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Missing (in-situ) snow cover data hampers climate change and runoff studies in the Greater Himalayas

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HIGHLIGHTS

- Remotely sensed snow-cover data need to be validated by in-situ measurements.
- More in-situ snow measurement programs are needed along representative valley profiles.
- Free access to snow data is a necessity in the context of changing climatic conditions.
- Extreme parameterization shall be used with precaution in climate change projections.

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ABSTRACT

The Himalayas are presently holding the largest ice masses outside the polar regions and thus (temporarily) store important freshwater resources. In contrast to the contemplation of glaciers, the role of runoff from snow cover has received comparably little attention in the past, although (i) its contribution is thought to be at least equally or even more important than that of ice melt in many Himalayan catchments and (ii) climate change is expected to have widespread and significant consequences on snowmelt runoff. Here, we show that change assessment of snowmelt runoff and its timing is not as straightforward as often postulated, mainly as larger partial pressure of H_2O, CO_2, CH_4, and other greenhouse gases might increase net long-wave input for snowmelt quite significantly in a future atmosphere. In addition, changes in the short-wave energy balance – such as the pollution of the snow cover through black carbon – or the sensible or latent heat contribution to snowmelt are likely to alter future snowmelt and runoff characteristics as well. For the assessment of snow cover extent and depletion, but also for its monitoring over the extremely large areas of the Himalayas, remote sensing has been used in the past and is likely to become even more important in the future. However, for the calibration and validation of remotely-sensed data, and even more so in light of possible changes in snow-cover energy balance, we strongly call for more in-situ measurements across the Himalayas, in particular for daily data on new snow and snow cover water equivalent, or the respective energy balance components. Moreover, data should be made accessible to the scientific community, so that the latter can more accurately estimate climate change impacts on Himalayan snow cover and possible consequences thereof on runoff.

1. Introduction

The Greater Himalayas are the source of eleven major river systems of Asia, namely the Amu Darya, Syr Daria, Indus, Ganges, Tsangpo/Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow, and Tarim (Fig. 1), and cover a surface of about 7×10^6 km^2. An estimated 1.3 billion people live in these river basins and depend on its waters (Xu et al., 2009). As a result of ongoing and projected climatic changes in the Greater Himalayas (Kumar et al., 2013), runoff and other water resources might be altered quite significantly, as might be biodiversity and local livelihoods, at least in the montane and alpine zones of the Greater Himalayas (Xu et al., 2009; Mathison et al., 2013). The expected changes in availability and timing of runoff, as well as socio-economic developments in the region will require challenging definition and prioritization of choices for adaptation measures (Moors et al., 2011).

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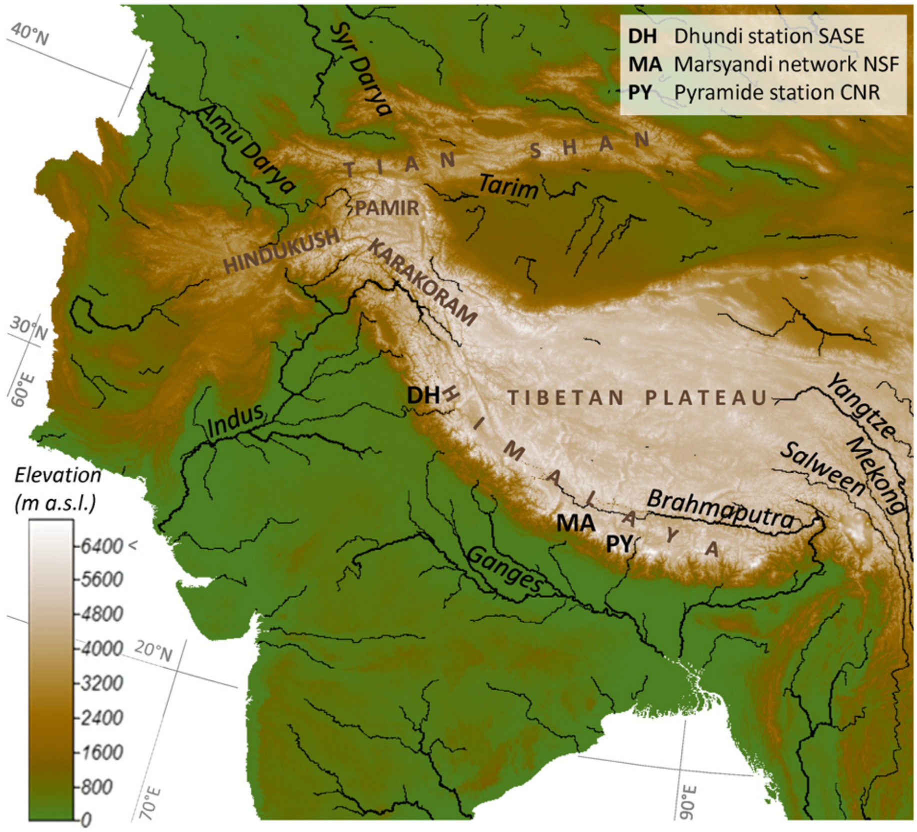

