type are most appropriate for large-scale studies, since they cover virtually every region in the world and contain readily accessible statistics on the location and morphometric parameters of every single glacier in a surveyed area. The disadvantage of this source is that there are few data gaps in the glacier inventories of the first generation, which have to be filled by expert estimates. Besides, since glacier inventories are compiled by data of single-date snapshots of glacier status at the date of a survey, glacier statistics for the areas with differences in the dates of glacier surveys or differences in methods of survey is not entirely compatible. However, since the inventories of the first generation had been compiled in the period when changes in glacier systems were relatively moderate, in general they are considered to be a suitable source for representing the baseline 1961-90 status of glaciers in High Asia (Cogley 2009a, 2012).

Inventories of the second generation are compiled of the raw remote-sensing imagery

obtained shortly before or after 2000, e.g., Global Land Ice Measurements from Space (GLIMS) initiative (Raup et al. 2007; http://www.glims.org/; updated version: http://www.glims.org/RGI/randolph.html) and Satellite Image Atlas of Glaciers of the World (SIAGW) (Williams and Ferrigno 2010). The disadvantage of these sources for large-scale studies is that a lot of analytical work is required to delineate and measure individual glaciers in order to assess the statistics on glacier parameters and patterns of spatial organization of glacier systems (Bajracharya and Shrestha 2011).

In this study, statistical description of glacier system parameters (number of glaciers, glacier-covered area and ice volume) is based on i) an analysis of a mega-dataset compiled from all the available up-to-date inventories of the first generation for each study basin (that includes 48,607 glaciers); ii) expert estimates for the existing data gaps, e.g., areas not covered by detailed inventories; and iii) published sources based on the inventories of the second generation (Table 1).

The first primary data source for glaciers in the study basins is the World Glacier Inventory (WGI) (WGMS and NSIDC 2009). The WGI is a searchable internet resource that contains information on: glacier's name, code (which points to the country, major river basin, sub-catchment and glacier's individual number); glacier's coordinates, maximum and minimum elevations, orientation, glacier's area, maximum, mean and minimum length, mean width, mean ice thickness, ELA; glacier type according to several classifications; dates and methods of glacier survey; and accuracy of given parameters (http://nsidc.org/data/docs/noaa/g01130_glacier_inventory/). The WGI data (WGMS and NSIDC 2009) are compiled from national inventories (e.g., Katalog Lednikov SSSR [Inventory of glaciers of the USSR] 1982; Kulkarni and Buch 1991), which have been digitized in 1996 (Haeberli et al. 1989; Bedford and Haggerty 1996). The WGI (WGMS and NSIDC 2009) is a perfect data source for glaciers in China and countries of the former USSR, i.e., Tajikistan, Uzbekistan, Kyrgyzstan, and Kazakhstan. It, however, gives inaccurate information for glaciers in Nepal and Bhutan and contains incomplete datasets for India, Pakistan and Afghanistan, covering just 89, 214 and 263 glaciers, respectively. From the river basin perspective, WGI (WGMS and NSIDC 2009) has full coverage for the Syr Darya and Mekong basins, partial coverage for the Brahmaputra, Amu Darya and Indus basins, and no information for the Ganges Basin. An extended version of WGI, so-called WGI-XF (Cogley 2009a, 2011) was compiled recently and is available on request from Graham Cogley (Trent University, Canada) and online (http://people.trentu.ca/~gcogley/glaciology/index.htm).

The second resource complementing WGI (WGMS and NSIDC 2009) in High Asia is the database of the International Centre for Integrated Mountain Development (ICIMOD 2007). The ICIMOD (2007) inventory fills almost all the blanks in the WGI (WGMS and NSIDC 2009), providing data for the entire Ganges Basin, Lower Brahmaputra Basin and major parts of the Indus Basin. It covers glaciers in Pakistan, Nepal, Bhutan and three out of the four states in India, where glaciers are located: i) Sikkim, ii) Himachal Pradesh, and iii) Uttarakhand (former Uttaranchal), leaving only Arunachal Pradesh uncovered. The ICIMOD (2007) database is structured as a series of national and sub-national inventories (Mool et al. 2001a, 2001b; Mool and Bajracharya 2003; Mool et al. 2005; Bhagat et al. 2004; Sah et al. 2005; Lizong et al. 2005) accessible on request from ICIMOD (infomenris@icimod.org). Each publication in this series (ICIMOD 2007) is presented by a report on geographical settings, materials and methods used in the survey, a general accuracy estimate and statistical summary of the data, supplemented with schematic sub-catchment maps and glacier inventories per se placed in the appendices of the reports.

Compared to WGI (WGMS and NSIDC 2009), the ICIMOD (2007) database is less

TABLE 1. Description of meta-database on glaciers compiled for this study.

Country, years of topographic survey		Number of glaciers	Area (km^2)	Volume (km^3)	Inventory-covered part of the glaciated area (%)	Source, comments
INDUS BASIN						
Pakistan, 1934, 1977		5,218	15,060	2,729	100	ICIMOD 2007; Mool et al. 2005. Data set has an overlap with WGI-XF and an error.
		(214)	(1,654)	n.s.	11	WGI series PK5Q130-131 (WGMS and NSIDC 2009). Small and biased sample, includes only large glaciers.
		5,052*	12,664*	2,039*	100	Authors' estimate based on identified overlaps and errors; ice volume estimate is done by application of ICIMOD (2007) method.
India, 1950-70s 1966-68	Himachal Pradesh	2,510	4,125	385	100	ICIMOD 2007; Bhagat et al. 2004 (excluding series Subbasin_3, glaciers 1-20, and series Subbasin_4).
		(89)	(244)	n.s.	2	WGI series IN5Q111 (WGMS and NSIDC 2009). Small sample.
	Jammu and Kashmir	n.s.	4,000*	n.s.	100	Cogley 2009a.
		3,377*	9,347*	n.a.	100	Authors' estimate, based on Cogley 2009a, 2011.
India, 1961-90		5,864	13,458	1,694*	100	Number of glaciers and area: WGI-XF series IN5Q150-IN5Q340 (Cogley 2009a); ice volume: authors' estimate done by ICIMOD (2007) method.
China, 1971-83		2,033	1,451	95	100	WGI series CN5Q142-CN5Q222 (WGMS and NSIDC 2009)
Afghanistan, 1972-82		656*	186*	8*	0	Number: (Shroder and Bishop 2010); area: authors' estimate based on Lebedeva and Larin (1991) and Lebedeva (1997); volume: authors' estimate based on scaling approach (Bahr et al. 1997).
1959		(263)	(130)	n.s.	70	WGI series AF5Q132 (WGMS and NSIDC 2009).
OVERLAPS and ERRORS		29	1,749	388		Subset of glaciers from disputed territory between India and Pakistan double counted in WGI-XF series 5Q151 (Cogley 2009a, 2011) and ICIMOD glacier Inventory (Pakistan) series Shyk_gr_194 to Shyk_gr_222 (ICIMOD 2007; Mool et al. 2005).
		137	647	61		Subset of glaciers from Yergiang (Tarim) basin erroneously listed as belonging to Indus Basin in glacier Inventory for Pasistan, series Hunza_914 to Hunza_1050 (ICIMOD 2007; Mool et al. 2005).
INDUS BASIN SUM		13,605*	27,759*	3,839*	99	Authors' estimate.

(Continued)

TABLE 1. Description of meta-database on glaciers compiled for this study (Continued).

Country, years of topographic survey		Number of glaciers	Area (km^2)	Volume (km^3)	Inventory-covered part of the glaciated area (%)	Source, comments
GANGES BASIN						
Nepal, 1950-70s, 1992,1996		3,252	5,323	482	100	ICIMOD 2007; Mool et al. 2001a.
1977		(130)	(1,642)	n.a.	31	WGI series NP5O120 (WGMS and NSIDC 2009). Small and biased sample, includes only large glaciers.
India, 1960-70s	Uttarakh and Himachal Pradesh	1,438	4,060	476	100	ICIMOD 2007; Sah et al. 2005.
		44	35	2	100	ICIMOD 2007; Bhagat et al. 2004. Series Subbasin_3 (glaciers 1-20), Subbasin_4
India, 1961-90		1,481	4,072	n.s.	100	WGI-XF series IN5O142-IN5O163 (Cogley 2009a).
China, 1970s		2,192	3,609	330	100	WGI series CN5O161-CN5O198 (WGMS and NSIDC 2009). The dataset erroneously includes several subsets of glaciers from India from the bordering territories.
China, 1961-90		2,027*	3,277*	297*	100	Authors' estimate based on identified overlaps and errors.
China, 1988-92		(1,578)	(2,906)	n.s.		ICIMOD 2007; Lizong et al. 2004.
China, 1999-2001		(1,578)	(2,864)	n.s.		ICIMOD 2007; Lizong et al. 2004.
China, 2005		(1,841)	(2,579)	n.s.		Bajracharya and Shrestha 2011.
OVERLAPS AND ERRORS		113	260	27		WGI series CN5O161 is erroneously included into Chinese inventory WGMS and NSIDC 2009. It overlaps partially with WGI-XF series IN5O152B (Cogley 2009a) and partially with ICIMOD inventory, Himachal Pradesh, India, series subbasin_3 (ICIMOD 2007).
		52	83	6		WGI series CN5O163 is erroneously included into Chinese inventory WGMS and NSIDC 2009. It overlaps with WGI-XF series IN5O153E (Cogley 2009a).
		42	144	15		WGI series CN5O195 is a closed interior basin, is not included in the basin total count.
GANGES BASIN SUM		6,719*	12,541*	1,243*	100	Authors' estimate.

(Continued)

TABLE 1. Description of meta-database on glaciers compiled for this study (Continued).

Country, years of topographic survey		Number of glaciers	Area (km^2)	Volume (km^3)	Inventory-covered part of the glaciated area (%)	Source, comments
BRAHMAPUTRA BASIN						
China, 1970s		10,816	14,493	1,292	100	WGI series CN5O204-CN5O291 (WGMS and NSIDC 2009). The data set erroneously includes several subsets of glaciers from India and Bhutan.
		10,453*	13,660*	1,209*		Authors' estimate based on identified overlaps and errors.
Bhutan, 1950-70s or 1990s		677	1,316	116	100	ICIMOD 2007; Mool et al. 2001b.
1978		(96)	(1,341)			WGI series BH5O111 (WGMS and NSIDC 2009) wrong number of glaciers.
India	Sikkim, 1990s, 2000s	285	576	65	100	ICIMOD 2007; Mool and Bajracharya 2003.
	1970s	449	705	n.s.	100	WGI-XF series IN5O201 (Cogley 2009a).
	Arunachal Pradesh ,1960s	417	566	n.s.	100	WGI-XF series IN5O207, 209, 211, 290, 291 (Cogley 2009a).
			500*	70		Kotlyakov 1997.
India all glaciers 1960s		866	1,271	162*	100	WGI-XFseries IN5O201-IN5O291 (Cogley 2009a).
OVERLAPS AND ERRORS		59	388	52		A subset from ICIMOD glacier inventory, Bhutan, series_Out (ICIMOD 2007; Mool and Bajracharya 2003) is erroneously double counted in WGI CN series CN5O212A, 240, 251 (WGMS and NSIDC 2009).
		91	173	13		A subset from WGI-XF series IN5O209 (Cogley 2009a) is erroneously double counted in WGI CN series CN5O220 (WGMS and NSIDC 2009).
		112	168	12		A subset from WGI-XF series 211AA, 211AB (Cogley 2009a) is erroneously double counted in WGI CN series CN5O221A (WGMS and NSIDC 2009).
		97	104	7		A subset from WGI-XF series IN5O290 (Cogley 2009a) is erroneously double counted in WGI CN series CN5O290 (WGMS and NSIDC 2009).
BRAHMAPUTRA SUM		11,996*	16,248*	1,487*	100	Authors estimate.

(Continued)

TABLE 1. Description of meta-database on glaciers compiled for this study (Continued).

Country, years of topographic survey	Number of glaciers	Area (km^2)	Volume (km^3)	Inventory-covered part of the glaciated area (%)	Source, comments
AMU DARYA BASIN					
Tajikistan, 1950-60s 1980	7,566	8,460	624	100	WGI series SU5X14301 to SU5X14317 and series SU5X14320 (WGMS and NSIDC 2009; Katalog Lednikov SSSR (inventory of glaciers of the USSR 1982)).
	9,805	7,257	468	100	Shetinnikov 1998.
Afghanistan, 1972-82 1970-80s	n.s.	3,018	180*	0	Number, area: Lebedeva and Larin (1991); volume: authors.
2005+3	2,493*	n.s.	n.s.	0	Shroder and Bishop 2010.
	(347)	(341)	n.s.	14	Small sample: WGI series AF5X140 (WGMS and NSIDC 2009).
	3,277	2,566	163	0	Bajracharya and Shrestha 2011.
OVERLAPS AND ERRORS	310	377	24		WGI series SU5X17 is a closed interior basin, it is not included in the basin total count.
AMU DARYA SUM	9,749*	11,101*	780*	71	Authors' estimate.
SYR DARYA BASIN					
Kyrgyzstan, Uzbekistan, Tajikistan, 1950-70s	3,429	2,522	133	100	WGI series SU5X141 (WGMS and NSIDC 2009; Katalog Lednikov SSSR (inventory of glaciers of the USSR) 1982) Series 14 (1) The glaciers of the former Soviet Republics bear common SU identification
MEKONG BASIN					
China, 1980s	380	316	18	100	WGI series CH5L (WGMS and NSIDC 2009).

Notes: Data used for the basin assessments as presented in Figure 3 are highlighted in grey.

* = Expert estimates; n.a. = non-applicable; n.s. = not stated. Figures in round brackets are statistically non-representative samples.

informative in the following respects: i) coding system for individual glaciers points only to the sub-catchment, but gives no indication of major river basin; ii) fewer parameters per glacier, i.e., only geographic coordinates, area, length, ice thickness, ice volume and glacier orientation (the data on glacier elevations are available only for Nepal, Bhutan and parts of India (Uttarakhand state)); iii) with the exception of Lizong et al. 2005, lack of clarity on the survey dates for individual glaciers (which may lead to significant discrepancies between measurements of the areal extent of glaciers taken from topographic maps produced in 1950-1970s and the recent satellite imagery of 1990-2000s, since both are reportedly used in the catalogues); and iv) lack of accuracy ratings for glacier morphometric parameters, except ELA.

The combined dataset of glacier inventories accessible online, i.e., WGI (WGMS and NSIDC 2009), WGI-XF (Cogley 2009a) and ICIMOD (2007), till recently had two major data gaps in the upper parts of the Indus and Amu Darya basins (Cogley 2009a). One gap has been the lack of detailed data on glaciers in the part of the Indus Basin that is located in the Indian State of Jammu and Kashmir, a tiny sample of which (133 glaciers with a total area of 94 km^2) had been catalogued by the Geological Survey of India (Kaul 1999), according to Sah et al. (2005). According to a preliminary estimate by Cogley (2009a), the entire glacier-covered area in this state was 4,000 km^2. This data gap has been filled recently by Cogley (2011): inventorization of individual glaciers in this study based on Soviet topographic maps produced in the 1970s yielded a figure of 9,345 km^2. Data on individual glaciers in the State of Jammu and Kashmir have been recently included in WGI-XF (Cogley 2009a, 2011).

The second data gap in the glacier inventories of the first generation, i.e., covering period 1961-1990, remains unfilled to date: it is the absence of detailed statistics on glaciers that make up in sum 85% of the glaciated area in Afghanistan. The WGI (WGMS and NSIDC 2009) only contains data for a small sample of 610 glaciers with a total area of 472 km^2, i.e., 15% of the glaciated area of the country. The expert estimates for the amount of glaciers, glacier areal extent and volume of ice are presented in Table 1. According to Lebedeva and Larin (1991), the University of Kabul had compiled a full glacier inventory of Afghanistan in 1984-1988, but the whereabouts of this document are unknown at present (Irina Markovna Lebedeva, Institute of Geography Russian Academy of Sciences, Moscow, Russia, pers. comm., August 2, 2012). The inventory of Kabul University contained data for 1,515 glaciers with a total area of 3,210 km^2, of which 186 km^2 were in the Indus Basin and 3,018 km^2 – in the Amu Darya Basin (Lebedeva and Larin 1991; Lebedeva 1997). Shroder and Bishop (2010) estimate the total number of glaciers in Afghanistan as 3,149 and the total glacier-covered area as 2,700 km^2. The differences between these sources are most likely due to the differences in the dates of surveys and the lowest area limit accepted for the glaciers to be recorded. None of the published sources provides estimates for the ice volume of glaciers in Afghanistan. The ice volume estimate presented here (Table 1) is made using glacier area-volume scaling approach (Chen and Ohmura 1990; Bahr et al. 1997).

Analysis of the meta-dataset on glaciers in the study basins (Table 1) revealed a number of data overlaps between different sources or otherwise conflicting information. In the datasets for the Indus Basin, there is a double coverage in WGI-XF and ICIMOD database for the territory disputed between India and Pakistan (ICIMOD 2007) with a total glacier area overlap of 1,749 km^2; and apart from that a subset of glaciers with a total area of 647 km^2 from the Tarim Inland Basin is erroneously listed in ICIMOD database (ICIMOD 2007) as belonging to the Hunza Sub-basin of the Indus Basin. In the datasets available for the Ganges Basin, WGI (WGMS and NSIDC 2009) attributes a Chinese code to two subsets of glaciers located in India with a total area of 332 km^2. There is also a similar confusion regarding 424 glaciers in

the Brahmaputra Basin with a total area of 833 km^2, which are located in the northern territories of Bhutan and India bordering China. ICIMOD (2007) provides no information on glaciers in Arunachal Pradesh State in its coverage for India, whereas WGI (WGMS and NSIDC 2009) contains data on these glaciers under a misleading country code of China.

