Preface

Mountain Hydroclimatology and Snow Seasonality—
Perspectives on climate impacts, snow seasonality and hydrological change in mountain environments

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INTRODUCTION

Mountain environments are extremely important to the world's water resources, weather systems and populations. This Special Issue of *Hydrological Processes* on 'Mountain hydroclimatology and snow seasonality' is a follow-up of the last Special Issue on Mountain Hydrology in *Hydrological Processes* (de Jong *et al*., 2005b). It is largely based on mountain and snow hydrology sessions at successive European Geosciences Union (EGU) General Assembly meetings in Vienna in 2005 and 2006, supported by some invited papers. These sessions dealt with the theme of 'Mountain hydrology and climatology: present state and future scenarios'. This introductory paper provides an overview of the hydrological importance of mountain regions, outlines some recent developments in the field and introduces the other 11 papers which comprise this timely Special Issue.

IMPORTANCE OF MOUNTAIN ENVIRONMENTS UNDER CHANGING CLIMATE AND ANTHROPOGENIC CONDITIONS

Mountain regions occupy 27% of the earth's continental surface, but receive a disproportionately large precipitation. However, mountains supply a much greater fraction of runoff and the world's population with water, and contain 70% of the world's freshwater (Casassa *et al*., 2007).

Runoff generated in mountain catchments benefits surrounding lowlands to varying degrees depending on the climatic zone and altitude. Therefore, mountain zones can be regarded as important 'water towers' (Liniger *et al*., 1998; Viviroli *et al*., 2007) which store and deliver fresh water to downstream areas. Snow and ice accumulation in mountain environments also has a profound influence on the surface energy and water budgets of regions with seasonal snow cover. The affected area is considerable (Figure 1 from Viviroli *et al*., 2007 and a review by Viviroli *et al*., 2007) shows those parts of the world where snowmelt is the dominant control on seasonal runoff, together with those regions of complex topography (inset, Figure 1). Barnett *et al*. (2005) estimated that about one-sixth of the world's population lives within this region (Figure 1). Furthermore, more than 40% of the world's population is located in catchments of rivers which are sourced in mountain ranges (Beniston, 2005).

Altitudinal gradients are substantial in mountains; even in the low mountain environments of western Britain, average annual precipitation rises with altitude at a rate of 2·8 mm m^{-1} (Lawler, 1987) and annual mean maximum temperatures decrease with altitude by about 8·5 °C km^{-1} (Harding, 1978). Moreover, several studies detail important feedback mechanisms by which glaciers can also affect climate (e.g. Casassa *et al*., 2007). In addition, mountain environments can also provide energy through hydropower potential, deliver important sediments, solutes and nutrients for downstream zones (Lawler *et al*., 2003; Bravard, 2008) and lead to increased flood risk, especially through rain-on-snow events. Apart from changing climatic and hydrological processes, mountain environments are increasingly modified by anthropogenic influences, in particular, those from mountain recreation and infrastructure. These can affect local catchment hydrology, erosion, suspended sediment, solute and nutrient transport and water and habitat quality (Wemple *et al*., 2007; de Jong *et al*., 2008). However, very few publications exist on issues such as the effects of ski resort development on catchment hydrology and water quality. Wemple *et al*. (2007) indicated that runoff was 18–36% higher in a catchment developed for skiing because of the high percentage of impervious surfaces from ski, housing and infrastructural developments.