Fig. 1. Schematic view of the Greater Himalayas with its large river systems and localization of three important in-situ measurement sites for meteorological and snow-related data.

Over the past few years, public and scientific interest was focused mainly on the state and fate of the wider Hindukush–Karakoram–Himalayan glaciers and the possible consequences of glacier wasting on runoff (e.g., Akhtar et al., 2008; Kaser et al., 2010; Bolch et al., 2012; Kääb et al., 2012; Sorg et al., 2012). At the same time, however, snow cover and changes thereof were paid comparatively little attention. Although the mean annual contribution of snowmelt to downstream runoff of the larger streams – such as the Ganges at the Indo-Bangladeshi border – might have a mean annual contribution of only 1–5% (Collins et al., 2013), it might be a very crucial runoff component in the upper parts of these streams, in particular if runoff is considered on a seasonal basis (Siderius et al., 2013; Collins et al., 2013). Moreover, snow cover variability in Eurasia, or in the Greater Himalayas, may not only have local and regional, but also continental and global consequences (Barnett et al., 1989; Yasunari et al., 1991), which may become by far more important than the ongoing and expected future glacier wasting.

Because of the large size of the Himalayan region and typically difficult access to high mountain areas – in particular during winter – large scale snow cover dynamics has mainly been assessed by remote sensing. Rikiishi and Nakasato (2006), for instance, reported that snow cover in the Greater Himalayas has decreased by about one-third between 1966 and 2001 and that snow-cover duration has been reduced by 23 days during the same period and at elevations of 4000–6000 m. Although these rates might be slightly overestimated due to the binary definition of the 25 × 25 km pixel information and decadal climate oscillations (Zhang et al., 2004), the decrease is still substantial and expected to represent a serious threat to sustainable water supply for agricultural and other uses in the headwaters of Himalayan streams.

The objective of this contribution is to review past and current research on future runoff from glaciers and snow cover in the Greater Himalayas and to discuss further needs for a solid scientific basis, also in view of providing robust information to decision makers for the development of adaptation measures.

We discuss the adequacy of the assumed stationary character of parameter values and related uncertainties by addressing a set of research issues, namely the (i) importance of runoff modeling from snow cover in the Greater Himalayas; (ii) possibilities and limitations of remotely-sensed data in determining snow cover characteristics; (iii) possible shortcomings of commonly used parameterizations in snow cover–runoff modeling for current and future climates; (iv) crucial role of in-situ measurements for the validation and calibration of snow cover–runoff models; and the (v) monitoring of snow cover and related variables with in-situ data.