Large-scale efforts to repeat the glacier inventorization, several decades after the first glacier surveys, were undertaken in the study basins several times but the resulting inventory (providing i.a. morphometric parameters of individual glaciers) was published only in one case/instance (Lizong et al. 2005). This is a re-inventorized subset of 1,578 glaciers from a part of the Ganges Basin located in China and previously surveyed in the 1970s-1980s (WGMS and NSIDC 2009).

Another effort of this kind is an unpublished inventory by A. Shetinnikov (Central Asian Institute of Hydrometeorological Studies, Tashkent), which includes 11,358 glaciers in Pamir and Gissar-Alay mountains, based on the materials of an aerial survey conducted in 1980. This territory had been previously covered by WGI data based on a survey conducted in the late 1950s to early 1960s (WGMS and NSIDC 2009). Statistical analysis and comparisons between old and new inventories for separate sub-catchments of Amu Darya and Syr Darya basins are available from Shetinnikov (1998).

An unprecedented large-scale glacier re-inventorization in the HKH region based on the satellite imagery from 2005$\pm$3, was finalized in 2011 under the leadership of ICIMOD (Bajracharya and Shrestha 2011). The report contains no data on individual glaciers, but provides an extensive statistical data summary on the various parameters of glacier systems at the sub-catchment level for the entire Brahmaputra, Ganges, Indus and Mekong basins, with partial coverage for the Amu Darya Basin (Bajracharya and Shrestha 2011).

Methods of Glacier Surveys and Associated Uncertainties of Primary Data

The principal statistical parameters used to describe large glacier systems are: a) number of glaciers; b) total glacier-covered area; c) total ice volume; d) average maximum and minimum elevations of glaciers; e) average vertical extent (i.e., the difference between maximum and minimum elevations of glaciers); and f) average ELA. The accuracy of estimates of these parameters varies a lot depending on the reliability of glacier inventories, the methods used to evaluate the morphometric characteristics of individual glaciers, the differences between the dates of glacier surveys for the separate subsets used to compile the entire dataset and the human factor in analyzing the data of glacier surveys.

The methods of glacier surveys make possible the accounting of every single glacier. The measurements of individual glacier parameters taken directly from topographic maps, and airborne and satellite imagery, such as glacier length, area and elevation-related parameters, have a high accuracy with error margins of the first few percent of the parameter value (Zemp et al. 2009a). However, the number of glaciers and individual glacier parameters typically have been changing in the course of past few decades under CC impact. Therefore, the accuracy of total and average estimates of those parameters for a glacier system is significantly less, since the datasets for the large territories are compiled from the surveys conducted on different dates.

An example of extreme uncertainty of glacier estimates derived from different sources is in the part of the Ganges Basin that is located in China. The first glacier inventory compiled for this territory, WGI (WGMS and NSIDC 2009) lists 2,027 glaciers with a total area of 3,267 km^2 based on the survey conducted during the period 1970-1980. Second inventory for the same territory (ICIMOD 2007; Lizong et al. 2005) includes 1,578 glaciers covering an area of 2,906

km^2 in 1990, which decreased to 2,864 km^2 by the year 2000 (Lizong et al. 2005). Since no coordinates are given for individual glaciers in the ICIMOD database (Lizong et al. 2005) and its glacier identification numbers are not compatible with those of the WGI (WGMS and NSIDC 2009), it is impossible to make glacier-by-glacier comparison of the two datasets. Hence it remains unclear, whether 450 glaciers disappeared within a time span of 10-20 years in the area where the following decade (1990-2000) saw no changes at all in the number of glaciers (Lizong et al. 2005), or the reason for the discrepancy in the number of glaciers between the two inventories can be attributed to the human factor in conducting glacier surveys.

Glacier estimates for the part of the Amu Darya Basin that is located in Tajikistan have high uncertainty too. In case the data from the inventory of Shetinnikov (1998) based on a glacier survey conducted in 1980, were used instead of WGI data based on surveys of late 1950s (early 1960s), the assessment of the number of glaciers in the entire basin would go higher by 20%, whereas the area estimate would have become lower by 20%. However, the WGI dataset (WGMS and NSIDC 2009) is not fully compatible with that of Shetinnikov (1998), since the former includes only glaciers > 0.1 km^2 whereas the latter listed all glaciers. In case the glaciers < 0.1 km^2 were excluded from the inventory of Shetinnikov (1998), the resulting estimate of glacier number and area in that part of the basin would drop by 8% and 2%, respectively, compared to the status of 1950s (early 1960s).In view of the discrepancy in the dates of the glacier surveys, size of a smallest glacier included in an inventory and human factor in data processing, the best possible accuracy for assessment of glacier numbers and area in High Asia for the baseline time period 1961-1990 is within ±20% (Cogley 2009a, 2009b, 2011; Dyurgerov 2010). To reduce the uncertainty range of glacier areal estimates, Dyurgerov (2010) suggested assessing the glacier areal extent in a certain year by adjusting the baseline glacier area by the rate of glacier areal reduction in the recent decades. However, in the opinion of the authors of this report, currently available data of glacier area monitoring are hardly sufficient to justify adoption of this measure for the study basins.

The assessments of ice volume and ice thickness of glaciers have even lower accuracy compared to glacier area and number of glaciers, since the methods employed for the evaluation of glacier ice volume in existing inventories of the first generation (ICIMOD 2007; WGMS-NCIDS 2009; Cogley 2009a) are simple empirical models validated with few dozens of field measurements at best, which certainly do not provide statistically reliable samples (Fountain et al. 2009; Farinotti et al. 2009; Cogley 2009b, 2012). The modern methods which allow assessment of glacier volume and thickness from the topographic maps and remote-sensing imagery with relatively good accuracy (Nuth and Kääb 2011; Farinotti et al. 2009) had not been developed at the time of most glacier surveys used in the glacier inventories of the first generation. As a result, the uncertainties of glacier ice volume estimates in glacier inventories remained in most cases simply undefined.

In order to assess the uncertainties of ice volume estimates in the study basins, a cross-comparison of the methods adopted in glacier inventories used in this report (ICIMOD 2007; WGMS and NSIDC 2009; Cogley 2009a, 2011) is carried out (Table 2). In the former USSR, the empirical models of ice volume evaluation were calibrated using relatively abundant data, i.e., around 60 radio-sounding records of ice thickness (Aizen et al. 2007). Hence, the assessments of glaciers' volume in the Aral Sea region are likely to be relatively accurate. The empirical model used in glacier inventories for the Chinese territory relies on the measurements from the Northern Tien Shan (Mi and Xie 2002). Its adoption for the Upper Brahmaputra Basin (WGMS and NSIDC 2009) is likely to increase uncertainty of the estimates, and even more so in the Lower Brahmaputra, Indus and Ganges basins (Mool et al. 2001a, 2001b; Mool and Bajracharya 2003; Bhagat et

al. 2004; Mool et al. 2005), where ice thickness estimates too are based on that model (Sah et al. 2005, p. 86). In other cases (ICIMOD 2007), ice volume assessments in the HKH region are based on a model developed for the Swiss Alps, which is also unlikely to yield accurate estimates of the glacier ice volume. For the assessment of the ice volume of the HKH glaciers in 2005±3 Bajracharya and Shrestha (2011) used the shear stress based model, which gives the most minimalistic estimate among all the currently employed ice volume estimation methods.

The calculations presented in Table 2 show that the ice volume estimates by the methods employed in existing glacier inventories may differ as much as twofold to threefold for glaciers of the same size. The differences are particularly great for the large glaciers. Since the large glaciers in any glacier system contain the most substantial portion of the basins' ice reserves, as demonstrated below, the error margins of ice volume evaluations for glacier systems in the major river basins may be roughly estimated as ±50-70% or worse.

Baseline (1961-1990) Status of the Glacier Systems

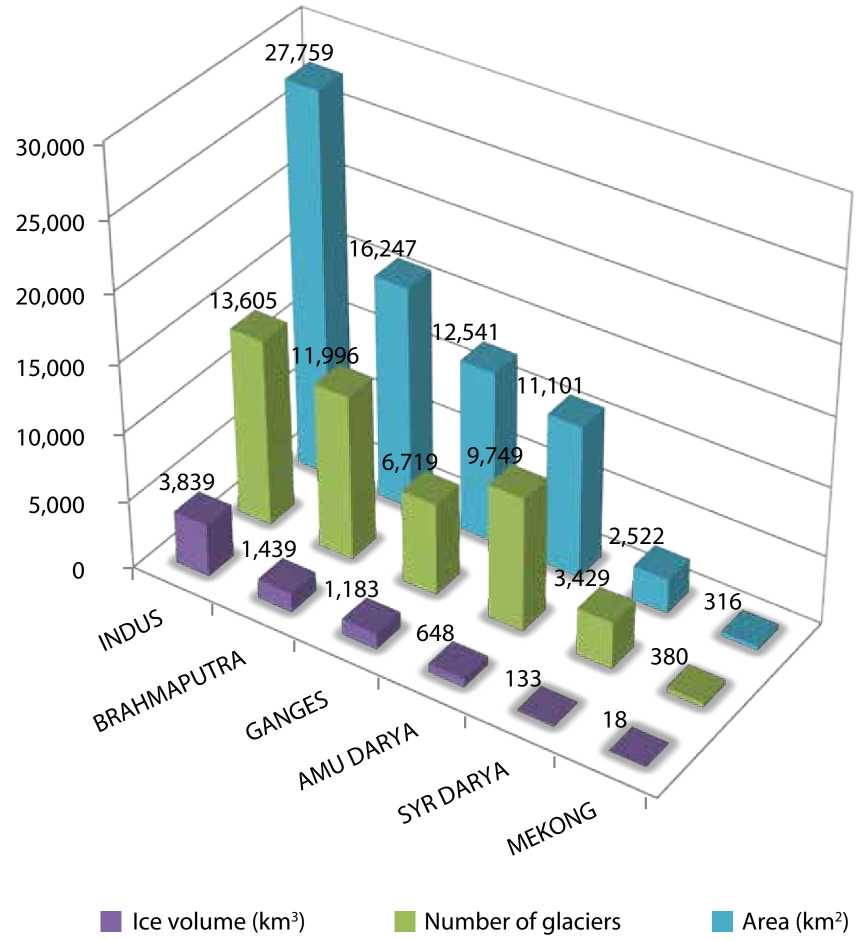
Assessment of the principal parameters of glacier systems in the study basins (number of glaciers, glaciated area and ice volume) for the baseline period 1961-1990 is presented in Figure 3. It is based on the analysis of the meta-database on individual glaciers described in Table 1.

Judging from all principal parameters describing baseline status of glacier systems in the study basins (Figure 3), the Indus Basin stands out as the one with the largest number of glaciers, largest glacier-covered area and largest ice volume. Next to it are the glacier systems in Brahmaputra and Ganges basins, which together have approximately the same ice volume and glaciated area as Indus Basin alone, but contain more glaciers. Glacier system in the Amu Darya Basin is closer to the Ganges and Brahmaputra than to the system of relatively modest proportions in the adjacent Syr Darya Basin. Glacier system of the Mekong Basin is the smallest glacier system among all the basins considered.

TABLE 2. The differences between ice volume estimates for the glaciers of the same areal size, as based on the methods employed in different glacier inventories.

Glacier area (km^2)	Ice volume estimate (km^2) by methods used in		
	WGI WGMS and NSIDC (2009)	ICIMOD (2007)	Bajrachariya and Shrestha (2011)
0.1	0.001	0.002	0.003
0.3	0.004	0.008	0.010
1	0.027	0.042	0.040
3	0.140	0.188	0.152
10	0.854	0.948	0.677
30	4.437	4.089	2.728
100	27.000	20.051	12.918
300	140.296	84.963	54.440
1,000	853.815	411.342	267.512

FIGURE 3. Baseline 1961-1990 parameters of glacier systems (in the Amu Darya and Syr Darya basins, glaciers < 0.1 km^2 are not included).



Data sources: As listed in Table 1.

Structural Features of Glacier Systems

The analysis of the systems' structure and spatial organization in this report is based on areal size frequency distributions of the number of glaciers, glaciated area and ice volume. Special attention is also given here to the elevation-related parameters: maximum and minimum glacier elevations, elevation interval and ELA.

Analysis of frequency distributions of the morphometric glacier parameters across areal size classes which increase in logarithmic order is the most optimal analytical tool for the groups composed of individual members, widely ranging in some characteristics (Haeberli and Hoelzle 1995). The frequency distributions presented in Figure 4 and Table 3 display a common pattern in all glacier systems, suggesting that glacier systems in all the study basins are structured in a similar way. The first feature that all basins have in common is that small glaciers dominate in numbers, but, in total, their share in the entire glacier-covered area is small and they contain a tiny fraction of the basin's ice reserves. For instance, in the Indus, Ganges and Brahmaputra basins, 71-75% of glaciers are from areal size classes of less than 1 km^2. Yet, the share of those glaciers in basins' glaciated area is around 12-17%, whereas the proportion of ice they store is a modest 3%, 4% and 8%, respectively.

Correspondingly, the bulk of the basin's ice is stored in a few glaciers belonging to the largest size classes. In the Indus Basin, the largest 112 glaciers (compound valley type, all larger than 33.3 km^2), comprise less than 1% of the entire glacier system, but contain 66% of its ice volume. Remarkably, 52% of the total ice reserves in the Indus Basin is stored in 25 extremely large Karakorum glaciers varying in size from 100 km^2 to over 1,000 km^2, which are among the largest mid-latitude glaciers on earth. The glacier systems in the Ganges and Brahmaputra basins are structured similarly: 69% and 60% of total ice reserves are stored in the largest three glacier size classes, which constitute 3.5% and 2.1% of all glaciers in those two basins, respectively, and are dominated by glaciers of the compound valley type.

The glacier size class distribution diagrams of the glacier systems in the Amu Darya and Syr Darya basins have the same pattern as those in the Ganges and Brahmaputra basins, with one essential difference: the number of areal size classes in Amu Darya and Syr Darya glacier systems is less than in the HKH region, therefore the role of the principal ice reserve storage is played by glaciers of smaller size classes (Table 3; Figure 4). In the Amu Darya Basin, 74% of ice is concentrated in medium-sized glaciers with areas between 1 and 33.3 km^2. In the Syr Darya Basin, 71% of its ice belongs to small to medium-sized glaciers ranging from 0.33 to 10 km^2. Correspondingly, the type of glaciers where bulk of glacier ice is stored in the Aral Sea region differs from that in the HKH region. In the Amu Darya Basin, simple valley glaciers start playing a role as the second principal ice reserves storage, although still lagging behind the glaciers of the compound valley type. In the Syr Darya Basin, simple valley and cirque glaciers are as important ice reserves as compound valley glaciers. In the Mekong Basin, bulk of the ice is stored mainly in cirque glaciers.

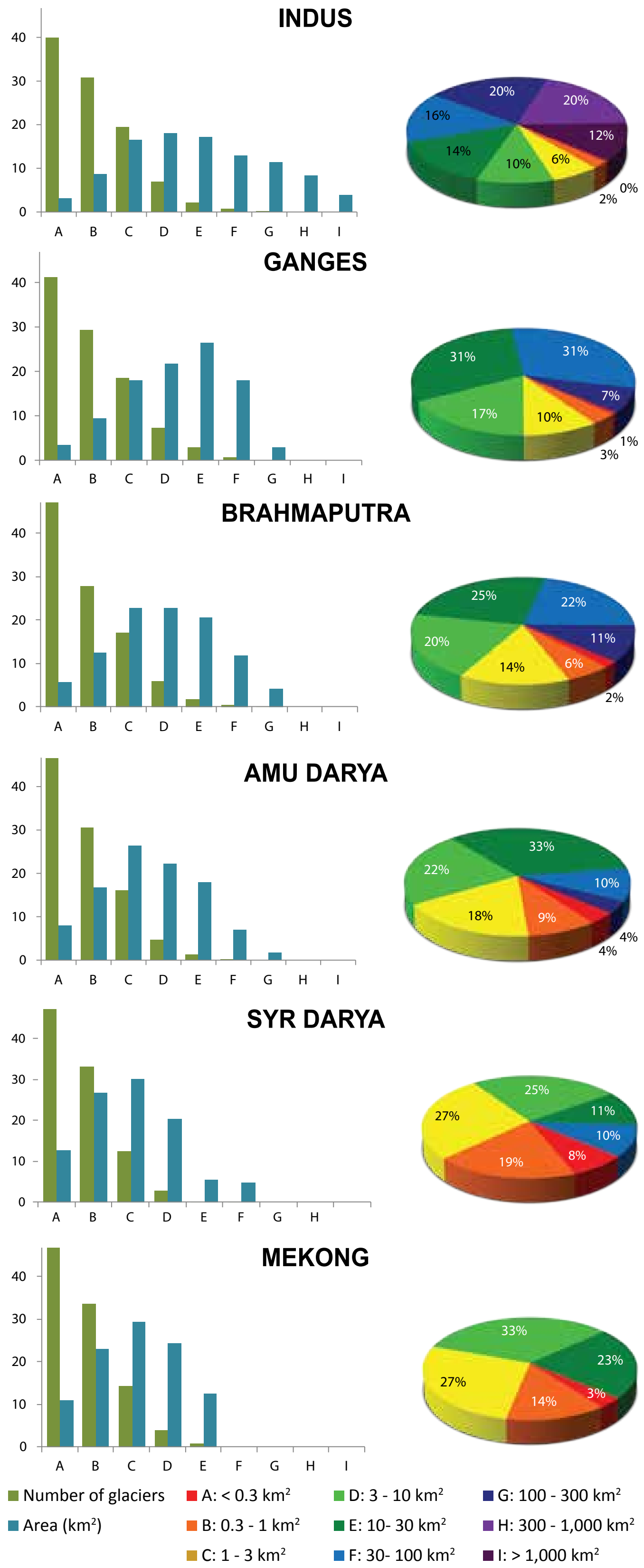
Thus, the principal feature of size class stratification of any glacier system is that the ice volume is distributed among glacier areal size classes unevenly, with small glaciers containing a small share of it and the bulk of the ice reserves concentrated in the largest glaciers. The distribution of the glacier-covered area follows the same pattern, but in this case the differences between smallest and largest size classes are less pronounced.

