Journal of Hydrology 518 (2014) 225–234

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Data and knowledge gaps in glacier, snow and related runoff research – A climate change adaptation perspective

Nadine Salzmann [a,b,*], Christian Huggel [b], Mario Rohrer [c], Markus Stoffel [d,e]

[a] Department of Geosciences, University of Fribourg, Chemin du Musée 4, 1700 Fribourg, Switzerland
[b] Department of Geography, University of Zurich, Winterthurerstr. 190, 8057 Zurich, Switzerland
[c] Meteodat GmbH, Technoparkstr. 1, 8005 Zurich, Switzerland
[d] Institute for Environmental Sciences, University of Geneva, Chemin de Drize 7, CH-1227 Carouge, Geneva, Switzerland
[e] Dendrolab.ch, Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland

ARTICLE INFO

*Article history:*
Available online 16 June 2014

*Keywords:*
Climate change adaptation
Glacier
Snow
Climate change impacts
Mountain environments

SUMMARY

Glacier and snow cover changes with related impacts on melt runoff can seriously affect human societies which are depending on fresh water from cryospheric sources. Observed trends and projected future evolutions of climatic and cryospheric variables clearly show the need to adapt to these changes. Accordingly, the topics addressed herein have been put on the agendas of many larger funding agencies. This article provides a brief overview on major ongoing activities on glacier, snow and related runoff research in order to then analyze data gaps and research needs from a climate change adaptation perspective. Major data needs are identified with respect to the spatial and temporal coverage of local-scale data and related needs for (data) services that distribute and maintain these data sets. Moreover, clear research needs are also recognized at the local scale where process knowledge needs to be improved (e.g., the influence of albedo on snow and ice or debris cover on glaciers) in order to derive plausible climate change impacts assessments. The paper then discusses directions on how to move forward to better serve the practical needs for climate change adaptation planning. In the future, substantial support by large funding agencies might be key for capacity building in target regions of climate change adaptation programs, for longer-term and more sustainable commitments, and for the development of approaches, which aim at assessing the transferability of data, techniques, and tools.



## 1. Introduction

Glaciers and seasonal snow cover in mountain areas are an important component of the water cycle and the climate system (Barnett et al., 2005). They supply a significant part of the water resources for fresh water, irrigation or power production in mountain regions and adjacent lowlands, particularly in arid or semi-arid environments (Viviroli et al., 2007). In the Colorado Rocky Mountains, for instance, high elevation snow pack provides about 70% of the annual runoff of the Colorado River and the seasonal runoff pattern is heavily dominated by winter snow accumulation and spring melt (Christensen et al., 2004). In the tropical Andes, with their distinct wet-dry climate, glacierized mountain ranges such as the Cordillera Vilcanota (Southern Peru) play a significant role in providing water from glacier melt during the dry period for irrigation, power production and fresh water supply, and are thus an important socio-economic factor (Vergara et al., 2007). In the headwaters of the Ganges, river flow variation has been shown to be driven by the summer monsoon. As a consequence, much of the discharge reductions since the 1960s (by 50% in the lower Sutlej and north-west Ganges basin) were caused by a weakening monsoon – with a related decrease in the temporary water storage in the form of snow – but less so by melting glaciers (Collins et al., 2013).

Mountain glaciers and snow are particularly sensitive to climatic changes because of their proximity to melt conditions. As air temperature is a major index for ice and snow melt processes (e.g., Hock, 2003), the observed and projected rise in global mean air temperature cause overall significant losses of ice masses worldwide (IPCC, 2013), an effect which is either damped or enhanced by changes in regional precipitation patterns. A large number of in situ and satellite based observations provides evidence of the global-scale shrinkage of mountain glaciers (Gardner et al., 2013). Similarly, various monitoring studies indicate a decline in snow cover extent in most months, and in

* Corresponding author at: Department of Geosciences, University of Fribourg, Chemin du Musée 4, 1700 Fribourg, Switzerland. Tel.: +41 26 300 92 50; fax: +41 26 300 97 46.

*E-mail address:* nadine.salzmann@unifr.ch (N. Salzmann).

http://dx.doi.org/10.1016/j.jhydrol.2014.05.058
0022-1694/

particularly in spring (Déry and Brown, 2007), since the early 20th century (Brown and Mote, 2009; Henderson and Leathers, 2010; Marty, 2008; Voigt et al., 2011). Since snow cover is a seasonal phenomenon, its spatial variability is accordingly much higher than for glaciers. For the future, modeling studies at various temporal and spatial scales and degrees of complexity consistently suggest a strong decrease in glacier extent, ice volume, and snow cover extent and duration (Huss et al., 2008; Marzeion et al., 2012; Salzmann et al., 2012; Brutel-Vuilmet et al., 2013).

The contribution of glaciers to downstream runoff depends on glacier size, proportion of glacier area to catchment size, and seasonal climatic conditions. There is substantial concern that warming will have a negative effect on freshwater supply, hydropower production and other eco-services (Finger et al., 2012; Huss et al., 2014). In fact, for some catchments in the Andes of Peru or the Alps, 'peak water', i.e. the point in time when runoff starts to decline, has probably already passed, based on documented long-term runoff monitoring (Collins, 2006; Baraer et al., 2012).