2. Contribution of snow cover to runoff from the Himalayas

Research has largely neglected the role of snow cover to runoff in the Greater Himalayas so far, despite the fact that its contribution can be much more important than that of ice melt in several of the Himalayan catchments. In one of the rare contributions focusing on runoff from snow melt, Prasch et al. (2012) state that only 2% of annual runoff stems from glacier melt in the high-altitude Lhasa river basin at Lhasa (Central Himalayas, catchment size: 26,000 km^2, elevation range 3600–7160 m asl., ca. 1.3% glacierization in 1970), whereas more than 50% originates from the melting of the seasonal snow cover (mean 1971–2000). Similarly, in the Annapurna region of Central Nepal, winter snowfall has been shown to contribute up to 35% of annual precipitation for elevations >3000 m asl. Here, snow water equivalent (SWE) can reach over 1000 mm (Lang and Barros, 2004), as evaluated by a temporary measuring network over a 5-year period in the Marsyandi valley. By contrast, satellite-derived TMPA (Huffman et al., 2007) and APHRODITE data (Yatagai et al., 2012) point to very limited winter precipitation in the Khumbu region (Eastern Nepal). At the same time, however, observational data from the Pyramid station (http://evk2.isac.cnr.it/) indicate that winter snow depth can be astonishingly high during individual years (also see Fig. 7).

Snow cover runoff is also substantial in the headwaters of the western catchments – in particular in Himachal Pradesh, Jammu and Kashmir, as well as further north and especially in the pre- and early monsoon season (April to June; Bookhagen and Burbank, 2010). In Dhundi (Himachal Pradesh; 32°21′20″, 77°07′41″E, 3050 m asl.), for instance, mean snowpack was 168 cm in March (measured for 1989/90–2003/04, Singh and Ganju, 2006) and total accumulated runoff from snow cover was 705 mm water equivalent (WE; measured between 13 January and 12 April 2005; Datt et al., 2008). Consequently, climatic changes in the form of increasing temperatures or decreasing winter precipitation might have severe impacts on the timing or amount of snowmelt with related and far-reaching societal consequences.

3. Interrelations of Himalayan snow cover with climate and climatic changes

Strong evidence exists for the fundamental role of snow cover–land feedbacks on warming in the Greater Himalayas, in particular at high altitudes. The existence of snow cover can reduce daily maximum (minimum) air temperatures by up to 4.5 °C (2.6 °C) on average for snow depths >10 cm over the grasslands of Central North America (Mote, 2008), thereby protecting the snow cover from synoptic scale influences. In this context, Gong et al. (2004) showed that snow cover is characterized by less absorbed shortwave radiation due to high snow albedo, more outgoing thermal radiation due to high emissivity of snow covered land, more outgoing latent heat fluxes due to snowmelt, evaporation and/or sublimation, and less incoming heat fluxes from the underlying soil due to low thermal conductivity of the snowpack. In case that snow cover extent is decreasing, air temperature, thermal conductivity and albedo will in turn increase, and outgoing thermal radiation and evaporation and/or sublimation will decrease and thereby act as a further source of snowmelt. As a consequence, based on remotely sensed albedo data at the hemispherical scale, Flanner et al. (2011) concluded that the cryospheric feedback would have contributed substantially to the recent (since ~1980) warming of the Northern hemisphere.

The altitudinal dependence of air temperature has been discussed much more controversially at the global scale. Based on a fairly small number of 56 stations, Ohmura (2012) concluded that worldwide variability and trends of air temperature are larger at higher altitudes, whereas Pepin and Lundquist (2008) or Rangwala and Miller (2012) stated that no general altitudinal trend existed for air temperature, at least not at the global scale. According to Bhutiyani et al. (2007) and You et al. (2010), a dependence of air temperature trends and altitude cannot be confirmed in the Greater Himalayas, whereas such a trend was reported by Qin et al. (2009) for the Tibetan Plateau and at altitudes of up to 4800 m asl.

Evidence also exists that increasing air temperature is not only driven by greenhouse gases in the Greater Himalayas, but that additional processes would contribute to warming as well. Ramanathan et al. (2007), for instance, suggested that atmospheric brown clouds might have contributed as much to recent warming as anthropogenic greenhouse gases, particularly at altitudes between 2000 and 4000 m asl., and that such clouds might also move up to altitudes of up to 6000 m asl. owing to the vertical transport of air masses. In the same line of thinking, Lau et al. (2010) stated that dust and black carbon from local emissions would have accelerated snow and ice melt in the Himalayas and the Tibetan Plateau through an effective transfer of sensible heat from a warmer atmosphere to land, which would in turn have enhanced the warming trend even further. Moreover, black carbon from fossil burning has been reported to lower snow albedo (Flanner et al., 2007; Yasunari et al., 2010) so as to contribute even further to the positive cryospheric feedback in the Greater Himalayas.