Diversity of a glacier system is reflected by the number of areal size classes, differences between smallest and largest glaciers (Table 4) and the elevation interval of glacier occurrences (Table 5). The data presented here suggest that diversity of glacier systems is higher in the basins with large numbers of glaciers and total glacier-covered area (Figure 4; Tables 3, 4 and 5). The lower a basin ranks in terms of the total number of glaciers and their areal extent and volume, the fewer glacier size classes it has, and the less are the differences between the largest and the smallest glaciers.

Average glacier parameters also reflect the diversity of a glacier systems' structure (Table 4). The difference between average ice volume per glacier in the Indus and Syr Darya basins is almost ninefold. An average glacier area too is smaller in glacier systems of smaller proportions. For instance, in the three largest glacier systems (the Indus, Ganges and Brahmaputra basins), average glacier size is between 1.3-2.1 km^2, whereas in the Syr Darya and Mekong basins it drops to 0.7-0.8 km^2.

Stratification of glacier systems can be compared to the stratification of human societies. Glaciers accumulate ice in a manner much similar to wealth accumulation in the societies with broadly differentiated incomes, where a majority of the population is 'impoverished', 'middle class' is relatively small in numbers and only a few individuals possess 'fortunes'. Spatial organization of glacier systems is 'social' too. In favorable environments, glaciers form huge 'urban centers' with a high 'population density', and have 'low-density rural populations' in areas with limited opportunities for ice accumulation (Figure 2). Furthermore, if a glacier system is compared to a country, the basins' ice reserves will stand for its gross domestic product (GDP) and average glacier size for GDP value per capita. In this case, too, glacier systems are somewhat human-like: the larger the country's GDP (net value and per capita), the more diverse is its stratification in

FIGURE 4. Size class frequency distributions of glaciers' number, glaciated area (histograms) and ice volume (circular diagrams).



Data sources: Authors' estimate based on data from WGI (WGMS and NSIDC 2009), WGI-XF (Cogley 2009a) and ICIMOD (2007).

TABLE 3. Distribution of the number of glaciers, glacier-covered area and ice volume across glacier size classes in the study basins.

Size class (km^2)	Number of glaciers	Share in basin total (%)	Area (km^2)	Share in basin total (%)	Ice volume (km^3)	Share in basin total (%)
INDUS BASIN (without parts of Afghanistan and India, 97% of glaciated area covered)						
< 0.33	5,358	41	869	3	18	0.5
0.33 to 1.0	4,009	30	2,377	9	83	2
1.0 to 3.3	2,533	19	4,572	17	244	6
3.3 to 10	912	7	4,977	18	393	10
10 to 33	286	2	4,748	17	549	14
33 to 100	87	0.6	3,579	13	595	16
100 to 333	19	0.14	3,149	11	760	20
333 to 1,000	5	0.04	2,300	8	752	20
> 1,000	1	0.01	1,056	4	442	12
SUM	13,210	100	27,627	100	3,836	100
GANGES BASIN						
< 0.33	2,769	41	437	3	9	0.7
0.33 to 1.0	1,973	29	1,183	9	41	3
1.0 to 3.3	1,243	18	2,261	18	122	10
3.3 to 10	492	7	2,725	22	216	17
10 to 33	198	3	3,314	26	383	31
33 to 100	42	1	2,254	18	379	31
100 to 333	2	0.03	366	3	92	7
SUM	6,719	100	12,541	100	1,243	100
BRAHMAPUTRA BASIN						
< 0.33	5,689	47	909	6	29	2
0.33 to 1.0	3,332	28	2,019	12	88	6
1.0 to 3.3	2,034	17	3,692	23	214	14
3.3 to 10	690	6	3,683	23	295	20
10 to 33	211	2	3,349	21	377	25
33 to 100	36	0.3	1,915	12	322	22
100 to 333	4	0.03	680	4	162	11
SUM	11,996	100	16,248	100	1,487	100
AMU DARYA BASIN (without parts of Afghanistan, 79% of glaciated area covered)						
< 0.33	3,742	47	701	8	23	4
0.33 to 1.0	2,241	28	1,299	15	50	9
1.0 to 3.3	1,432	18	2,434	28	115	18
3.3 to 10	386	5	1,993	23	143	22
10 to 33	98	1	1,602	18	215	33
33 to 100	13	0.2	616	7	65	10
100 to 333	1	0.01	156	2	23	4
SUM	7,913	100	8,801	100	641	100

(Continued)

TABLE 3. Distribution of the number of glaciers, glacier-covered area and ice volume across glacier size classes in the study basins (Continued).

Size class (km^2)	Number of glaciers	Share in basin total (%)	Area (km^2)	Share in basin total (%)	Ice volume (km^3)	Share in basin total (%)
SYR DARYA BASIN						
< 0.33	1,750	51	320	13	10	8
0.33 to 1.0	1,139	33	676	27	26	19
1.0 to 3.3	428	13	759	30	36	27
3.3 to 10	101	3	513	20	33	25
10 to 33	9	0.3	136	5	15	11
33 to 100	2	0.1	119	5	13	10
SUM	3,429	100	2,522	100	133	100
MEKONG BASIN						
< 0.33	166	44	30	9	0.5	3
0.33 to 1.0	142	37	77	24	2.5	14
1.0 to 3.3	53	14	90	28	4.7	27
3.3 to 10	16	4	80	25	6.1	33
10 to 33	3	1	39	12	4.1	23
SUM	380	100	316	100	17.9	100

Data sources: WGI (WGMS and NSIDC 2009) and ICIMOD (2007).

Note: To make visual comparison easier, each glacier areal size class is highlightened in its own color. The color palette corresponds to the one used in Figure 4 and Table 8.

TABLE 4. Average and largest glacier size and volume per basin as indicators of glacier system diversity.

Basin	Average glacier area (km^2)	Average glacier volume (km^3)	Number of size classes in a basin	Area of the largest glacier (km^2)	Ice volume of the largest glacier (km^3)
INDUS	2.1	0.31	9	1,056	442
GANGES	1.9	0.18	7	263	71
BRAHMAPUTRA	1.4	0.13	7	207	52
AMU DARYA	1.3	0.09	7	156	23
SYR DARYA	0.7	0.04	6	70	8
MEKONG	0.8	0.05	5	16	1.7

Data sources: WGI (WGMS and NSIDC 2009) and ICIMOD (2007).

terms of differences between 'poor' and 'wealthy' social classes. For instance, in glacier-'poor' Syr Darya and Mekong basins, the wealthiest members are still poor compared to glacier-'rich' Amu Darya and basins of the HKH region.

The absolute altitudes of glacier occurence in all basins vary widely, ranging from 2,500 m to 8,000 m. This is due to the fact that mountain glaciers are products of interplay between regional climate and local topography (e.g., aspect, underlying geometry, steep slopes in the vicinity, etc.), which determines the features of the microclimate with an implication that favorable conditions for glacier existense occur at different elevations (Kulkarni and Buch 1991; Ohmura et al. 1992; Karma et al. 2003). Spatial organization of glacier systems reflects climatic heterogenity. In favorable environments, e.g., around high peaks and where precipitation is abundant, glaciers form hubs with a ratio of glaciated to ice-free

terrain of over 1:1. At lower elevations and in areas with limited precipitation, glaciers are, in general, smaller and scattered loosely across mainly ice-free terrain (Figure 2). However, a cross-comparison of variability of elevation-related parameters of glacier systems in different basins (Table 5) conforms with the tendency discussed in respect to size-frequency distributions - the more glaciers and ice reserves there are in a basin, the more diverse the glacier system is. In this case, in terms of increase in the vertical extent of glacier occurence.

The scope of diversity of glacier elevations within one glacier system can be illustrated by data on ELA variability (Table 5). In the HKH region, the highest ELA in a basin is located up to 5,000 m higher than the lowest ELA. In the Aral Sea region, this difference is around 2,500-4,000 m. The standard deviation of ELA from basin-averaged value typically makes 400-500 m in the three HKH basins and in the Amu Darya Basin, dropping to a still impressively high 200-300 m in Syr Darya and Mekong basins.

The spatial pattern of ELA variability demonstrates dependency on several factors, the most important being: i) location of a sub-catchment with respect to the precipitation-bearing winds; and ii) glacier exposure. Under the influence of these factors, regional ELAs and other elevation parameters are the lowest in the well-nourished periphery of the large mountain systems and the highest in the headwaters, which typically receive less precipitation (Kayastha and Harrison 2008). At the mesoscale, ELA of south-facing glaciers is higher compared to the north-facing glaciers (Dyurgerov et al. 1995; Mool et al. 2001a).

An important feature of glacier systems, which has far-reaching implications for CC impact studies, is that the vertical extent of an individual glacier, i.e., the difference between its maximum and minimum elevations, contrary to elevations of glacier occurrence, shows little dependency on local microclimate and has a high correlation (0.73) with the glacier area (Figure 5). According to the analysis of the glacier elevation variability carried out for this study, average altitude intervals of all the size classes vary from basin to basin within a range of just ±10-15% of the size class average value of the entire dataset. Little dependency of vertical glacier extent on the microclimate implies that CC is likely to affect all glaciers in a basin in a similar way irrespective of the absolute altitudes of their location. In other words, glaciers at higher altitudes are as likely to be affected by CC as those at low altitudes, and the magnitute of the CC impact is determined not by glacier location but by its vertical extent, which correlates with the glacier areal size class. The implication is that glacier sensitivity to CC is determined mainly by its areal size.

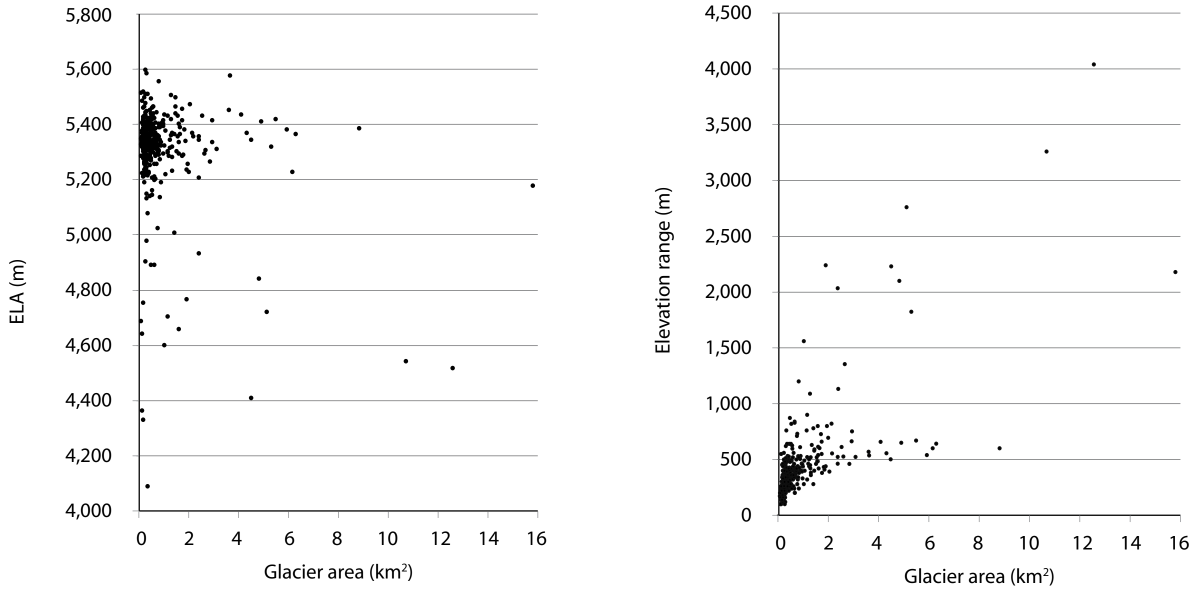
TABLE 5. Variability of ELA in the study basins (The Indus Basin is not included, because the glacier inventories for this basin did not contain information on the elevation-related glacier parameters).

Basin	Highest ELA (m)	Lowest ELA (m)	Basin-average ELA (m)	Standard Deviation (m)
GANGES	8,110	2,760	5,470	450
BRAHMAPUTRA	7,000	2,270	5,420	433
AMU DARYA	6,710	2,810	4,430	530
SYR DARYA	5,380	2,870	4,030	300
MEKONG	5,600	4,090	5,310	180

Data sources: WGI (WGMS and NSIDC 2009); ICIMOD 2007.

FIGURE 5. The relationship between (a) ELA and glacier area, and (b) elevation range and glacier area in the Mekong Basin.

a) Coefficient of correlation = 0.21 b) Coefficient of correlation = 0.73



Data source: WGI (WGMS and NSIDC 2009).

Note: Elevation range of a glacier is the difference between altitude of the highest and lowest points.

Changes in Glacier Systems between 1961-1990 and 2001-2010

Data and Methods of Glacier Monitoring and Associated Uncertainties

As early as in the 1950s, several countries started national programs of glacier monitoring, which initially included only observations of glacier front fluctuations, but were expanded a decade later to include records of glacier area and volume changes. In 1986, with the support of the United Nations Environment Programme (UNEP), the World Glacier Monitoring Service (WGMS) was established as a coordinating body for the collection and dissemination of glacier data for several hundreds of mountain glaciers worldwide. Data of national monitoring programs have been published in roughly five-year intervals (IAHS (ICSI)-UNESCO 1967, 1973, 1977, 1985; IAHS (ICSI)-UNEP-UNESCO 1988, 1993, 1998; IUGG (CCS)-UNEP-UNESCO 2005, 2008). Publication of another regular edition, a glacier-mass-balance bulletin (GMBB) was initiated in 1991. The GMBB is issued biannually (WGMS 1991, 1993, 1994, 1996, 1999; 2001, 2003, 2005, 2007, 2009, 2011) and is accessible online (http://www.geo.uzh.ch/microsite/wgms/gmbb.html). These two publication series represent one of the principal sources of primary information on glacier changes in the past few decades. In addition to the efforts coordinated by the WGMS, rapid development of remote sensing (RS) techniques in the past few decades revolutionized glacier monitoring (Bishop

et al. 2000; Bhambri and Bolch 2009). As a result, the second principal source of information on the recent glacier changes include numerous research publications which, in many instances, surpass the first source in terms of quantity and quality.

The records of glacier changes can be subdivided into three major categories: i) data on frontal variations of glaciers; ii) changes of areal extent; and iii) glacier mass-balance measurements. Frontal variations are derived by mapping or photographing the position of the glacier termini. It is the earliest, easiest to obtain and the most common type of records for in-situ measurements. Changes in glacier length and the annual rate of glacier termini retreat or advance can be calculated from a series of subsequent records. However, the use of that type of data for glacio-climatological studies is limited, because the CC forcing signal does not impact glacier length directly, but is mediated through changes in glacier mass balance and, therefore, glacier length is affected by CC signal with delays of varying duration. There are modeling attempts to link glacier length changes with glacier volume changes (Oerlemans 2005; Lüthi et al. 2010), but since all the models require detailed topographic information for calibration, the value of the glacier length records in regional studies is limited to providing evidence on the dominant patterns of glacier behavior in a certain time interval (Bolch et al. 2012).

The data on the changes of the elevation of glacier front position and its ELA (e.g., Fujita et al. 1997; Dobhal et al. 2008; Bajracharya et al. 2011) are much more relevant for glacio-climatological studies, since changes of vertical glacier extent are tightly and directly controlled by climate, contrary to glacier length. In addition, ELA responds to CC without a delay.

The data on changes in glacier areal extent were relatively rare before the year 2000, when they were assessed from aerial photographs, topographic maps and in-situ recorded positions of glacier termini (Table 6). The recent advances in this field are closely related with the rapid development in RS- and GIS-based modeling techniques (Kääb 2005; Kulkarni et al. 2005; 2007; Bolch 2007; Konovalov and Desinov 2007; Raup et al. 2007; Bhambri and Bolch 2009). The major challenges for RS methods are related either to image quality, e.g., a need to fill the voids left by cloud covers and deep mountain crest shadows, or to data interpretation bias involved in both automated and manual delineation of glaciers from RS products (Bhambri and Bolch 2009). Particularly problematic is the identification of small-sized glaciers and differentiation between debris-covered glacier tongues and ice-cored glacial landforms. Nonetheless, the application of RS techniques makes a real breakthrough in terms of increasing statistical reliability of data by increasing the sample size, and thereby enhancing the credibility of the large-scale regional assessments (Racoviteanu et al. 2009).