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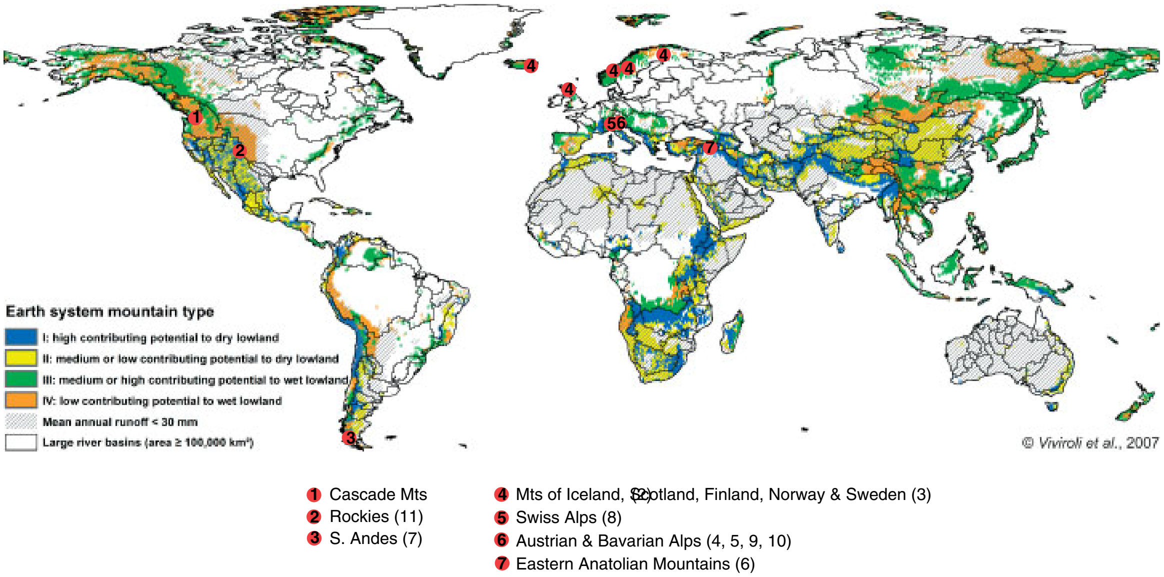

Figure 1. Location of all study sites dealt in the chapters of this special issue relative to the world's water towers after Viviroli *et al*., 2007. Numbers in brackets refer to the logical sequence of articles in the special issue associated with the different mountain ranges (with the exception of the first article that is a global study)

De Jong *et al*. (2008) demonstrated for alpine catchments that seasonal patterns of hydrology and single extreme flood events can considerably change under the influence of artificial snow melt at the sub-catchment scale. Thus the maximum summer discharge can be delayed by several months, and peak flood discharge can be augmented by up to 30%. Wemple *et al*. (2007) found that suspended sediment concentrations were more than twice as high as normal levels and all major solute concentrations were higher. Evaporation losses also need to be considered from intensive ski run management through artificial snow application. Arabas *et al*. (2008) were able to detect changes in relative humidity and dew point by aircraft measurements before and after the start of artificial snow production in the low elevation catchment of Oberlarn, Austrian Alps. Consumptive losses from artificial snow-making are estimated to range between 13 and 37% of water used for snow-making (Eisel *et al*., 1988). At the same time, artificial snow increased annual precipitation by only 4% in the study by Wemple *et al*. (2007). Vanham *et al*. (2008) and Teich (2007) found that in the Austrian and Swiss Alps, between 20 and 40% of the total water annual water consumption goes into snow production, which is the equivalent of more than 50% of the total drinking water consumption. Other studies focus on tracers and GIS to evaluate the effects of land use change, in particular, forest clearing, road construction, grazing and burning of moorlands on the local hydrology in the Cairngorm mountains, Scotland (Tezlaff *et al*., 2007).

From an analysis of publications through time, Figure 2 shows that interest in mountain environments has grown significantly ($p < 0{\cdot}01$) from 1998 to 2007, as their importance is increasingly recognized. On average, the annual rate of publication in the field of mountain hydrology has increased by almost eight papers per year (Figure 2), and the last 3 years have seen at least 120 papers per annum devoted to the topic. Some recent advances are briefly outlined below.

DEVELOPMENTS IN HYDROCLIMATE AND SNOW SEASONALITY RESEARCH IN MOUNTAIN ENVIRONMENTS

The major developments in the field of hydroclimatology and snow seasonality in mountain environments can be subdivided into three general categories: first, the linkage between general circulation patterns, climate and hydrological response; second, the future climate and human impacts on mountain environments; and third, hydrological modelling of snow and glacier melt.