Changes in seasonality of runoff will also be significantly influenced by snow cover and related modifications due to climatic changes. Combined effects of glacier and snow cover changes will thus exacerbate shifts in seasonality of runoff. The importance of snow cover on the availability and timing of runoff in the Greater Himalayas has been outlined recently by Rohrer et al. (2013). Water supply in the Greater Himalayas often strongly depends on the sub-region and even on the particular watershed, as can be illustrated by the example of two villages in Mustang (Nepal). The people of these two villages heavily depend on the highly variable and increasingly reduced runoff from snow cover. As a consequence of seriously felt changes, both villages have now decided to move down-valley to locations where water provision is more diversified. A third village in the same Himalayan valley has considered searching for a new location as well, but finally decided that water resources are still sufficient, at least for the time being (Kamforsud-Supsi, 2012).

These considerations and experiences clearly signal the need for mountain and downstream societies to respond and adapt to changes of water resources. The increasing number of climate change adaptation programs with a clear focus on water resources (e.g. PACC (Salzmann et al., 2009; IH-CAP (http://www.ihcap.in); CAWa (Vorogushyn et al., 2008) clearly demonstrate that the challenge has been understood and is being addressed at high political levels. However, while there is a clear observed and projected global trend of increasing air temperature, the pattern for precipitation is less consistent (Fig. 1) and at regional to local scales also the magnitude of air temperature increase can vary considerably, particularly in regions with distinct high-elevation topography (Schauwecker et al., 2014). In combination with differences in the climate sensitivities of earth surface processes, the effective impacts can vary significantly as illustrated by Fig. 2, which shows the observed cumulative changes in glacier mass balance of selected glaciers of the Swiss Alps. This fact of high spatial and temporal variability of key climate variables and physical impacts is a serious drawback for adaptation efforts, since it underlines the need for data and knowledge to be available at the local scale, in addition to the development of adequate adaptation measures within the local socio-economic context.

This article aims at providing a general overview on directions and recent progress in glacier, snow and related runoff research as often supported by major funding institutions such as the European Commission (under its past Seventh Framework Programme or now in Horizon 2020), the World Bank, or governmental development agencies (e.g., Swiss Agency for Development and Cooperation SDC). Rather than addressing issues related to fundamental research, we are adopting a perspective of needs for climate change adaptation measures to be developed. Thus, we strive (i) to analyze how progress in data acquisition, management and research is supportive for the development of adaptation measures, (ii) to identify research and data gaps in view of adaptation needs, and (iii) to discuss possible ways to move forward. Consequently, we are far from aspiring a comprehensive state-of-the-art analysis or review of monitoring, research and data gaps in the fields of glacier and snow runoff. Rather, we select a number of key issues that are relevant from a climate impacts and adaptation perspective, including selected examples from different mountain regions of the world.

## 2. General overview and selected examples of glacier, snow and runoff research

Adverse impacts associated with a decrease of snow and ice and the related changes in melt runoff can affect societies seriously (Barnett et al., 2005; Beniston et al., 2011; Viviroli et al., 2011). International programs (e.g. UNEP, WMO under the Global Terrestrial Network GTN) and funding agencies (e.g. EU, World Bank) have responded to these challenges with a multitude of research programs and funding schemes dedicated to glacier and snow research. In the following, we provide a brief overview in the form of selected examples from large research programs in glacier and snow runoff research without attempting to being comprehensive or to including all major ongoing initiatives.

### *2.1. Glaciers*

As glaciers are among the most obvious, because most clearly visible indicators of climate change, great efforts have been put into global glacier monitoring programs in the past. While some of these programs have been running for several decades (e.g. World Glacier Monitoring Service, WGMS), others started more recently (e.g. Global Land Ice Measurements from Space, GLIMS) and when new methods and techniques became available. These programs complement each other in terms of monitored variables, spatial coverage and applied methods.

Some of the longest records of standardized glacier mass balance measurements and length changes are compiled and disseminated by the WGMS. The data is based on standardized in situ measurement methods such as stake networks, and is disseminated online and in the form of printed products (e.g. Glacier Mass Balance Bulletin (GMBB) or Fluctuations of Glaciers (FOG)). From Fig. 3, it becomes obvious that the observed glaciers are not evenly distributed in space. In particular, regions with high vulnerabilities to glacier change (IPCC, 2013), such as the Andes (cf. Fig. 6) or Central Asia dispose only of a limited number of long-term observational records, whereas the Alps have a fairly dense network of long observation series.

The aforementioned in situ monitoring measurements are complemented by data from optical satellite instruments. GLIMS provides worldwide glacier outlines and collects the corresponding satellite scenes, mainly from ASTER imagery. The data products offered by GLIMS have recently been supplemented by the new and freely available global glacier inventory, the Randolph Glacier Inventory (RGI; Arendt et al., 2012), an initiative that was considerable supported by the GlobGlacier, Glacier_cci (funded by ESA; Paul et al., in press), Cryoclim (funded by ESA), and ice2sea (funded by the EU FP7 program) projects. The compilation of the RGI was motivated by the release of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). RGI provides worldwide glacier outlines based on various data sources such as satellite data, dating back to the 1950s, or the World Glacier Inventory (WGI) dataset, and includes data until 2010. In that sense, and in difference to some other, more regional products, the RGI does not represent the state of glaciers for a certain point in time or a specific decade.