Glacier mass-balance, i.e., a figure indicating annual or long-term average gain or loss of glacier ice in water equivalent (w.e.), may be calculated from the geodetic measurements of glacier volume change and density of ice and snow (Bamber and Rivera 2007; Cogley 2009b). Indirectly, ice volume changes can be assessed either by modeling glacier volume at subsequent dates based on known changes in areal extent (Kulkarni et al. 2004) or by glacier water budget calculations (Dyurgerov 2010).

The direct measurement of glacier mass-balance is one of the most accurate methods in glacier assessments (Kaser et al. 2002, 2006). Its error margin is in order of $\pm$5-10%, the inaccuracy of snow density estimates being the major source of errors. Because of the high reliability of this method, a number of regional assessments of glacier mass loss had been already carried out based on the mass-balance monitoring data (Meier and Dyurgerov, 2002; Meier et al. 2003; Dyurgerov and Meier 2005; Oerlemans 2005; Kaser et al. 2006; Ohmura 2006; Raper and Braithwaite 2006; Oerlemans et al. 2007).

The question of representativeness of the mass-balance measurements of individual glaciers for the the large-scale glacier systems, however, is widely debated (Kaser et al. 2006; Paul and Haeberli 2008; Fountain et al. 2009; Cogley 2009b). The major problem is the extreme scarcity of direct measurments of the glacier mass balance, related to the fact that the methods of direct mass balance

measurements are both time- and labor-consuming (Kaser et al. 2002). Therefore, out of the mass-balance observations available for a little over 300 glaciers on the planet, only 30 records extend over 30 years (Zemp et al. 2008, 2009b). In addition, existing long-term records most likely constitute a biased sample, since the early measurements were carried out mostly on small glaciers (Dyurgerov and Meier 2005; Dyurgerov 2010).

The main argument in favor of using single-glacier records for the regional assessment of mass loss of large glacier systems is the good correlation of the long-term variations of the specific mass-balance of the glaciers scattered hundreds and thousands of kilometers apart (Meier and Dyurgerov 2002; Meier et al. 2003; Dyurgerov and Meier 2005; Dyurgerov 2010). However, careful consideration of the mass-balance records suggests that the cumulative mass-balance curves have much weaker correlation, if any, even between glaciers located in the vicinity of each other (Fountain et al. 2009). For instance, records from a Tuyuksu group of nine glaciers in the headwaters of Malaya Alamaatinka Valley in Northern Tien Shan (WGMS 1991, 1993, 1994, 1996, 1999; 2001, 2003, 2005, 2007, 2009, 2011) provide strong evidence that there are significant differences in the local patterns of glacier mass-balance variability (Figure 6).

The unique character of the Tuyuksu dataset is that it is obtained from glaciers located in a single sub-catchment, unlike all other records in High Asia. The long-term observations indicate that out of nine glaciers, eight were losing mass over a period of 25 years (1965-1990), whereas one glacier – Partizan (43°N, 71°E) – gained annually an average of 280 mm w.e. (Figure 6). There is strong correlation between annual specific mass-balance curves for all glaciers, (e.g., coefficient of correlation between records from Tsentralniy Tuyuksu glacier and Partizan glacier is 0.89). Nonetheless, the differences of the total value of the annual specific mass-balance between some glaciers in that group are up to 2,000 mm (Figure 6a). In other words, the variability of mass-balance at the local scale (Figure 6b) is as high as its variability accross the globe (Figure 6c). This strongly implies that mass-balance record from a single glacier is, in fact, a random measurement. Its extrapolation to wider areas is likely to result in a considerable, but hard to determine degree of uncertainty from regional assessments. In the opinion of the authors of this report, single-glacier mass-balance records may not be representative even for its immediate surrounding, let alone the large region.

An alternative way of assessing glacier mass-balance is the planimetric or geodetic method, based on the mapping of the glacier surface at regular intervals, is (Bishop et al. 2000; Bamber and Rivera 2007; Cogley 2009b). This method allows deducing glacier volume changes much easier than in the case of direct field measurements. A breakthrough in planimetric measurements was achieved in the past decade through the application of RS techniques, particularly the use of DEMs of high resolution derived from oblique satellite images (Bouillon et al. 2006; Berthier et al. 2007; Berthier and Toutin 2008; Bolch et al. 2008, 2011; Kääb et al. 2012). Another novel RS technique based on satellite-gravimetry data (Jacob et al. 2012) offers new possibilities for large-scale glacier mass-balance studies, but with a very coarse spatial resolution and high uncertainty regarding the interpretation of the data obtained by this method for the mountain regions in general. As in assessments of glacier areal changes, the application of RS techniques for the mass-balance assessments allows the sample size to be increased substantially, but at the expense of the method's accuracy. The uncertainties of the method are related to uncertainties of the mapping techniques and inaccuracies in assessments of snow and ice density. However, despite a certain need for fine-tuning, the new RS techniques which have been developed and tested in several locations in High Asia have high potential for yielding a lot of new data in the near future (Bhambri and Bolch 2009; Kääb et al. 2012; Jacob et al. 2012).

Lessons Learned from Glacier Monitoring

The data on changes in glacier length are not considered in this study, because of their low

relevance for water storage properties of glaciers. The monitoring records for several dozens of glaciers in High Asia are available from regular publications (IAHS (ICSI)-UNESCO 1967, 1973, 1977, 1985; IAHS (ICSI)-UNEP-UNESCO 1988, 1993, 1998; IUGG (CCS)-UNEP-UNESCO 2005, 2008) and on request from the WGMS (www.wgms.ch). Overviews of the glacier length changes in the HKH and the Aral Sea regions can be found in Ageta et al. (2001), Aizen et al. (2006), WWF (2005), Zemp et al. (2009a), Armstrong (2010), Raina (2009), UNEP (2009), Malone (2010), Dyurgerov (2010), Braun et al. (2009), Miller et al. (2012) and Bolch et al. (2012).

The summary of the data on glacier areal changes in the study basins is given in Table 6. One of the principal sources of information on the areal extent of glacier systems in 2005±3 is the recent ICIMOD report (Bajracharya and Shrestha 2011), where it is derived from a repetetive glacier survey based on satellite imagery. The data of Bajracharya and Shrestha (2011) cover all three major basins in the HKH region, the Mekong Basin and part of the Amu Darya Basin that is located in Afghanistan. However, the findings of Bajracharya and Shrestha (2011) in some respects are contradictory to a number of previous studies in the region.

Prior to publication of the ICIMOD report (Bajracharya and Shrestha 2011), in the Ganges glacier system, 34% of glaciated area had been covered by a variety of studies on glacier changes in the past decades (Mool et al. 2004; Lizong et al. 2005; Bajracharya and Mool 2006; Chen et al. 2007; Bolch et al. 2008; Salerno et al. 2008; Bhambri et al. 2011). In the Brahmaputra and Indus basins, only 13% and 9% of glaciated area has been covered, respectively (the Brahmaputra Basin: Karma et al. 2003; Liu et al. 2005; Ye et al. 2006, 2007; Frauenfelder and Kääb 2009; Bolch et al. 2010; the Indus Basin: Kulkarni et al. 2007; Ye et al. 2008). The spatial scatter of sampled areas in the Brahmaputra Basin is definitely better than in the Indus Basin, since it does not leave any essential gaps. The records available for the Indus Basin were from the Western Himalaya, with one exception – a study carried out in the Chinese part of the basin (Ye et al. 2008), which was leaving Karakorum and Hindu Kush, the major mountain systems of the basin where two-thirds of all glaciers in the basin are concentrated, not covered.

In the Aral Sea region, the Amu Darya Basin has 100% coverage, although the data (Shetinnikov 1998; WGMS and NSIDC 2009) for 75% of the glaciated area that is located within former USSR boundaries refer to the interval from late 1950s (early 1960s) to year 1980. The remainder of the territory is covered by data from Bajracharya and Shrestha (2011) extending till 2005±3. The Syr Darya Basin coverage is around 60% with most data extending into the 2000s (e.g., Aizen et al. 2006; Kutuzov and Shahgedanova 2009; Narama et al. 2009).

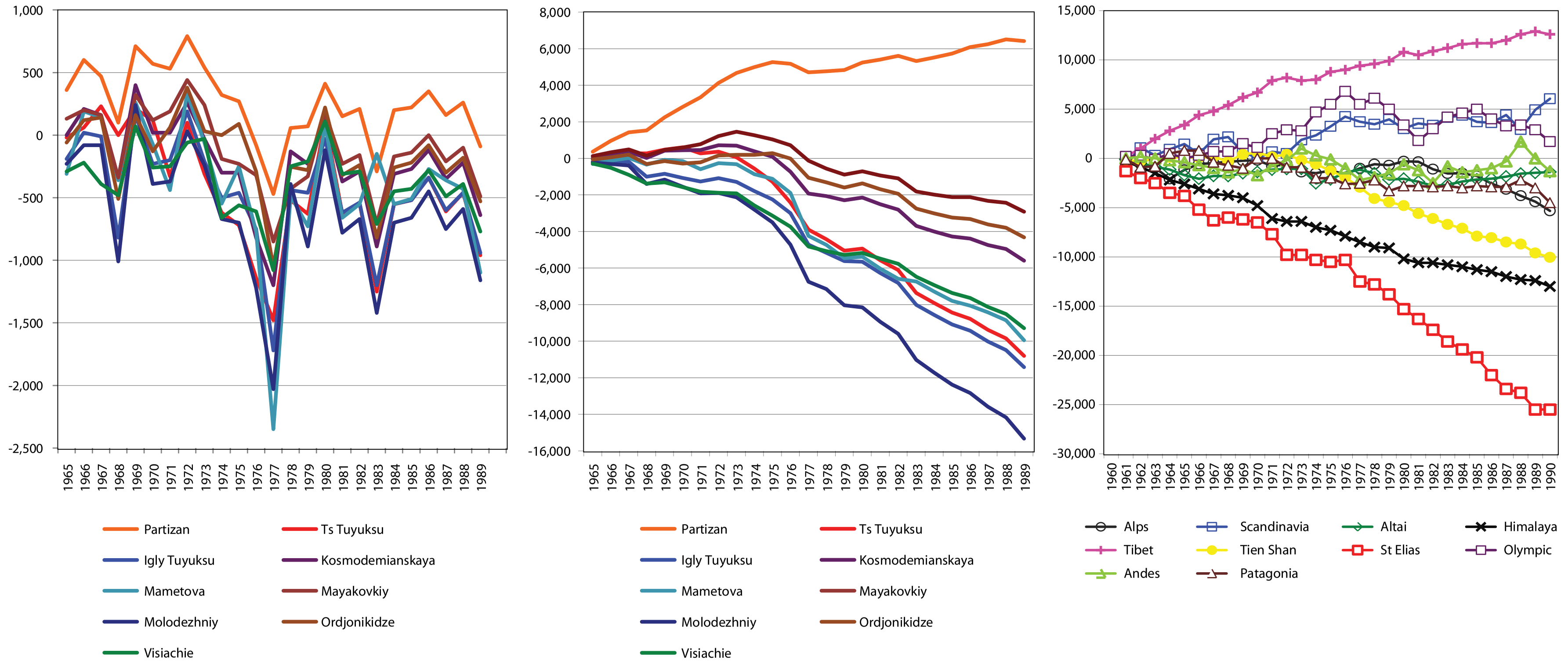
Comparison of the data from Bajracharya and Shrestha (2011) for 2005±3 (Table 6) and data on glacier status in the baseline period 1961-1990, based on glacier inventories of the first generation (Table 1), shows that the glacier area has reduced by 28% and 24% in the Ganges and Indus basins, respectively, and only by 14% in the Brahmaputra Basin, suggesting annual glacier reduction rate of approximately 0.8-0.9%/year (the Ganges and Indus basins) and 0.5%/year (the Brahmaputra Basin). These figures are significantly higher than those derived from previously published evidence for this region (Table 6), particularly for the upper part of the Indus Basin located in Karokoram, where, according to Hewitt (2005), Mayer et al. (2006) and Copland et al. (2011), the large glaciers, sampled randomly, were either advancing recently or remained stable since the beginning of the twentieth century and evidently gained mass (Gardelle et al. 2012).

Other records of glacier changes in the HKH region derived from small samples (Table 6) confirm that glaciers are in a general state of retreat from 1960s onwards, with the rates of areal reduction varying in extremely wide intervals between different study sites, i.e., in the Indian part of the Indus Basin: 0.23-0.53%/year; in the Ganges: 0.07-1.30%/year; and in the Brahmaputra: 0.01-1.10%/year.

High spatial and temporal variability of the rates of areal reduction is also recorded

FIGURE 6. Local variations of glacier mass-balance: long term (1965-1990) measurements from the Tuyuksu group of glaciers in Malaya Almaatinka Valley, Northern Tien Shan.

a) Tuyuksu group of glaciers: specific mass-balance at ELA time series b) Tuyuksu group of glaciers: cumulative mass-balance time series c) Cumulative mass-balances of selected glacier systems compiled from individual time series



Data sources: a), b): WGMS 1991, 1993, 1994, 1996, 1999; 2001, 2003, 2005, 2007, 2009, 2011; c): adopted from Dyurgerov and Meier 2005.

for the basins of the Aral Sea region: Amu Darya 0.2-1.4%/year, and Syr Darya 0.07-0.7%/year (Shetinnikov 1998). There is an evidence suggesting the reduction of glacier-covered area in some catchments of the Amu Darya Basin in Afghanistan by more than 50% during twentieth century (Yablokov 2006), whereas in the Karakul Catchment in Central Pamir (Tajikistan) glacier area increased by 4% between the late 1950s and year 1980 (Shetinnikov 1998). Comparison of data on glacier status in the Wakhan Corridor Valley in Afghanistan in the 1960s and 1970s (Lebedeva and Larin 1991) and in 2005±3 (Bajracharya and Shrestha 2011) indicates an areal increase by 10%, which is within the range of the assessment accuracy in this area. On average, in the past 50 years, total glacier-covered area in the Amu Darya and Syr Darya basins reduced by 15% and 22%, respectively, i.e., at the annual rates of 0.50%/year and 0.73%/year. During the same period, the glacier area in the Mekong Basin reduced by 26%, at an average rate of 0.86%/year.

The basins' coverage by sources listed in Table 6 appears reliable enough to suggest high spatial variability of glacier areal reduction. The basin average annual rates of areal reduction between 1961-1990 and 2001-2010 have been, in general, two to three times lower in the Brahmaputra and Amu Darya basins than the areal reduction rates in the Ganges, Indus, Syr Darya and Mekong basins.

Data on the volumetric changes of glaciers in the study basins (Table 7) are much more rare and sporadic compared to the data on areal changes. The records of glacier mass-balance monitoring of a short duration are available only for five glaciers in the HKH region located in the Ganges Basin (Zemp et al. 2009a). The mass balance evaluations derived from RS evidence (Berthier et al. 2007; Kulkarni et al. 2007; Bolch et al. 2011; Gardelle et al. 2012; Kääb et al. 2012) provide a reasonably good coverage for the Indus and Ganges basins, and Lower Brahmaputra Basin, but their duration is limited only to the past decade. The major part of currently available long-term records is from the case studies carried out on single glaciers by field measurements of mass-balance, e.g., in the Indus Basin (Raina et al. 1977; Singh and Sangewar 1989; Srivastava and Swaroop 1989; Dobhal et al. 1995; Shanker 2001; Srivastava et al. 2001; Wagnon et al. 2007; Pithan 2011; Azam et al. 2012), in the Ganges Basin (Gautam and Mukherjee 1989; Srivastava and Swaroop 1989; Fujita et al. 1997, 1998, 2001a, 2001b; Kadota et al. 1997; Tangborn and Rana 2000; Dobhal et al. 2004, 2008; Nakawo 2009) and in the Brahmaputra Basin (Sharma 1999; Aizen et al. 2002;Yao et al. 2007; Yang et al. 2008; Frauenfelder and Kääb 2009). Studies conducted to date in the major basins of the HKH region cover from just 1-6% (Ganges, Brahmaputra) to 17% (Indus) of basins' glaciated area.

In the Aral Sea region, the situation is somewhat better. In addition to a number of mass-balance records from the four benchmark glaciers (Dyurgerov et al. 1995), there are data of assessments at the sub-catchment level based on the data of areal reduction of glaciers in the Gassar Alay and Pamir mountains between the late 1950s and 1980 (Shetinnikov 1998). Thus, the Amu Darya and Syr Darya basins have 75% and 35% coverage, respectively. Both basins, however, lag behind the HKH basins in another aspect: since most monitoring programs here were terminated in the 1990s, only few studies extend beyond this date (Surazakov and Aizen 2006; Aizen et al. 2007).

Similar to the data on glacier areal reduction, the data on mass-balance changes show consistency in two respects: apart from the data for Karakoram glaciers, all the available records for other basins indicate that glaciers were losing mass and that the rates of mass-loss had high spatial and temporal variability (Kääb et al. 2012; Jacob et al. 2012). This evidence is in good agreement with more consistent and spatially representative data on areal reduction of glaciers, which suggest that spatial and temporal patterns of glacier reduction are far from uniform too.