Linking circulation, climate and hydrological response

There have been many notable developments in establishing links between recent atmospheric circulation change, climate variability and associated responses of glaciers, snow packs, river flows or other hydrological systems (e.g. de Jong *et al*., 2005a; Lawler *et al*., 2003; Vincent *et al*., 2005). Many of these studies are reviewed by Kingston *et al*. (2006a) and placed in a simple model to illustrate chains of causality in northern North Atlantic environments (Figure 3). A key observation is that deglaciation is now occurring in most mountain environments across the globe (Barnett *et al*., 2005). A declining number of snow days at low-altitude (<1300 m) stations in Switzerland over the last several decades have also been noted by Scherrer *et al*. (2004). Kingston *et al*. (2006b), for the first time, have established teleconnections in circulation-driven river flows between eastern North America and montane northern Europe in autumn and between northern Europe and lower relief areas to the south during April–May and July–December. However, it is especially difficult to link

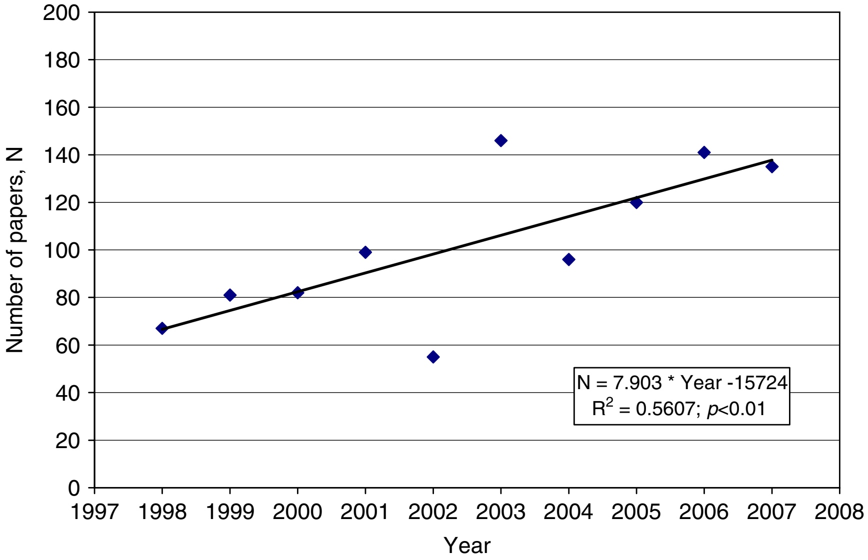

Figure 2. Number of publications per year with Mountain Hydrology as Topic, 1998–2007 (analysis using ISI Web of Knowledge, 2008)

patterns of climate change to hydrological responses in mountain environments, and much more work is needed to develop extrapolation techniques suitable for complex topography, and new remote-sensing outputs are likely to play a key role here (e.g. Marcus and Fonstad, 2008).

Future climate and human impacts on mountain environments

Studies that assess likely future climate impacts on mountain environments are growing rapidly, and many of these have been reviewed by Bales *et al.*, (2006) and Barnett *et al.* (2005). In the mountains of western USA, for example, near-surface air temperature is projected by 2050 to be 0·8–1·7 °C higher than present values, though little change in precipitation is anticipated. The largest impact predicted by 2050 was a reduction in snowpack and a shift in runoff seasonality, with peak runoff occurring about a month earlier than present (Bales *et al.*, 2006, Barnett *et al.*, 2005). The Rhine River basin may shift from a mixed snow-rainfall to a more rainfall-dominated regime, with higher winter discharges and lower summer flows; this is likely to reduce supplies when they are most needed, and raise the level of flood risk in parts of the Rhine floodplain. New concerns for reliable drinking water supplies also arise in those karstic catchments that will lose their glaciers within the next 30–50 years and will soon rely only on precipitation (Gremaud, 2008). The new climate scenarios of IPCC (2007) are likely to trigger further international impact studies. Other studies in the Pyrenees show that climate change effects on hydrology cannot be isolated and that environmental change and water management effects are now a major issue (Lopez-Moreno, 2008).