Flanner et al. (2009) did global climate simulations to explore the influence of carbonaceous particles and snow darkening on springtime snow cover area (SCA). They found that incorporation of present black carbon (BC) and organic matter (OC) emissions from a global inventory representing the year 1996 in the National Centre for Atmospheric Research (NCAR) Community Atmosphere Model (CAM) 3.1 had significant consequences on SCA: Only applying an albedo reduction of the snow cover with the mentioned dust emissions reduced Eurasian spring (MAM) SCA already by 1.52 10^6 km^2. Also considering dimming

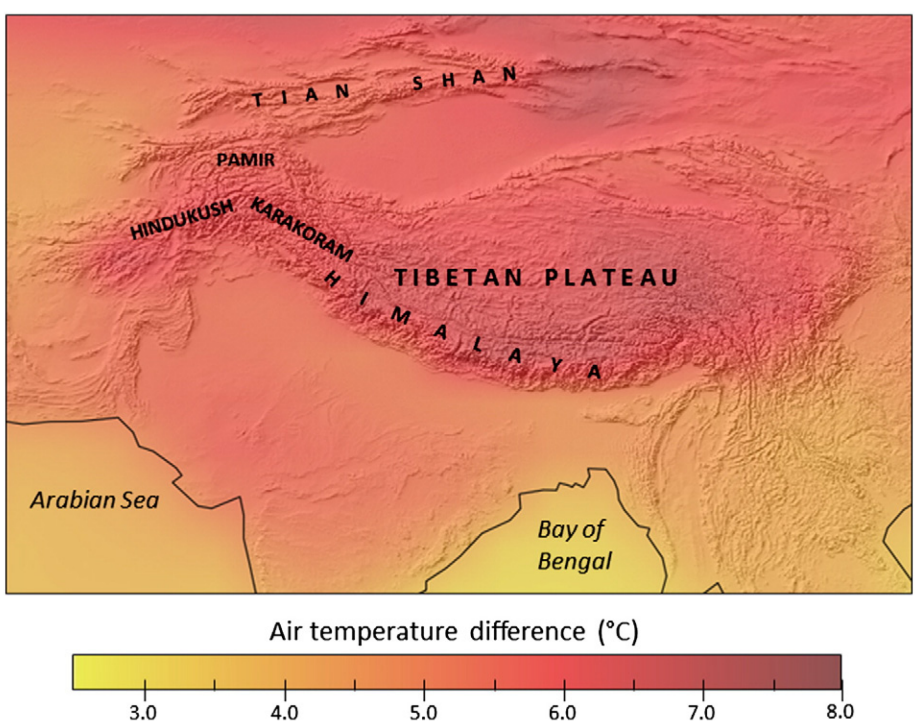

Fig. 2. Projected mean 2-m air temperature increase for March by the end of the 21st century as compared to 1981-2000 based on 39 models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) for the Representative Concentration Pathway (RCP) 8.5 for the Fifth Assessment Report (AR5) of IPCC. (Data: www.IPCC-data.org).

(scattering) and heating (absorption) effects from BC and OC in the atmosphere reduced Eurasian spring SCA even by $1.70 \cdot 10^6$ km^2. These results where significant at the 0.05 level. The corresponding Eurasian spring SCA in the control experiment was 20.5×10^6 km^2. Moreover, forcing by BC and OC was extraordinary high on the Tibetan Plateau compared to other Eurasian regions for the described experiment.

In the case of the Greater Himalayas, general projections of climate change are rather coherent (e.g., Kumar et al., 2013) in the sense that most models identify positive air temperature trends, which are by far more pronounced at higher altitudes. This trend has been confirmed recently by the latest model runs for the Fifth Assessment Report (AR5) of the IPCC (Fig. 2) and is still being attributed to the implementation of the snow-cover feedback in the models (Giorgi et al., 1997). At the same time, however, the effect of black carbon-induced albedo lowering on snow cover has only been implemented in the NASA Goddard Earth Observing System (version 5) land surface model so far (Yasunari et al., 2011).