Glacier ice volume for the three HKH basins, the Mekong Basin and the Afghan part of the Amu Darya Basin in 2005±3 is evaluated by Bajracharya and Shrestha (2011). However, the method employed for this assessment gives much lower estimates with up to threefold disparities (Table 2) compared to the methods used in

TABLE 6. Overview of published data on the areal changes of glaciers in the study basins in the past 50 years.

Location (sub-catchment)	Period	Number of glaciers	Glaciated area first measured (km^2)	Glaciated area last measured (km^2)	Areal reduction (%/year)	Source	Sample size (% of glaciated area of the major basin)
INDUS BASIN							
Entire basin	1960-80s-2005±3	All	27,759	21,193	-0.78	Authors's estimate; Bajracharya and Shrestha 2011	100
Chenab Basin	1962-2001/4	359	1,441	1,110	-0.53	Kulkarni et al. 2007	5.7
Parbati Basin (Beas Basin)	1962-2001/4	88	488	379	-0.55	Kulkarni et al. 2005, 2007	1.9
Baspa Basin (Satluj Basin)	1962-2001/4	19	173	140	-0.48	Kulkarni et al. 2007	0.7
Mapam Yumco (Satluj Basin) Tibet	1974-2003	n.s.	108	100	-0.23	Ye et al. 2008	0.4
GANGES BASIN							
Entire basin	1960s-2005±3	All	12,541	9,012	-0.93	Authors' estimate, Bajracharya and Shrestha 2011	100
Chinese territory	1990-2000	1,578	2,906	2,864	-0.14	Lizong et al. 2005	22.3
Pumqu Basin	1970-2001	999	1,462	1,330	-0.30	Jin et al. 2005	11.2
Tamor Basin	1970-2000	261	474	n.s.	-0.20	Bajracharya and Mool 2006	3.6
Dudh Koshi Basin	Late 1950s early 1990s	29	404	385	-0.12	Salerno et al. 2008 (Glaciers < 1 km^2 not included)	3.1
Rongxer Basin	1970-2001	200	334	324	-0.10	Lizong et al. 2005	2.6
Garhwal Himalaya Saraswati/Alakhanda	1968-2006	69 75	324	306	-0.14	Bhambri et al. 2011	2.5
Garhwal Himalaya Bhagirathi	1968-2006	29	275	266	-0.08	Bhambri et al. 2011	2.1
Poiqu Basin	1970-2001	153	237	232	-0.07	Lizong et al. 2005	1.8
	1988-2000	153	229	n.s.	-0.42	Mool et al. 2004	1.8
	1986-2001	153	229	183	-1.30	Chen et al. 2007	1.8
Khumbu Himal	1962-2005	5	92	87	-0.12	Bolch et al. 2008	0.7

(Continued)

TABLE 6. Overview of published data on the areal changes of glaciers in the study basins in the past 50 years (Continued).

Location (sub-catchment)	Period	Number of glaciers	Glaciated area first measured (km^2)	Glaciated area last measured (km^2)	Areal reduction (%/year)	Source	Sample size (% of glaciated area of the major basin)
BRAHMAPUTRA BASIN							
Entire basin	1961-90-2005±3	All	16,248	14,020	-0.48	Bajracharya and Shrestha 2011	100
Southeast Tibet Gangrigabu Range	1980-2001	88	798	796	-0.01	Liu et al. 2005	4.9
Tibet, northwest from Lhasa	1970-2000	476	535	430	-0.70	Frauenfelder and Kääb 2009	3.3
Nyaingentanglha Range, southeast slope	1976-2001	521	505	475	-0.23±0.12	Bolch et al. 2010	3.1
Northwest Himalaya North from Mount Everest	1980-2000	197	449	373	-0.80	Frauenfelder and Kääb 2009	2.7
Southern Tibet Yamzhog Yumco	1980-2000	n.s.	218	215	-0.07	Ye et al. 2007	1.3
Bhutan Himalaya	1963-1993 1993-2003	66	147	135	-0.27 -0.90	Karma et al. 2003	0.9
	1980-2000	n.s.	n.s.	n.s.	-1.10±0.2	Frauenfelder and Kääb 2009	
Naimona'nyi region, Western Himalaya	1976-2003	53	84	79	-0.31	Ye et al. 2006	0.5
AMU DARYA BASIN							
Pamir	1960-1980	7,071	7,780	7,240	-0.35	Shetinnikov 1998	Sampled area extends beyond Amu Darya Basin
Gissar-Alay Range	1960-1980	4,287	2,347	2,040	-0.65	Shetinnikov 1998	
Central Pamir Muksu Catchment	1966-1980 1980-2000 1966-2000	n.s.	1,272 1,239 1,272	1,239 1,199 1,199	-0.25 -0.13 -0.2	Desinov and Konovalov 2007; Konovalov and Desinov 2007	10
Central Pamir Seldara Catchment	1959-1980 1959-2000 1959-2000	n.s.	732 699 732	699 689 689	-0.23 -0.07 -0.15	Desinov and Konovalov 2007; Konovalov and Desinov 2007	5
Within Tajikistan	1960-1980	7,781	8,802	7,257	-0.88	Shetinnikov 1998	70
Within Afghanistan	1970s-2005±3	All	3,018	2,566	-0.50	Lebedeva and Larin 1991; Lebedeva 1997; Bajracharya and Shrestha 2011	30

(Continued)

TABLE 6. Overview of published data on the areal changes of glaciers in the study basins in the past 50 years (Continued).

Location (sub-catchment)	Period	Number of glaciers	Glaciated area first measured (km^2)	Glaciated area last measured (km^2)	Areal reduction (%/year)	Source	Sample size (% of glaciated area of the major basin)
SYR DARYA BASIN							
Tributaries from Gissar Alay Range	1961-1980	1,207	660	574	-0.65	Shetinnikov 1998	26
Pskem, West Tien Shan	1968-2000	525	220	177	-0.61	Narama et al. 2009	8.7
	2000-2007		177	169	-0.67		
Naryn, Ak-Shiyrak	1943-1977	178	429	405	-0.12	Aizen et al. 2006 (Only 213 km^2 of the sample belongs to Syr Darya Basin)	8.4
	1977-2003		405	370	-0.33		
	1943-2001	n.s.	n.s.	n.s.	-0.45	Khromova et al. 2003	
Southeast Fergana	1968-2000	306	190	173	-0.29	Narama et al. 2009	7.5
	2000-2007		173	172	-0.07		
Naryn	1990-2003	109	120	105	-0.30	Kutuzov and Shahgedanova 2009	4.8
Terskey Alatau	1968-2000	192	114	100	-0.37	Narama et al. 2009	4.5
At-Bashy	2000-2007		100	96	-0.60		

the inventories of the first generation for the glacier status in 1961-1990 (ICIMOD 2007; WGMS and NSIDC 2009). This implies that the largest currently available datasets are unsuitable for a reliable assessment of ice volume changes between 1961-1990 and 2001-2010. More methodologically consistent data on glacier mass-loss in the HKH region (Table 7) cover from 1 to 15% of basins' glacier-covered areas, with the largest samples being representative only for the past decade. The value of the reviewed mass-balance data, therefore, is in providing a robust assessment of actual ranges of mass-loss rates in the past 50 years.

The analysis of data presented in Table 7 suggests that glaciers in richly nourished areas of the HKH region, particularly south-facing valleys of the Ganges and Indus basins in Central and Western Himalaya, tend to lose mass more rapidly, i.e., at a rate of about 600-900 mm/year than glaciers in Eastern Himalaya, where the corresponding figures are 400-700 mm/year. The lowest annual mass-loss rates of around 100-300 mm/year among available records are from poorly nourished cold areas in the Upper Brahmaputra and Upper Indus basins, with some studies suggesting glaciers gaining mass in the Karakoram part of Upper Indus Basin.

So-called 'Karakoram anomaly' has recently attracted a good deal of attention, with a number of studies (Hewitt 2005; Gardelle et al. 2012; Cogley 2012) suggesting mass gain for glaciers in this part of the Upper Indus Basin. The CC factors that have contributed to this phenomenon have been identified by Fowler and Archer (2005) as i) an increase in winter precipitation leading to a higher accumulation, and ii) a decrease in summer air temperature leading to lower ablation. However, the largest sampled area in the Indus Basin, where mass gain has been observed in the 2000s, makes only 9% of the total glacier-covered area of the basin (Gardelle et al. 2012). For the remaining part of the basin, there is a strong indication that the dominating tendency in the past 50 years has been the considerable mass loss with the rates varying from 200 mm/year in Hindu Kush up to 550 mm/year in Western Himalaya (Kääb et al. 2012). The satellite-gravimetry based data too suggest an overall mass loss in the HKH region in the 2000s (Jacob et al. 2012).

The assessments available for the Aral Sea region are statistically more reliable, with 75% of glacier-covered area sampled in the Amu Darya Basin and 35% in the Syr Darya Basin (Table 7). These data indicate that, in the period 1961-1990 the average mass-loss rate in the region was between 300 and 700 mm/year marked by high spatial variability too.

The quality and quantity of available data on areal reduction and ice loss is by far insufficient for drawing reliable statements on the patterns of temporal variability of glacier reduction. According to some sources, glacier reduction rates increased drastically in the 2000s (Ageta et al. 2001; Ye et al. 2006; Miller et al. 2012). However, this is in disagreement with the recent evidence on glacier mass-loss rates in the HKH region, which have been in the range of 30 mm/year to 550 mm/year in 2003-2010 (Kääb et al. 2012), i.e., at the level they were before 2000 (Table 7). The lack of long-term time-series records, in particular, hampers further analysis. For example, there are only seven records of extremely high rates of mass loss in the HKH region exceeding 1,000 mm/year, and those are from glaciers with areas between 0.6 km^2 and 131 km^2, of which three are observations made prior to the year 2000 and the other four – after 2000 (Table 7). The sample can hardly be considered statistically reliable because the records are based either on single-date or single-glacier observations, or both.

Climate Change (CC) Impact on Glacier Systems

Methods Used in CC Impact Assessments

Application of currently available glaciological methods for the large-scale modeling of glaciers under CC-impact faces the usual trade-off between being physically accurate on the one hand, and representative of large-scale areas on the other (Lamadrid and MacClune 2010; Bolch et al. 2012). Complex models designed to simulate the behavior of a single glacier, e.g., mass-energy fluxes and ice flow dynamics, depend on detailed knowledge of local topography and, correspondingly, require a thorough ground-truth verification (Kadota et al. 1997; Oerlemans 2001; Pithan 2011). This makes their application in large-scale assessments unfeasible given the diversity of glaciers and heterogenity of glacier environments (Radić and Hock 2011).

Spatial parameters of glacier systems under future CC scenarios may be assessed by projecting the current trends of glacier changes, assuming that the rates of changes in a given region remain constant or increase with time (Kadota et al. 1997; Vilesov and Uvarov 2001; Dyurgerov 2010; Cogley 2011). This approach, however, is rather simplistic and is not frequently used. A more sound approach to quantifying future changes of glacier systems is based on simulations of ELA changes under CC forcing. The ELA's key role in glacio-climatological modeling is well justified. First, ELA is a transmitter of CC signals. Second, its response to CC is easy to simulate. Third, the relationship between ELA and other glacier parameters too are easy to simulate (Barry 2006). With type-specific patterns of glacier geometry and glacier area-altitude distribution known, ELA's vertical shift may be firmly linked with changes in glaciers elevation interval and areal extent, and subsequently - with changes in ice volume and glacier runoff (e.g., Savoskul and Glazirin 2001; Aizen et al. 2007; Alford et al. 2009; Glazirin 2009).

The mechanism of CC impact on individual glaciers may be described as follows. Glaciers receive CC signal instantly through a vertical shift of the ELA. How much the ELA shifts upwards or downwards does not depend on the size of the glacier or its absolute altitude, but only on the magnitude of the CC itself. Correspondingly, glacier sensitivity to CC is determined by its vertical extent: under the same CC signal, the glaciers stretching across a large range of altitudes are likely to experience smaller areal reduction and lose less mass compared to those with a small vertical extent.

Complexity of ELA modeling depends on the type of climate scenario. Under the simplest scenario, which assumes no changes in precipitation and considers temperature change as the only driving factor, ELA is expected to shift upwards approximately by 150-160 m for each degree of temperature rise accompanied by global average 3%/^{o}C increase in precipitation, depending on the adiabatic lapse rate adopted for the assessment (Benn and Lehmkuhl 2000; Oerlemans 2001; Zemp et al. 2006).

For more complex scenarios, which include precipitation change in addition to temperature change (Figure 7), ELA modeling requires assessment of future glacier mass budget components (Ananicheva and Davidovich 1997; Lebedeva 1997; Savoskul and Glazirin 2001; Xie et al. 2006; Rivera et al. 2007). Mass budget approach relies on the established relations of precipitation and air temperature at ELA (Krenke 1982; Ohmura et al. 1992; Braithwaite et al. 2006). It is discussed in detail by Savoskul and Smakhtin (2013). Glacier mass budget approach is better suited for small scale assessments because variability of mass budget items in the mountains is extremely high.

A large-scale assessment of CC impact on glaciers can be done in a semi-distributed mode, which represents a reasonable level of spatial resolution in dealing with the arbitrary scenarios as well as General Circulation Model (GCM)-derived scenarios with a coarse resolution (Savoskul 2001). More complexity is required from

TABLE 7. Overview of published data on mass-balance of glaciers in the selected basins in the past 50 years.

Location	Period	Specific mass balance (mm w.e./year)	Method	Number of glaciers	Glaciated area at the beginning of observations (km^2)	Sample size (% of glaciated area of the major basin)	Source
				INDUS BASIN			
Karakoram	1999-2008	+110±220	RS	n.s.	(5,615)	9	Gardelle et al. 2012 (approximately half to two-thirds of the sample belongs to the Indus Basin)
Karakoram	2003-2009	-30±40	RS	n.s.	n.s.	n.s.	Kääb et al. 2012
Hindu Kush	2003-2009	-200±60	RS	n.s.	n.s.	n.s.	Kääb et al. 2012
Jammu and Kashmir State, Western Himalaya	2003-2009	-550±80	RS	n.s.	n.s.	n.s.	Kääb et al. 2012
Himachal Pradesh State, Western Himalaya	2003-2009	-320±60	RS	n.s.	n.s.	n.s.	Kääb et al. 2012
Siachen Glacier, Nubra Valley, Karakorum	1986-91 average	+358 to -1,084 -514	MB	1	987	3	Bhutiyani 1999
Spiti-Lahaul Valley (Sutluj Basin) Western Himalaya	2000-2004	-700 to -850	RS	n.s.	915	3	Berthier et al. 2007
Baltoro Glacier, Karakorum	n.s.	0-250	n.s.	1	524	2	Mayer et al. 2006
Chenab Basin	1962-2001/4	-940	RS	359	n.s.	1.5-2.0	Kulkarni et al. 2007
Parbati Basin (Beas Basin)	1962-2001/4	-790	RS	88	n.s.	1.0	Kulkarni et al. 2005, 2007
Baspa Basin (Sutluj Basin)	1962-2001/4 2001/2 2002/3	-640 -900 -780	RS	19	n.s. n.s. n.s.	0.5	Kulkarni et al. 2004, 2007
Bara Shigri Glacier	2000-2004	-1,000 to -1,300	MB	1	131	0.5	Berthier et al. 2007
Parbati Glacier	2001	-860	RS	1	11	0.04	Kulkarni et al. 2007
Chhota Shigri Glacier Himachal,	2000-2004	-1,000 to -1,100	MB	n.s.	11	0.06	Berthier et al. 2007
	2002-2006	-975 -1,400 to +100	MB	1	9	0.03	Wagnon et al. 2007
	2002-2010	-670±400	MB	1	9	0.03	Azam et al. 2012

(Continued)

TABLE 7. Overview of published data on mass-balance of glaciers in the selected basins in the past 50 years (Continued).