Hydrological modelling of snow and glacier melt

Considerable advances have been made in snow and glacier melt modelling recently, but geographically this is still very much limited to the Alps, Rockies, eastern US mountains, Scandes, Himalayas and to a lesser extent to the Andes (Figure 1 belongs to Viviroli *et al.*, 2007). Topically, these studies have concentrated more on precise determination of snow and glacier distribution and discharge rather than on evapotranspiration, sublimation and condensation (de Jong, 2005; Molotch *et al.*, 2007; Christensen *et al.*, 2008). Investigations of mountain hydroclimatology are less common than mountain climatology. Most studies focus on accurate determination of distribution of snow and snow water equivalent (SWE) (e.g. Erxleben *et al.*, 2002). Potential radiation and index of wind sheltering are found to have the greatest effect on predicted snow depths (Erickson and Williams, 2005). Assessment of current and future runoff from highly glacierized basins shows that runoff first increases, then decreases below the current level as a result of glacier shrinkage (Horton *et al.*, 2006; Huss *et al.*, 2008). Runoff increases in spring and early summer, but decreases significantly during the summer. Surface and subsurface flow relations at high elevations in the Colorado Rocky Mountains during snowmelt are complex, indicating that subsurface flow may contribute more than two-thirds to streamflow (Liu *et al.*, 2004).

All studies remain limited by the lack in density of high elevation meteorological measuring stations. In the Himalayas, recent studies by Konz *et al.* (2006) indicate that glacier melt can be modelled adequately, but that more information is required on the rapidly evolving glacier tongue volume, avalanche activity, debris-covered glaciers, sublimation and wind drift. In the tropical Paute Basin in the Andes, where the highest peak at 4680 m is neither snow- nor glacier-covered, discharge predictions remain difficult since discharge variability is high, depending only on rainfall data from few meteorological stations (Celleri *et al.*, 2007). Recently, focus has been shifted to the hydrological response of smaller catchments in the Pyrenees (Anderton *et al.*, 2004; Latron *et al.*, 2008). Hydrological studies on major

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water towers such as the High Atlas remain sparse (Schulz and de Jong, 2005; Chaponniere *et al*., 2008) and have to overcome problems of data scarcity. They are mostly based on multidisciplinary approaches including field measurements, based on automatic weather stations and snow pillows, modelling and remote sensing.

Nevertheless, smaller important mountain chains that significantly contribute to food security in their forelands through snowmelt discharge, such as those around the Mediterranean basin, have been much neglected. These are often shared watersheds with trans-boundary surface and subsurface reservoirs that plan to intensify hydropower and irrigation. In Lebanon, the El-Kabir River that drains from snow-covered regions from more than 1900-m elevation, has lost over 40% of its discharge in the last 50 years as a result of a combination of climate change and water extraction (Shaban *et al*., 2005). Other Mediterranean studies include those of the Upper Jordan basin with Mount Hermon by Rimmer and Salinger (2006) that demonstrate the sensitivity of snowmelt processes in karst basins.

In terms of melt modelling, Hock (2005) argues that more complex energy balance models perform better than simpler temperature-based approaches, and are becoming more popular (Hock, 2003), especially where modelling needs to be done at high spatial and temporal resolution (e.g. diurnal timescales). However, the necessary spatially distributed input datasets are more difficult to obtain routinely (Hock, 2003) though new remotely sensed data sources and digital elevation models (DEMs) for mountain areas (e.g. Marcus and Fonstad, 2008) should help significantly to improve modelling efforts here.