In a similar way, low heat transport from snow-covered ground to the atmosphere can have large-scale consequences (Yasunari et al., 1991). The first director of the Indian Meteorological Department (IMD), Sir Henry F. Blanford, for instance, suggested a connection between Himalayan snowfall and the onset of the monsoon (Blanford, 1884). His pioneering observation was confirmed almost one century later by Hahn and Shukla (1976). More recently, however, Gong et al. (2004) realized that snow cover extent alone cannot explain these teleconnection patterns, and that snow depth is an equally important indicator. In addition to regional consequences of snow cover–land feedbacks, variations and longer-term trends of Himalayan snow cover may significantly influence hemispheric circulation and hence global climate as well (Vavrus, 2007). As a consequence, monitoring of snow cover in the Greater Himalayas should become even more important and a clear priority for future research.

4. Possibilities and limitations of remotely-sensed data to monitor snow cover in the Greater Himalayas

Remote sensing is an inevitable and useful tool for the monitoring of snow cover in the Himalayas, especially in view of the virtual impossibility of realizing a coherent synopsis based on potential in-situ measurements in the typically hardly accessible high-mountain areas. While snow coverage and distribution are the relevant sources of information for climatic reasons, WE of the snow cover represent the essential variable for runoff modeling. Maskey et al. (2011) state that snow melt, subsequent river flow regimes and water resources availability will be affected not only by snow covered area but also by SWE. However, direct estimation of WE in alpine environments has proven difficult if based on satellite passive microwave sensors, mainly because of relief energy, vegetation, wet snow and snow crystal growth (Foster et al., 2005; Tong et al., 2010). Current state-of-the-art products in the field — such as the ESA GlobSnow data records (Takala et al., 2011), are thus typically masking out alpine environments. As a consequence, it does not seem surprising that Kumar et al. (2006) could not find a good correlation between SWE derived with the NASA Aqua Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) and ground truth data from Dhundi and Patsio (Himachal Pradesh, India). The use of Landsat-enhanced thematic mapper plus images – and the compatible Operational Land Imager (OLI) data of Landsat 8 – might be helpful in this respect and facilitate the estimation of snow grain size indices and other properties of the snow cover, which in turn would render the correction of a passive microwave assessment of SWE more feasible (Butt, 2012). The author nevertheless concludes that additional in-situ measurements would be helpful to improve the accuracy of grain size estimation significantly.

The large difference in dielectric constant between water and ice has largely hampered estimation of SWE using microwave based methods in the past. At the same time, however, this difference could be used to detect melting snow with active microwaves from space – using for instance the Ku-band of SeaWinds on QuikSCAT (Bartsch, 2010) – for which regular measurements cover the period 1999–2009. Panday et al. (2012) have utilized this product to assess both the timing and the duration of snowmelt in the Greater Himalayas.

However, snowmelt is usually not analyzed at present, and most work only retrieved snow cover area and snow cover fraction. On a global basis, mainly Moderate Resolution Imaging Spectro-radiometer (MODIS) data have been used with a rather coarse resolution of ca. 500×500 m (Fig. 3). Nevertheless, in regions with scarce snow cover field data – as is the case in most parts of the Greater Himalayas – MODIS products can serve as a solid basis for the inspection of year-to-year differences in snowmelt. A MODIS-derived example with strongly differing snow cover distribution in the Nepalese Himalaya is presented in Fig. 4. In the case of India, Resourcesat-1 has been used as an alternative with its Advanced Wide Field Sensor (AWiFS) with spatial and temporal resolutions of ca. 50 m and 5 days, respectively (Negi et al., 2009; Kulkarni et al., 2010; Subramaniam et al., 2011; Arora et al., 2010), and has allowed illustration of important year-to-year variations in snow cover in the Central and Western Indian Himalayas (Kulkarni, 2010).

MODIS can also be used to derive snow albedo information by using its reflectance data. Painter et al. (2012) used data of one particular day to assess dust induced lowering of albedo in the Hindukush–Himalaya and recognized an astonishingly high dust forcing of up to 250 W m^{-2}. However, and as indicated by Warren (2013), a distinction of atmospheric dust from dust deposits on the snow surface is often difficult. Moreover, and as a consequence of the large tile size of MODIS products, variations in natural reflectance stemming from surface structures (e.g., vegetation) are still difficult to be incorporated in the algorithm.