Location	Period	Specific mass balance (mm w.e./year)	Method	Number of glaciers	Glaciated area at the beginning of observations (km^2)	Sample size (% of glaciated area of the major basin)	Source
	1987-88	-154 -115 or 190	MB	1	16	0.03	Dobhal et al. 1995
Gara Glacier, Himachal	1974-83	-324	MB	1	5.2	0.02	Raina et al. 1977
Shaune Garang Glacier, Himachal	1984-89	-407	MB	1	4.9	0.02	Singh and Sangewar 1989
Gor Garang Glacier, Himachal	1976-85	-572	MB	1	2.0	0.01	Shanker 2001
Neh Nar Glacier, Kashmir	1976-84	-535	MB	1	1.2	0.005	Srivastava and Swaroop 1989; Dobhal et al. 2008
Ruling Glacier, Ladak	1980-81	-105	MB	1	0.	0.005	Srivastava et al. 2001
GANGES BASIN							
Uttarakhand, West Nepal, Central Himalaya	2003-2009	-320±60	RS	n.s.	n.s.	n.s.	Kääb et al. 2012
Everest area	1970-2007 2002-2007	-320±80 -790±520	RS	10	62	0.5	Bolch et al. 2011
Gangotri Glacier	1999-2004	-1,050	RS	1	126	1	Berthier et al. 2007
Glacier AX010 Shorong Himal Nepal	1978-1991 1978-1999 1991-1996 1996-1999	-530 -720 -1,140 -800	MB MB MB MB	1	0.6	0.005	Kadota et al. 1997 Nakawo 2009 Kadota et al. 1997 Fujita et al. 2001a
Rikha Samba Group Nepal, Hidden Valley	1974-1994	-550	MB	8	23	0.2	Nakawo 2009
Rikha Samba Glacier Hidden Valley, Nepal	1974-1994 1998-1999	-630 -750	MB MB	1	5.7	0.05	Fujita et al. 1997 Fujita et al. 2001b
Yala Glacier, Central Nepal	1982-1996 1982-1994 1994-1996	-390 -310 -1,050	MB MB MB	1	2.5	0.02	Nakawo 2009 Fujita et al. 1998 Fujita et al. 1998
Dokriani Glacier, Uttaranchal	1962-1995 1992-2000	-150 -320	MB MB	1	9.3	0.1	Dobhal et al. 2004 Dobhal et al. 2008
Langtang Glacier	1987-1997	-110	MB	1	68	0.5	Tangborn and Rana 2000
Lirung Glacier	1987-1997		MB	1	7.2	0.05	Tangborn and Rana 2000

(Continued)

TABLE 7. Overview of published data on mass-balance of glaciers in the selected basins in the past 50 years (Continued).

Location	Period	Specific mass balance (mm w.e./year)	Method	Number of glaciers	Glaciated area at the beginning of observations (km^2)	Sample size (% of glaciated area of the major basin)	Source
Dunagiri Glacier, Uttaranchal	1984-90	-1,038	MB	1	6.9	0.05	Srivastava and Swaroop 1989
Tipra Bank Glacier, Uttaranchal	1981-88	-241	MB	1	20	0.2	Gautam and Mukherjee 1989
BRAHMAPUTRA BASIN							
East Nepal, Bhutan, Eastern Himalaya	2003-2009	-300+90	RS	n.s.	n.s.	n.s.	Kääb et al. 2012
Northwestern Himalaya	1980-2000	-260 to -590	RS	197	449	2.7	Frauenfelder and Kääb 2009
Northwest from Lhasa	1970-2000	-160 to -250	RS	576	535	3.3	
Upper Brahmaputra	1970/80-2000	-300	RS	n.s.	n.s.	n.a.	
Xixibangma Glacier	1991	-34	WB	1			Aizen et al. 2002
Changme Khangme Glacier Sikkim	1979-1986	-298	MB	1	4.5	0.03	Sharma 1999
Gurenhekou Glacier, UB	2006	-700	MB	1	n.s.		Yao et al. 2007
Glacier No 4, Parlang Zangbo Catchment, Southeast Tibet	2006-2007	-700	MB	1	13	0.1	Yang et al. 2008
Glacier No 10, Parlang Zangbo Catchment, Southeast Tibet	2006-2007	-1000	MB	1	5.1	0.03	Yang et al. 2008
Glacier No 94, Parlang Zangbo Catchment, Southeast Tibet	2006-2007	-760	MB	1	3.1	0.03	Yang et al. 2008
Glacier No 12, Parlang Zangbo Catchment, Southeast Tibet	2006-2007	-1,600	MB	1	0.95	0.01	Yang et al. 2008
AMU DARYA BASIN							
Pamir	1961-1980	-650	AC	7,071	7,780	70	Shetinnikov 1998
Gissar-Alay Range	1961-1980	-450	AC	4,287	2,347	5	Shetinnikov 1998
Abramov Glacier Pamir Alay	1968-98	-457	MB	1	26	0.05	WGMS 1991, 1993, 1994, 1996

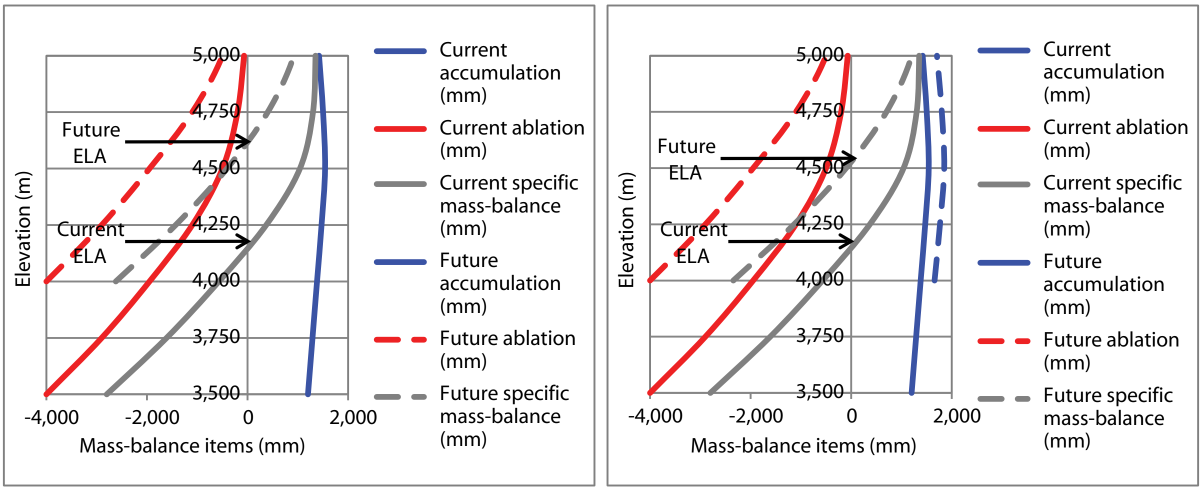
(Continued)

TABLE 7. Overview of published data on mass-balance of glaciers in the selected basins in the past 50 years (Continued).

Location	Period	Specific mass balance (mm w.e./year)	Method	Number of glaciers	Glaciated area at the beginning of observations (km^2)	Sample size (% of glaciated area of the major basin)	Source
				SYR DARYA BASIN			
Tributaries from Gissar-Alay Range	1961-1980	-450	AC	n.s	660	26.2	Shetinnikov 1998
Ak-Shiyrak	1943-1977	-240	AC	n.s.	238	8.4	Aizen et al. 2007;
	1977-2003	-580	RS				Surazakov and Aizen 2006
	1977-1999	-660					
	1943-1977	-256	WB				Dyurgerov et al. 1995
Grigoriev Glacier, Terskey Alatau Range	1987-1988	-291	MB	1	9.5	0.04	Dyurgerov et al. 1995; WGMS 1991
Sary-Tor Glacier, Ak-Shiyrak	1985-1989	-125	MB	1	3.6	0.01	Dyurgerov et al. 1995; WGMS 1991

Notes: Methods used for the mass-balance: MB – direct mass-balance measurements; RS – planimetric measurements based on remote-sensing; WB – water budgeting; AC – models based on monitored areal changes.

FIGURE 7. A schematic representation of the full glacier mass budget approach for the determination of future ELA position under the assumption of steady-state glaciers. Left: current and future mass budget components under a scenario of mean air temperature increase by +3 °C and no changes in precipitation. Right: the same under precipitation rise by 20% from its current value. Under the same warming signal, upward ELA shift from its current position is expected to be greater by 20-25% under a scenario with no changes of precipitation (right graph) compared to the scenario with increased precipitation (left graph). The mass budget curves shown here are representative for glaciers in temperate climate.



a model to accommodate downscaled regionalized scenarios based on GCM-outputs, which could be ideally met by fully distributed models, already available for the thoroughly studied mountain regions such as the Alps (Klok et al. 2001; Machguth et al. 2006, 2012; Kotlarski et al. 2010a, 2010b; Paul and Kotlarski 2010; Paul and Linsbauer 2012). In this case, the CC-scenario is represented as a fine-grid set of change fields outlining future changes of baseline climatological variables, e.g., air temperature and precipitation. Correspondingly, future ELA can be represented as a change field depicting its future deviation from the baseline value. Glacier datasets in point format derived from glacier inventories of first generation are ideally suited for this purpose.

Two principal approaches used to evaluate changes in glacier areal extent based on the estimates of the future ELA are: i) toe-to-headwall altitude ratio[1] (THAR); and ii) accumulation-area ratio (AAR) (Meierding 1982; Meier and Post 1962). The THAR ratio introduced by Meierding (1982) is calculated based on ELA and maximum and minimum glacier elevations, H_{max} and H_{min}, as shown in Equation (1):

$$THAR = (H_{max} - ELA) / (H_{max} - H_{min}) \qquad (1)$$

The THAR shows an average value around 0.5-0.55 and variability in the range of ±20% depending on climate and glacier morphological type. Assuming that THAR and H_{max} will remain the same under CC, the future H_{min} can be calculated from simulated ELA positions. The corresponding glacier extent can be derived from the topographic maps, DEMs and glacier area-altitude distributions.

The AAR introduced by Meier and Post (1962) is a relation of the accumulation area and total glacier area. The AAR of a steady-state glacier is around 0.6-0.7 in humid climate and 0.5-0.6 in continental climate, and its variability within ±20% range depends on the same factors as THAR variability. Future accumulation area of

[1] Expression “toe to head” is used to denote the difference between minimum and maximum glacier elevations.

a single glacier or a number of glaciers can be estimated from the topographic maps or glacier area-altitude distribution curves as a part of current accumulation area, which will remain above simulated ELA. The corresponding total area of a reduced glacier can be calculated assuming that future AAR will not change under CC.

Both methods are optimally suited for large-scale modeling. The associated uncertainties derived from variability of AAR and THAR from one glacier to another and the quality of topographic and hypsometric data can be minimized by calibrating the model separately for different morphological types of glaciers (Benn and Lehmkuhl 2000).

The methods described above work under the assumption of a steady-state future glacier status. There is, however, one serious methodological difficulty affecting overall certainty of large-scale simulations of glacier changes made under this assumption. In view of the high pace of the current CC, the uncertainties are already inherent in the calibration of the models. A simple conceptual scheme explains this. Under CC forcing, ELA instantly moves upwards from its former steady-state position, thus enlarging the ablation area and reducing the accumulation area. The former sheds off some mass by releasing more water into streamflow until it reaches the size corresponding to the reduced accumulation area. The steady-state models describe the results of this process as if it occurred simultaneously with the upward shift of the ELA. In reality, the glaciers need years to arrive to a new equilibrium; the larger the glacier, the more time it takes. The process may take decades and even hundreds of years, depending on glacier size and the rate of glacier mass-exchange. Meanwhile, the climate changes further and sends new signals to the glaciers, some of which have not yet fully responded to the previous signals. The observations of small glaciers retreating faster compared to the large glaciers, where the pattern of retreat is not so much of an areal reduction but an overall thinning of ice (Fujita et al. 1997, 1998), may simply be explained by the fact that to melt down the sheer ice volume of large glaciers takes more time. Thus, the data on glacier monitoring, in general, give a somewhat distorted image of a continuous state of retreat instead of providing data for a new equilibrium, which are needed to calibrate steady-state models. In addition, long-term monitoring records are really rare and short-term records available are not sufficient to capture the long-term trends of changes, since both CC signal and glacier response to it are heavily ‘contaminated’ by the noise produced by their short-term variations (Zemp et al. 2008, 2009b; Dyurgerov 2010).

Review of Published CC Impact Assessments on Glaciers in High Asia

The topic of retreating glaciers in High Asia became a highly politicized issue recently and, as such, got a lot of attention from developing agencies, international donors, governments, NGOs, mass-media, etc. All those efforts (WWF 2005, 2009; Jowit 2008; Hasnain 2009; UNEP 2009; ADB 2009; Raina 2009; Absar 2010; Malone 2010), however, did not yield much in terms of clarifying the issue, since many publications share a high degree of incompetence with regards to basic knowledge of glacier science. Many sources consistently mix up and misuse the terms, misread and exaggerate the numbers, and thereby lead to general confusion.

An example can be quoted from an otherwise highly competent source (Cruz et al. 2007, p. 493). “Glaciers in the Himalaya are receding faster than in any other part of the world, and if the present rate continues, the likelihood of them disappearing by the year 2035 and perhaps sooner is very high if the earth keeps warming at the current rate... Its total area will likely shrink from the present 500,000 to 100,000 km^2 by the year 2035...” The issue stirred a hot debate (e.g., The Economist 2010; Schiermeier 2010; Qiu 2010; Cogley et al. 2010) and IPCC (2010) admitted a number of serious errors in the relevant section, with one source offering an explanation (http://www.msnbc.msn.com/id/34958926/ns/us_news-environment/) that a typing error caused the confusion, and that ‘2035’ was supposed to stand for ‘2350’. However, regardless of the date of future change,

‘shrinkage’ of glacier area in the HKH region to 100,000 km^2 still means a double-fold expansion from baseline 1961-1990 glacier-covered area of approximately 50,000 km^2.

Professional studies that are focused specifically on modeling future status of entire glacier systems in the study basins are rare and hardly compatible because of the methodological differences, particularly in constructing CC scenarios. For instance, Cogley (2011) makes a prognosis of glacier status in the year 2035 for the entire HKH region without subdividing it into separate basins. This assessment is based on assumptions of constant and accelerated rates of i) decline in glacier numbers, and ii) glacier mass-loss. The author concludes, “If mass loss were to remain constant at the average rate for 1975–2008, from 3,000 to 13,000 more glaciers might disappear by 2035. If mass loss were to continue to accelerate as inferred for 1985–2008, only a few thousand to a few hundred glaciers might remain in 2035. Total area and total mass would each decrease by about one-half (constant-rate assumption) or three-quarters (constant-trend assumption)…” (Cogley 2011, p. 69). The evidence provided by repetitive glacier inventorization (Table 1), however, contradicts this statement, showing an increase in number of glaciers due to disintegration of large compound valley glaciers into a number of simple valley and cirque glaciers.

Xie et al. (2006, p 313) model of CC-impact on glacier systems in China suggests that by the end of the twenty-first century, “the glacier area of China will on average be reduced by 14%, 40% and 60% under the climatic scenarios of 0.01, 0.03 and 0.05 ^{o}C /year, respectively.” The model of Xie et al. (2006) utilizes glacier mass budget approach, however, since it is run for a number of glacier systems within national boundaries of such a large country as China, the modeling outputs are hardly compatible with models run at a smaller scale because of the local differences in glacier sensitivity to CC.

Another large-scale assessment conducted in the HKH region is that of Alford et al. (2009), who evaluated the glacier area changes in nine sub-catchments of the Ganges Basin within the national boundary of Nepal. The model was run for the year 2100 under the assumption of a temperature rise of 3 ^{o}C with no changes in precipitation. The assessment is based on semi-distributed glacier budget modeling based on glacier area-altitude distributions in the selected sub-catchments. The modeling results suggest that ELA rise will be 450 m, 41-67% of the currently glaciated area will remain ice-covered and the glacier volume will decrease by 60% (Alford et al. 2009; Alford and Armstrong 2010).

In the Aral Sea region, the situation is slightly better than in the HKH region. The CC-impact assessment for the glaciers of the entire Tien Shan Mountains by Aizen et al. (2007, p. 1) suggests that “an increase in mean air temperature of 4 ^{o}C and precipitation of 1.1 times the current level could increase ELA by 570 m during the 21st century. Under these conditions, the number of glaciers, glacier covered area, glacier volume and glacier runoff are predicted to be 94%, 69%, 75%, and 75% of current values. The maximum glacier runoff may reach as much as 1.25 times current levels while the minimum will likely equal zero.” The assessment of ELA change is carried out in this study by the modeling of glacier mass budget (Aizen et al. 2007). Glacier area changes are simulated based on the assumption that glacier area-altitude distributions of a large glacier system at any stage of its evolution can be approximated by a normal distribution, the parameters of which are described by the vertical glacier extent in the system and the average of the ELA. Simulated ELA is used to determine minimum elevation of glaciers and total glacier-covered area under the adopted climate scenario.

CC-impact assessment on glacier systems in the Syr Darya Basin and adjacent areas of Tien Shan Mountains run under a set of similar scenarios by Savoskul (2001), suggests that CC-impact on glaciers will be more significant compared to that modeled by Aizen et al. (2007). The study used the regionalized scenarios based on the outputs from two GCMs for 2070-2099, downscaled to 1 x 1 km^2 (Savoskul 2001). The first scenario derived from HadCM2 outputs suggests warming of 3-4 ^{o}C accompanied by a

precipitation increase up to 25-30% relative to the baseline (1961-1990) value. Under the second scenario, based on ECHAM4, air temperature will increase by 5-6 °C and precipitation only by 5-10%. Simulated ELA rise will be 350 m (HadCM2-based scenario) and 650 m (ECHAM4-based scenario). Under a more moderate first scenario, 23% of the glaciated area remains ice-covered. Under the second scenario, only 4% of the currently glaciated area will retain glaciers (Figure 8).

In the Amu Darya Basin, future glacier extent and water availability has been assessed only for the Pyanj catchment, which contains just 3% of glaciated area of the entire basin (Hagg et al. 2011, 2013). The modeling was conducted under two arbitrary scenarios for the year 2050, which suggests a temperature rise of 2.2 °C and 3.1 °C, with no changes in precipitation. The results show a reduction of the glacier extent by 36% and 45% for the two arbitrary scenarios, respectively.