AIM OF THE SPECIAL ISSUE

With increasing concerns over changes to climate, glacier extent and hydrological extremes, especially in important mountain environments, this Special Issue is appropriately timed. The aim of this initiative is to collect together, in one highly accessible international journal, a series of recent studies of the controls and impacts of hydrological and hydrometeorological change and snow seasonality in a range of mountain environments (Figure 1 belongs to Viviroli *et al*., 2007). It is well documented that 'glaciers are in retreat over most (but not all) of the world' (Barnett *et al*., 2005, p. 306) and mountain snowpacks declined over the latter part of the 20th century for most of the few areas where records are available (e.g. Aizen *et al*., 1997; Laternser and Schneebeli, 2003; Mote, 2003). It is important, therefore, that we improve our knowledge of rates and process of ablation/accumulation imbalances, refine our ability to model, monitor and predict glacier and snowfield response to climate change, identify system thresholds and impacts, and make inputs to management strategies.

Contributions deal with monitoring, modelling or remote sensing of the water and energy balance in different mountain systems, at a range of spatio-temporal scales. Such studies also help to support investigations of the potential impacts of a warming climate on water availability in snow-dominated mountain catchments and downstream regions.

THE SPECIAL ISSUE PAPERS

This issue is divided into three main themes: first, global climate change, global circulation and mountain snowmelt hydrology over the large scale; second, snow processes in mountains; and third, snowmelt and glacier runoff processes and modelling at the catchment scale.

The first theme is covered by three papers. The Special Issue begins with an invited paper by Adam *et al* assessing the implications of global climate change for snowmelt hydrology in the 21st century. Using a physically based hydrological model, they show that most of the global land area northward of the 40° latitude is very likely to experience systematic shifts in runoff timing because of warming-related losses of snowpack. However, they emphasize that annual runoff changes remain clearly related to precipitation changes. Overall, the changes in snowpack and warm season runoff are largest in the warmer areas of the globe affected by snow, such as the western USA. In the Eurasian high latitudes, there is an expected increase in warm season runoff despite losses of snowpack because of compensation by increased precipitation.

Kennedy *et al*. analyse the association between climate teleconnection indices and snowmelt-driven seasonal streamflow into the Upper Klamath Lake, an arid mountainous basin in the Cascade Mountains, Oregon. This lake is particularly important with relation to water management and the Klamath Irrigation Project and other competing water uses. The authors investigate large-scale climate features affecting inter-annual hydrologic variability of stream flow. Of the six large-scale climate indexes that were evaluated for their ability to explain inter-annual variation of the major hydrologic inputs into the Upper Klamath Lake, the Trans-Nino Index is most efficient. This index considerably reduces the streamflow forecast uncertainty. A forward shift in the timing of peak streamflow and decreased snow storage may decrease water availability later in the season. Seasonal forecasts should therefore be based on the month of March, 1 month earlier than that traditionally used.

Kingston *et al*. investigate the relation between large-scale climate drivers and river flow across montane and lowland environments in northern Europe including Scotland, Denmark, Norway, Sweden, Finland and Iceland. They use cluster analysis at the regional scale to identify different river flow regions. High and low flow is associated with large-scale patterns of temperature and precipitation variation. They suggest that the North Atlantic Oscillation (NAO) is a strong driver of river flow for the winter half-year. An inverse climate–flow relation is found between northern and southern Scandinavian River flow regions because of differences in snowmelt and orography. In the mountain environments over the summer half-year, other variables such as snow and glacier melt strongly influence the flow regime.

The second theme—monitoring, modelling and forecasting of snow processes in mountain environments—includes five papers, each with a different geographical focus. Long-term records of snow in mountainous regions are rare. Schöner *et al.* investigate trends and variability in snow depth measurements extending back to 1928 for the Sonnblick region in the Austrian Alps. Winter snow depths have declined from high values in the 1940s and 1950s. A significant positive relationship with the North Atlantic Oscillation is found for winter temperatures, but not for precipitation or snow depth. Spatial extremes of snow depth are strongly influenced by wind redistribution.

Modelling of wind transport of snow for a high alpine area in the Berchtesgaden National Park, Germany, is discussed by Bernhardt *et al*. The calculation of wind fields for alpine terrain is challenging; an archive of wind fields for typical synoptic situations was generated with an atmospheric mesoscale model which generated data to drive a snow transport model at reasonable computational expense. Although this type of physically based modelling can give improved understanding of snow processes in complex mountain landscapes, conceptual or empirical models are often used for forecasting runoff from snow and ice melt.