One possibility to derive snow depth values by remote sensing could be the new ICEsat2 satellite, which is planned to be in orbit from 2016 on. But this product is still in the phase of a feasibility study (Jasinski and Stoll, 2012).

In summary, remote sensing studies of snow cover in the Greater Himalayas have focused mainly on snow cover extent and its depletion curves in the past, whereas satellite-based direct estimations of SWE have only rarely been realized. The general lack of SWE analyses mainly reflects the difficulties in assessing this parameter with remotely-sensed data, particularly in mountainous environments. As far as the assessment of a possible lowering of the albedo coming from black

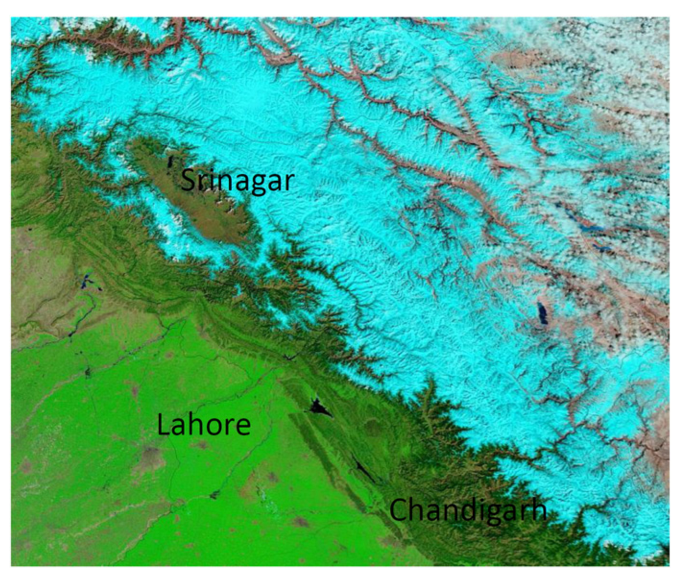

Fig. 3. Snow cover extent (given in blue) as seen from MODIS Aqua swath on 2 March 2012 over Himachal Pradesh and Kashmir.
Data: NASA.