Results of other medium-scale assessments available from (Ananicheva and Davidovich 1997; Lebedeva 1997; Glazirin 2009), do not change the general state of current research: previous studies are too scarce and, as such, do not allow quantification of the potential changes of the glacier extent in the study basins in a methodologically coherent manner, i.e., following standard protocol for creating regional climate scenarios (Lamadrid and MacClune 2010).

Glacier Sensitivity to CC

Instead of evaluating changes in glacier systems under a range of warming scenarios, quantification of CC impact on glaciers in this report is approached through evaluation of a warming scenario which would cause total disappearance of all glaciers in a basin. Conceptually, a glacier will disappear if its ELA will move upwards beyond the highest glacier elevation (H_{max}), because this means the disappearance of the accumulation area that sustains the glacier. The threshold value of an ELA upward shift ($dELA_{max}$) that is expected to eliminate a glacier can be estimated by multiplying the baseline glacier vertical interval $(H_{max} – H_{min})_{1961\text{-}1990}$ by the factor of THAR.

$$dELA_{max} = (H_{max} – H_{min})_{1961\text{-}1990} * THAR \qquad (2)$$

Consequently, the threshold value of the temperature increase from baseline value (dT_{max}) can be estimated from $dELA_{max}$ through the application of adiabatic lapse rate (ALR) as:

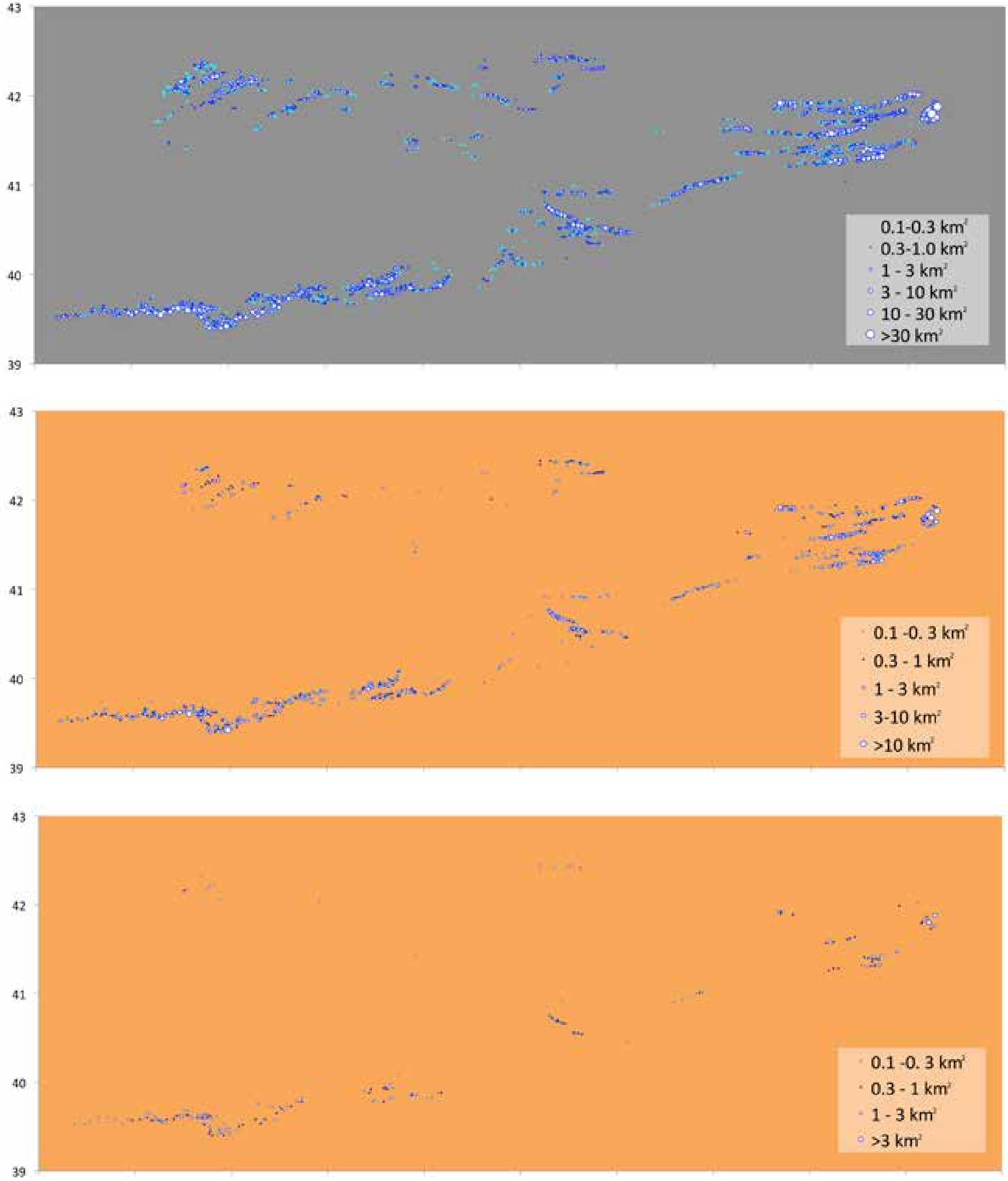
$$dT_{max} = dELA_{max} * ALR \qquad (3)$$

This approach allows glacier areal size classes to be categorized according to their sensitivity to CC, based on size class average elevation interval. Sensitivity of a glacier size class to CC is defined in this report as size class average dT_{max} with a reference to its baseline value in the period 1961-1990. As discussed above, glacier elevation interval shows a variability of ±10-15% from basin to basin, and glacier areal size can, therefore, be taken as an approximation of its sensitivity to CC irrespective of the location of the glacier. Correspondingly, the average value of the highest dT_{max} for the largest glacier size class in a glacier system quantifies the critical warming signal, which would be required for the complete disappearance of all glaciers in a basin, and as such, it determines the entire basin glacier system sensitivity to CC in the study basins.

Assessment of glacier size class and glacier system sensitivity to CC (Tables 8 and 9) has been carried under assumptions of i) increase in precipitation from baseline value in 1961-1990 by 3% for each degree of air temperature increase from its baseline value (dT); ii) uniform ALR of 0.65 °C/100 m of elevation; and iii) THAR of 0.55. Under these conditions, an upward ELA shift (dELA) is expected to be 155 m for each degree of dT.

The accuracy of the assessment of dELA is within ±15-20% range. The inaccuracies arise from the following factors: i) most regional climate models predict slight precipitation changes from -1% to +5% of its current value for each degree of dT (Singh et al. 2011); ii) actual variability of ALR is within ±15% (this report); and iii) THAR variability is around ±10-15% (Meierding 1982). Analysis of the worst-case scenario

FIGURE 8. Baseline (1961-1990; grey background) status of glacier system (top); and simulated changes in the Syr Darya Basin under regionalized scenarios for the period 2070-2099 (orange background), based on outputs of HadCM2 (middle) and ECHAM4 (bottom). Each dot represents a glacier and indicates its areal size. In the areas of intensive glacierization the dots are overlapping (Adopted from Savoskul 2001).



of the future precipitation change (Figure 7) indicates that a precipitation increase by 7%/°C of air temperature rise is likely to offset dELA by only 7-8%, which means that even in the worst case the accuracy of dELA remains within ±15-20% range. Therefore, the uncertainty of this assessment is enveloped by the uncertainty range of currently available GCMs in projecting regional changes in future precipitation and air temperature (Cruz et al. 2007).

According to our assessment, an air temperature rise by 13-15 °C from the baseline 1961-1990 value would be required to make the Indus Basin ice-free. In the Ganges and Brahmaputra basins, an air temperature rise of 10-12 °C would be needed to melt all glaciers down. In the Amu Darya Basin, a warming of 6-8 °C would eliminate all glaciers. Under an air temperature increase by 4-5 °C, the most likely global air temperature rise scenario for the end of the twenty-first century (2070-2099) (Cruz et al. 2007), only Syr Darya and Mekong basins are likely to become almost ice-free. In the other four basins, only glaciers from the largest and medium size classes are likely to survive a temperature rise by 4-5 °C from its baseline 1961-1990 value (Table 8). Simple projection of the current glacier mass-loss rates and ice volume loss suggests that, by the end of the twenty-first century, 25 to 50% of baseline 1961-1990 ice reserves will remain in the Indus, Brahmaputra, Ganges and Amu Darya basins (Table 9).

Conceptual Model of Glacier Evolution under CC Impact

A basin's deglaciation is a complex process, which can be conceptually modeled based on the structural analysis of the glacier systems conducted in this study (Tables 4 and 5).

TABLE 8. Glacier sensitivity to CC according to size class.

Glacier size class (km^2)	Vertical extent (m)	dT_{max} (°C)	CC-sensitivity
0.1-0.3	270-350	1	High
0.3-1.0	500-600	2-3	High
1-3	750-900	3-4	High
3-10	1,000-1,350	4-5	Medium
10-30	1,500-2,000	6-8	Medium
30-100	2,200-2,500	8-10	Low
100-300	3,100-3,600	10-12	Low
>300	4,000-4,500	13-15	Low

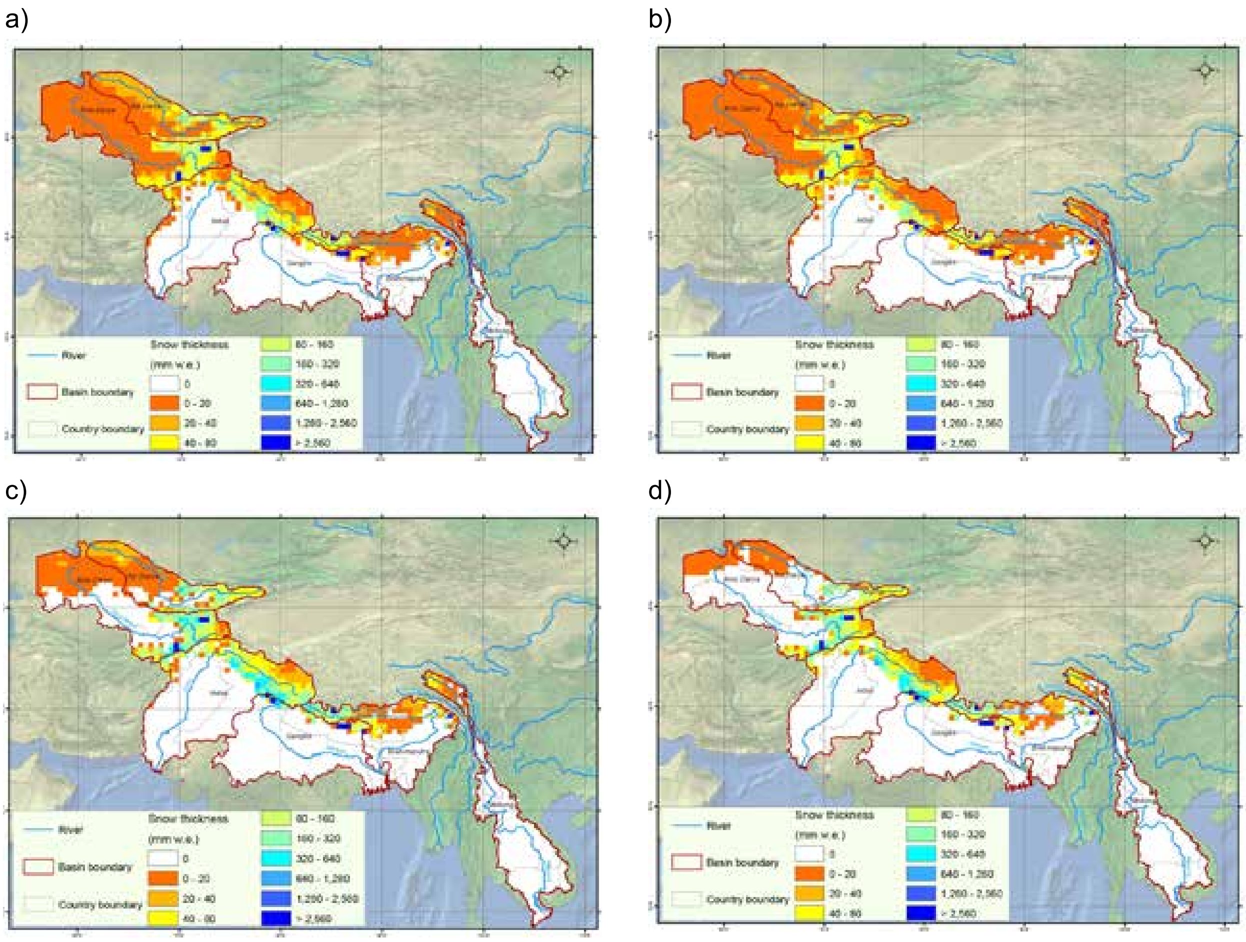
Note: The color palette corresponds to the one used in Figure 4 and Table 3

TABLE 9. Sensitivity of glacier systems to CC and likely changes by the end of the twenty-first century.

Basin	Elevation interval of the largest size classes (m)	Critical value of dELA relative to 1961-1990 (m)	Critical value of air temperature departure from its reference value in 1961-1990 (°C)	Ice volume, under air temperature rise by 4-5 °C (% of basin total in 1961-1990)
INDUS	4,500	2,300	13-15	40-50
GANGES	3,500	1,800	10-12	25-35
BRAHMAPUTRA	3,100	1,500	10-12	35-45
AMU DARYA	2,250	1,200	6-8	20-25
SYR DARYA	1,400	700	4-5	4-8
MEKONG	1,000	500	3	0-5

The entire sequence of the glacier size class distributions in the study basins (Figure 4), starting from the Indus Basin and ending up with the Mekong Basin, can be perceived as a scenario of glacier system evolution under CC-impact, which unfolds in the following way. The glaciers currently belonging to the smallest classes will disappear first. However, this class will be simultaneously “refilled” by the glaciers, which currently belong to larger size classes, but will be reduced in size under temperature increase. For instance, the simulation results from the Syr Darya Basin (Figure 9) suggest that in the western fringes of the basin glaciers from the current areal size class 1-3 km^2 will move to size class of 0.3-1.0 km^2 under a HadCM2 based scenario (Savoskul 2001). This process also involves changes in the glacier type: shift from simple valley glaciers to the cirque type, disintegration of compound valley glaciers into a number of separate glaciers of various types, etc. As a result, the larger size classes will become less numerous and gradually disappear one by one with the progresseion of deglaciation. Thus, glacier system diversity will decrease under CC-impact. The general pattern of glacier system stratification, however, is not likely to be affected. The smallest glaciers will still dominate in numbers, whereas the larger ones will still contain the bulk of the basin’s ice.

FIGURE 9. a) Maximum annual snow extent in the baseline 1961-1990 period (30-year average for January); b) Maximum annual snow extent in 2000-2008 (9-year average for January); c) Maximum annual snow accumulation in the baseline period 1961 (30-year average for March); and d) Maximum annual snow accumulation in 2000-2008 (9-year average for March).



Data source: University of Delaware Terrestrial Water Budget Archive (http://climate.geog.udel.edu/~climate/; Willmott and Matsuura 2006).

Seasonal Snow Cover

The attention paid in this report to glaciers and seasonal snow is disproportional due to the following reasons: i) significantly more complicated nature of the glacier systems, marked by large spatial heterogeneity and pronounced diversity of individual glaciers in many respects; ii) availability of primary data sources: in order to arrive at certain conclusions on glaciers on a basin-scale level, a vast number of partially overlapping datasets had to be compared and analyzed, whereas data sources for seasonal snow parameters are relatively uniform, straightforward and easy to access and process; and iii) availability of published research: the papers focused on glaciers in the study region by far outnumber those concerned with seasonal snow cover.

Data Source

Data for the assessment of the changes in seasonal snow extent and depth are acquired from the data archive of simulated terrestrial water budgets available from the University of Delaware web portal on climatology (Willmott and Matsuura 2006). The data archive provides full coverage for the reference period 1961-1990 and partial coverage for the period 2001-2010 at a spatial grid of 0.5 x 0.5 degrees and a temporal resolution of one month. The unique character of the database (http://climate.geog.udel.edu/~climate/; Willmott and Matsuura 2006) is that it offers data on snow depth. Its only disadvantage is that it does not extend beyond 2008. Therefore, the average basin totals for the period 2000-2008 are taken here to represent the first decade of the current millennium (2001-2010). Other principal resources of readily-available data based on RS materials only offer short-term data on areal extent and no evaluation of the water storage properties of seasonal snow cover (e.g., Zhetker and Tsarev 1991; Gurung et al. 2011; Butt 2012).

Recent Changes in Seasonal Snow Cover and Likely CC Impact

Based on this study analysis of long-term average data, maximum seasonal snow cover in all study basins has been observed in February, January (Ganges) or March (Mekong). However, maximum accumulation in terms of total snow volume (w.e.) occurs in March in all the basins apart from the Syr Darya Basin, where it occurs in February. Table 10 presents the average data on maximum average snow cover extent and water storage capacity and their changes from baseline (1961-1990) to current (2000-2009) time intervals. The basin monthly snow water storage capacity is assessed from the monthly data on snow cover depth (Figure 9). The accuracy of the estimates of the maximum seasonal water storage capacity is ±40%.