Şorman *et al.* apply a conceptual hydrological model to a small mountainous Turkish basin in the headwaters of the Euphrates river. Limited ground-based input data are supplemented with snow cover data from remote sensing. The model is first calibrated against measured discharge and then used to successfully forecast runoff using meteorological data from a mesoscale model.

Sauter *et al.* use a neural network model to forecast runoff for a partly glaciated catchment in the Patagonian Andes. The results are compared with results from multiple linear regression and analysed to quantify dependencies on meteorological input data. The artificial neural network method is a very efficient tool for simulating runoff in glacerized, alpine catchments from meteorological data. Despite the large glaciarized area within the catchment, nearly 50% of the discharge is controlled by precipitation.

Schmidt *et al.* analyse seasonal snow cover depletion in the Swiss Loetschental at the micro- to mesoscale. Detailed terrestrial images and micro-scale point measurements are used to determine snow cover duration at different topographical locations. They show that topographical features can only partially explain snow cover distribution and duration. Other influences such as avalanches and turbulent and advective heat fluxes originating from snow-free areas can be important determinants as well.

The third theme, glacier and snowmelt runoff modelling, is covered by three papers. Kling and Nachtnebel compare the results of two conceptual water balance models using different spatio-temporal discretizations in the mountainous catchment of the River Gail, Austrian Alps. One model uses semi-distributed and daily data, whereas the other uses spatially distributed discretization and monthly data. Both approaches yield equally good results for runoff simulations. There is a strong temporal correlation for the two models. However, the models correlate less well for the spatial distribution of the long-term mean annual water balance components, in particular, for evapotranspiration. This is caused mainly by differences in parameter estimation and calibration.

Koboltschnig *et al.* analyse glacier melt of the small Goldbergkees basin in the Austrian Alps contributing to runoff under the extreme climate conditions caused by the heat wave of the summer 2003. During this summer, the lowest solid fraction of precipitation (only 35%) in nearly 80 years was registered. Increased supraglacial snow melt during the extremely hot summer was also influenced by decreased albedo resulting from the deposition of Saharan dust. The timing of snow cover retreat at the glacier surface directly influences the beginning of icemelt. Calculations of the long-term air temperature anomaly showed that the year 2003 was outstanding. Although the winter balance did not show any anomalies, the specific summer net balance of the glacier was negative and has remained so since then. With a maximum glacier melt rate of 2·7 mm h^{-1}, glacier melt contributed to over 80% of the total runoff. In hot, dry summers, an accurate simulation of icemelt is therefore necessary.

Molotsch reconstructs SWE in the Rio Grande headwaters, a basin $\sim$3500 km^2 in size, using remotely sensed snow cover data and a spatially distributed snowmelt model. The fractional snow cover area has not been estimated at this scale before using Landsat Enhanced Thematic Mapper images. Basin-wide SWE varies significantly from year to year; for example, it was 2·6 times higher in 2001 than in 2002, indicating major climatological difference between the two years. Reconstructed values were correlated with the observed values. Spatial variability in SWE is well explained by the model. The reconstructed SWE estimates have potential for real-time modelling. Basin-wide snowpack water storage was highly sensitive to snow cover area during the year 2002 with relatively shallow snow packs. The advantage of this technique is that SWE estimates rely on remote sensing snow cover depletion data and not on ground-based SWE observations.

Future work will be directed at improving our understanding of the physics (Barnett *et al*., 2005), and reducing uncertainties in predictive models. This Special Issue of 12 papers summarizes several key advances in the field to help identify significant knowledge gaps and prepare the ground for such further research. Following this short introductory paper on the importance of the field and selected developments, 11 papers that deal with hydroclimatological and snowmelt issues follow at a variety of space and time scales across a wide range of mountain systems.

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