In the baseline period (1961-1990), seasonal snow cover in the Ganges and Mekong basins did not extend over large areas; it covered a mere 6% of the basin's area. In the Indus and Brahmaputra basins, maximum seasonal snow extended over 27-28% of the basin area. In the Amu Darya and Syr Darya basins, stable seasonal snow cover was forming over the major part of basin area, i.e., Amu Darya: 66% and Syr Darya: 90%. The maximum seasonal water storage capacity of snow in the baseline period (1961-1990) was the largest in the Indus, Amu Darya, Syr Darya and Brahmaputra basins, making 49 km^3, 34 km^3, 24 km^3 and 17 km^3, respectively. In the Ganges and Mekong basins, it was 9 km^3 and 2 km^3. Ratio of maximum storage capacity of seasonal snow to mean annual flow (MAF) is significant only in the Aral Sea region (42-63%) and in the Indus Basin (21%).

Data on the changes in maximum seasonal snow extent (Table 10) indicate that in four basins maximum seasonal snow cover extent decreased by 5-15% in the past 50 years. There were no significant changes only in the Ganges and Mekong basins. However, the maximum seasonal snow water storage capacity in all basins apart

from Mekong shows much more significant reduction in the range of 9-27%.

Maximum snow coverage and its water storage capacity are indicative of changes in total winter precipitation. The observed monthly differences between baseline and current time periods (Figure 10), however, reflect the impact of an overall increase in air temperature. In the Aral Sea region, November, February and March are the months with the most pronounced differences between baseline and current snow cover extent. In the HKH region, the months with the largest differences are October, April and May. These findings are indicative of the overall shortening of the duration of stable seasonal snow cover at lower altitudes, where at present snow cover forms later and melts earlier compared to the baseline period (1961-1990). This explains why maximum seasonal water storage capacity of snow has significantly reduced in all the study basins apart from the Mekong Basin, where it was negligible in comparison to mean annual flow. The changes are particularly large in the Indus, Ganges, Amu Darya and Syr Darya basins, where maximum seasonal storage capacity of snow decreased by 21-27% (Table 10).

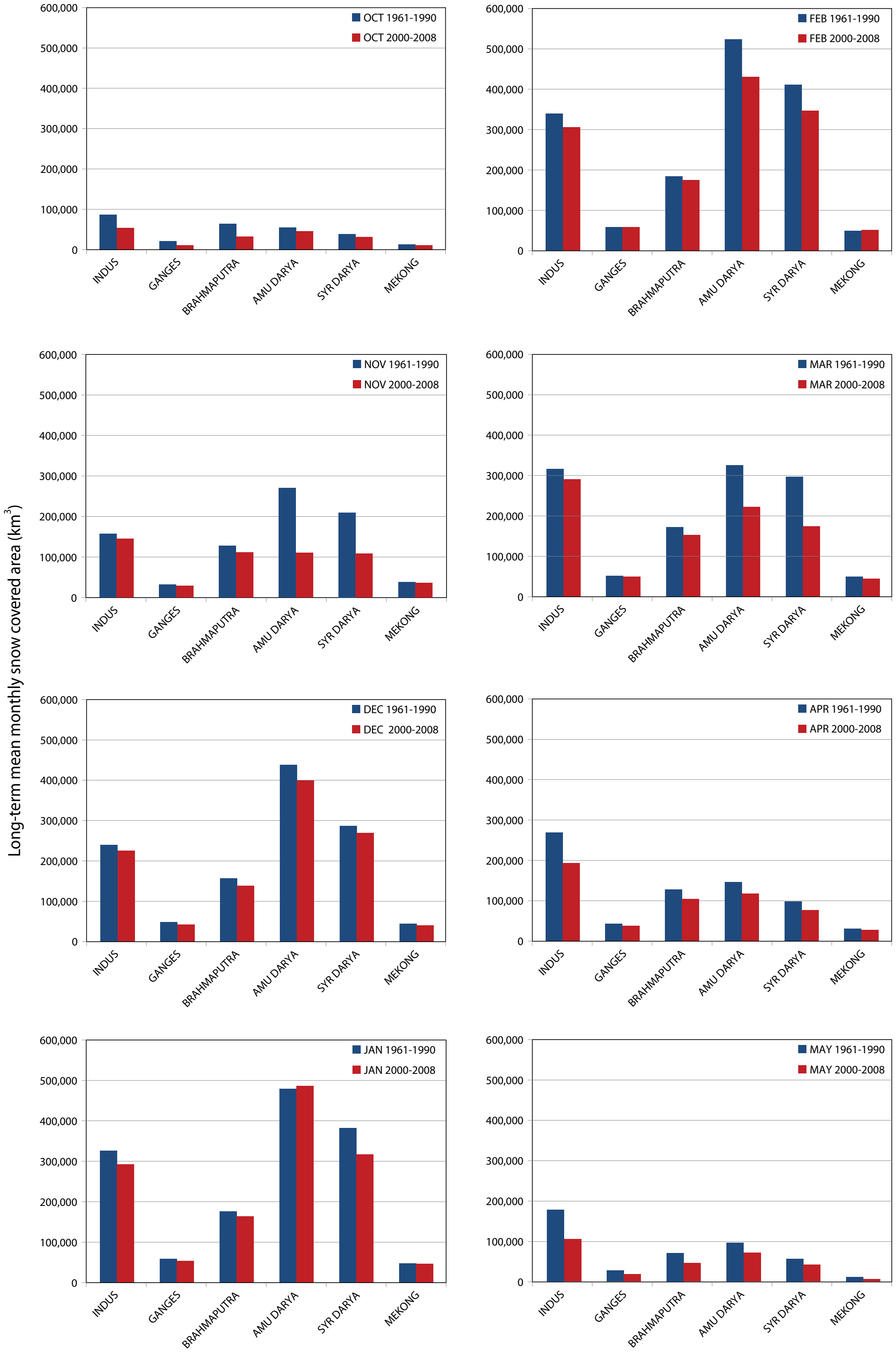
At present, the available large-scale studies addressing CC impact on snow in the study basins are too few (Zhetker and Tsarev 1991; Singh and Bengtsson 2003; Gupta et al. 2005; Barnett et al. 2005; Immerzeel et al. 2009, 2010; Tahir et al. 2011; Gurung et al. 2011), and do not provide sufficient data for a comprehensive and methodologically consistent assessment of future changes. The CC impact on seasonal snow in mountain catchments can be conceptualized as extrapolation of the tendency already observed, i.e., decrease in areal extent, water storage capacity and duration (Barnett et al. 2005; Bookhagen and Burbank 2010).

TABLE 10. Changes in average maximum seasonal snow area and water storage capacity in the past 50 years.

Basin	Maximum seasonal extent (long-term mean for 1961-1990)			Difference between 1961-1990 and 2001-2010 (% of 1961-1990 value)	Maximum seasonal water storage capacity (long-term mean for 1961-1990)			Difference between 1961-1990 and 2001-2010 (% of 1961-1990 value)
	Month	Area (km^2)	Share in basin total area (%)		Month	Volume, (km^3 w.e.)	(% of MAF)	
INDUS	February	341,191	28	-10	March	49	21	-21
GANGES	January	59,134	6	-2	March	9	2	-18
BRAHMAPUTRA	February	184,678	27	-5	March	17	2	-9
AMU DARYA	February	527,049	66	-7	March	34	42	-24
SYR DARYA	February	413,428	90	-15	February	24	63	-27
MEKONG	March	50,209	6	3	March	1.9	0.4	5

Data source: Snow extent and duration: University of Delaware Terrestrial Water Budget Archive (http://climate.geog.udel.edu/~climate/; Willmott and Matsuura 2006). MAF: AQUASTAT database of the Food and Agriculture Organization of the United Nations (FAO) (http://www.fao.org/nr/water/aquastat/main/index.stm); United Nations Environment Programme (UNEP) Global Environment Outlook (GEO) data portal (http://geodata.grid.unep.ch/).

FIGURE 10. Changes in monthly mean areal extent (km^2) of seasonal snow from 1961-1990 to 2001-2010.



Data source: University of Delaware Terrestrial Water Budget Archive (http://climate.geog.udel.edu/~climate/; Willmott and Matsuura 2006).

Conclusions

1. For the first time, the baseline (1961-1990) and current (2001-2010) water storage properties of glacier systems and seasonal snow cover have been systematically analyzed at the basin scale for six major Asian river basins. The assessment of water storage-related properties of glacier systems such as number of glaciers, glacier-covered area and ice volume, relies on the meta-database for 48,607 glaciers, which has been compiled specifically for this study based on all available glacier inventories and represents a new data product in its own right. Seasonal snow cover is characterized by maximum seasonal areal extent and maximum seasonal water storage capacity assessed by analysis of monthly mean simulated values derived from the terrestrial water budget data archive of Delaware University, USA.

2. Critical review of the currently available data and methods of assessment of water storage properties of glaciers and snow cover suggests the following range of accuracies. The methods of glacier surveys make possible the accounting of every single glacier and measurements of glacier area with an accuracy of ±5%. However, the total number of glaciers per basin and the total glacier covered area as a 30-year or decadal mean should be considered as an approximation with ±20% accuracy, since these parameters may change from year to year and hence are affected by the date of glacier survey, the size of the smallest glacier class included in the inventories and apart from the human factor in data processing. Areal extent of seasonal snow is assessed here with a spatial resolution of 0.5 x 0.5 degrees. Estimates of total basin glacier ice volume have a very low accuracy of ±50-70% due to systematic errors in the models employed for ice volume evaluation in the currently available glacier inventories, and the extreme scarcity of field measurements of glacier thickness. The estimates of total basin ice volume changes may be slightly improved through cross-validating them by records of annual rates of glacier mass-loss, which have much better accuracy (within ±10%). However, in most basins, these data are available only from very small samples. The best possible accuracy for basin seasonal snow water storage capacity is in ±40% range. The CC sensitivity of glaciers is estimated with an accuracy of ±20%.

3. The analysis of areal size class frequency distributions of spatial parameters of individual glaciers reveals that glacier systems are structured in a broadly similar pattern across all the study basins. Approximately half to two-thirds of the total basin ice volume is concentrated in just a few dozens of the largest glaciers, which in sum constitute the first few percent of total glacier numbers. The larger the glacier system the more structurally diverse it is in terms of differences between the smallest and the largest glaciers, number of glacier areal size classes and glacier morphological types, vertical interval of glacier occurrence, ELA variability, etc.

4. The observed and reconstructed changes in glacier systems between 1961-1990 and 2001-2010 are marked by the overall areal reduction and ice volume loss. At the same time, the number of glaciers in most basins (e.g., the Indus, Ganges, Mekong basins and parts of Amu Darya Basin), increased due to disintegration of large glaciers into a number of smaller ones. The monitored changes in glacier systems (areal reduction, mass loss, changes in glacier numbers) are far from uniform in temporal and spatial respects, suggesting that spatial and temporal magnitude of the recent changes are highly variable due to high regional and local variability of the recent CC signal.

5. The assessment of areal reduction of the glaciers between 1961-1990 and 2001-2010 made in this study is based on data obtained

from i) repetitive glacier inventories; ii) data of glacier monitoring; and iii) published research based on remote sensing. In the Indus, Brahmaputra, Ganges and Mekong basins, such records are available for 100% of the basin glacier-covered area, but in the basins of the Aral Sea region the records are available only for 60-75% of the glacier-covered area. The estimated mean annual rates of basin total glacier-covered area reduction vary from 0.4-0.5%/year (the Brahmaputra and Amu Darya basins) to 0.7-0.9%/year (all the other basins). In some catchments of the Indus and Amu Darya basins, however, the observations indicated either no pronounced reduction in glacier area or even a slight increase.

6. With regards to ice volume changes in the past 50 years, much less data are available. The poorest area coverage is in the Ganges Basin, where just 1% of the glaciated area is sampled, and in the Indus and Brahmaputra basins it is 15% and 6%, respectively. In the Amu Darya and Syr Darya basins, the sampled area is 75% and 35% of ice-covered terrain, respectively. On average all the glacier systems lose glacier mass with the estimated annual rates of ice volume losses varying from 0.4%/year (Brahmaputra) to 1%/year (Ganges).

7. It is shown that the conceptual model of glacier system evolution under CC, in the long run, will be the decrease of system's diversity in terms of number of areal size classes, vertical extent of glacier occurence, differences between the largest and the smallest glaciers, etc. The principal system structure, however, is not likely to change: small glaciers will dominate in numbers, whereas the bulk of a basin's ice will remain in the largest and medium-sized glaciers.

8. It has been found that glacier system sensitivity to CC depends on the diversity of the glacier systems' structure. Correspondingly, highly diverse glacier systems in the Indus, Ganges, Brahmaputra and Amu Darya basins have low to medium sensitivity to CC change. The air temperature rise (relative to baseline period 1961-1990) that is likely to lead to complete meltdown of all glaciers is 13-15 ^{o}C in the Indus Basin, 10-12 ^{o}C in the Ganges and Brahmapura basins, and 6-8 ^{o}C in the Amu Darya Basin. For comparison, glacier system in the Mekong Basin is projected to dissapear under a temperature warming of 3 ^{o}C, and in the Syr Darya Basin, the glacier system will be reduced to a dozen of glaciers under warming of 4-5 ^{o}C.

9. Under the most widely accepted scenario of CC by the end of the twenty-first century, i.e., 4-5 ^{o}C temperature rise accompanied by 3%/^{o}C increase in precipitation, large glacier systems are likely to retain 40-50% (Indus Basin) to 20-25% (Amu Darya Basin) of their baseline ice reserves.

10. Maximum seasonal snow cover area in the baseline 1961-1990 varied from 6% of total basin area (the Ganges and Mekong basins) to 90% (Syr Darya Basin). Maximum seasonal water storage capacity in the same period was between 49 km^3 (the Indus Basin) and 2 km^3 (the Mekong Basin). In 50 years, maximum seasonal snow extent decreased in most basins apart from the Ganges and Mekong basins. The maximum seasonal water storage capacity of seasonal snow has reduced too in most study basins apart from the Mekong Basin. The CC impact on seasonal snow in mountain catchments can be conceptualized as extrapolation of the tendency already observed, i.e., decrease in maximum seasonal areal extent and maximum seasonal water storage capacity.

11. Table 11 summarizes the baseline (1961-1990) and current (2001-2010) states and possible future changes of water storage-related properties of glacier systems and seasonal snow cover in the study basins more specifically.

12. Water storage capacity of glacier systems in the study basins by far exceeds that of seasonal snow cover, from approximately 120-fold (in the Indus Basin) to sixfold (in the Mekong Basin). However, this proportion difference has not changed significantly in the past 50 years.

TABLE 11. The summary of current state, recent changes, and possible CC-impacts on glacial systems and seasonal snow cover.

	Indus	Ganges	Brahmaputra	Amu Darya	Syr Darya	Mekong
BASELINE (1961-1990)						
Number of glaciers	13,605	6,719	11,996	9,749	3,429	380
Glacier-covered area (km^2)	27,759	12,541	16,248	11,101	2,522	316
Glacier-covered area (% of basin area)	2.7	2.7	2.4	1.7	0.6	0.04
Ice volume (km^3 w.e.)	3,839	1,243	1,487	648	133	18
Maximum elevation of glacier occurrence (m)	8,500	8,800	8,300	7,300	5,200	6,700
Minimum elevation of glacier occurrence (m)	2,400	3,600	3,700	2,100	2,400	2,700
Area of the largest glacier area (km^2)	1,056	263	207	156	70	16
Maximum seasonal snow areal extent (km^2)	341,191	59,134	184,678	527,049	413,428	50,209
Maximum seasonal snow extent (% of basin area)	28	6	27	66	90	6
Maximum seasonal snow water storage capacity (km^3 w.e.)	49	9	17	34	24	2
CURRENT STATUS (2001-2010)						
Number of glaciers	18,495	7,963	11,497	n.a.	n.a.	482
Glacier-covered area (km^2)	21,193	9,012	14,020	8,736	1,967	235
Ice volume (km^3 w.e.)	2,696	794	1,303	538	105	10.7
Maximum seasonal snow areal extent (km^2)	307,807	57,963	175,155	488,289	349,358	51,465
Maximum seasonal snow extent (% of basin area)	25	6	26	61	76	6
Maximum seasonal water storage capacity of snow (km^3 w.e.)	39	7	15	26	18	2
CHANGES BETWEEN 1961-1990 and 2001-2010						
Reduction of glacier-covered area relative to 1961-90 (%)	-24	-28	-14	-15	-22	-26
Ice volume reduction relative to 1961-90 (%)	-30	-33	-11	-17	-21	-40
Changes of maximum seasonal snow areal extent relative to 1961-90 (%)	-10	-2	-5	-7	-15	3
Changes of maximum seasonal snow water storage capacity, relative to 1961-1990 (%)	-21	-23	-9	-24	-27	0
SENSITIVITY TO CC AND POSSIBLE CC IMPACT						
Glacier system sensitivity to CC	Low	Low	Low	Medium	High	High
Critical air temperature rise required for overall glacier disappearance (°C)	13-15	10-12	10-12	6-8	4-5	3
Number of glaciers likely to survive air temperature rise by 4-5 °C (end of twenty-first century)	268	251	260	118	11	3
Share of basin total ice volume concentrated in the above glaciers (% of basin total for 1961-1990)	85	68	63	47	22	23
Ice volume under air temperature rise by 4-5 °C (% of basin total for 1961-1990)	50	35	45	20	8	7

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+94-11-2880000

Fax
+94-11-2786854

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ISSN: 1026-0862
ISBN: 978-92-9090-766-4