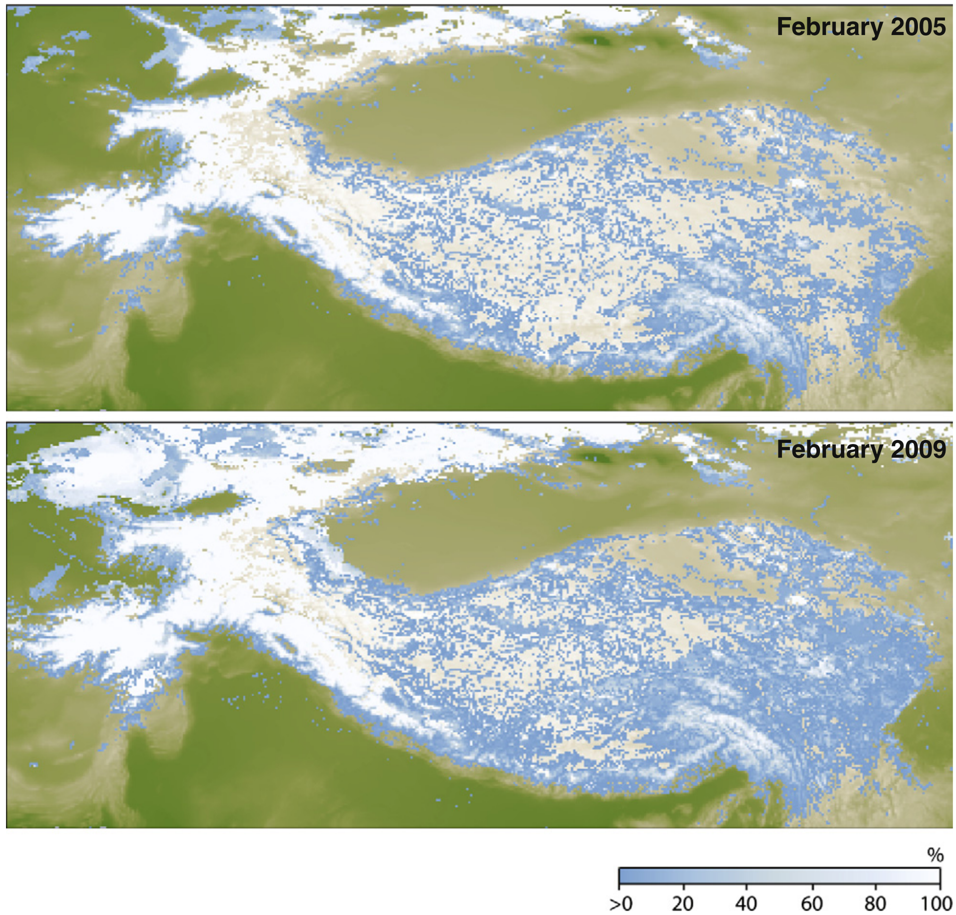

Fig. 4. Monthly mean snow cover fraction (%) as derived from daily Terra/MODIS scenes for February 2005 (upper part) and February 2009 (lower part). In February 2005 snow was also present in regions of the Nepalese Himalayas where snow tends to be less abundant.
Data: NASA.

carbon and other dust sources is concerned, we realize that remote sensing is currently only suited for the identification of heavily polluted snow (Warren, 2013).

5. Modeling snow cover runoff in the Greater Himalayas under present conditions

5.1. Snow cover accumulation

In mountainous basins with important snowmelt contributions, runoff modeling approaches clearly have to consider the important role and contribution of accumulated snow cover. Precipitation stored in the form of snow will not be available immediately for runoff and snow stored on glaciers will have important implications on runoff from the glacier, as albedo will be increased quite drastically from ca. 0.3 to up to 0.9 (Klok and Oerlemans, 2004).

The transition of rain to snow is closely related to air temperature and its threshold typically lies between 0 and 3 °C, depending mainly on the (i) type of the meteorological station recording (i.e. ventilated or non-ventilated), (ii) season and (iii) temporal resolution of air temperature values (i.e. hourly, daily, or term measurements). The type of the station as well as the temporal resolution of the measurements are important and critical parameters in defining snow–rain threshold values (Rohrer, 1989). Nevertheless, air temperature can be considered a good measure to discriminate snow from rain and to assess snow cover accumulation in mountainous environments.

The other key variable for snow cover accumulation is the precipitation sum, but only very few precipitation gauges are located in the Greater Himalayas, particularly at altitudes >3000 m asl. (Lang and Barros, 2004) where meteorological stations are generally rare, as shown by Salzmann et al. (2013) for the Andes. Here, satellite-based devices such as the Tropical Rainfall Measuring Mission (TRMM) can partly fill gaps and provide more frequent estimates of snowfall precipitation (Scheel et al., 2011). TRMM offers several products to analyze snowfall precipitation, such as (i) the first spaceborne instrument designed to provide three-dimensional maps of storm structures, the active radar from space, the so-called Precipitation Radar (PR, Fig. 5), (ii) passive microwave sensor designed to provide quantitative rainfall information over a wide swath under the TRMM satellite, the TRMM Microwave Imager (TMI), and (iii) the combination products (e.g. 3b42). In addition, the height of the bright band estimation might be used as a proxy for the distinction of above and below snowline precipitation, a potential that has not been further evaluated so far. Instead, the active PR has been utilized more frequently as it yielded the best results (Lang and Barros, 2004), despite its narrowest swath. The TRMM passive microwave sensor has the same horizontal resolution (about 5×5 km) and a slightly larger swath width. The TRMM-Multisatellite Precipitation Analysis (TMPA) also provides a coherent spatio-temporal product of precipitation back to 1998 and with a horizontal resolution of ca. 25×25 km (Huffman et al., 2007). Scheel et al. (2011) have shown that TMPA has some limitations when used on a daily or even sub-daily level, but that the correlation between satellite-derived and in-situ measurements becomes quite significant when monthly values

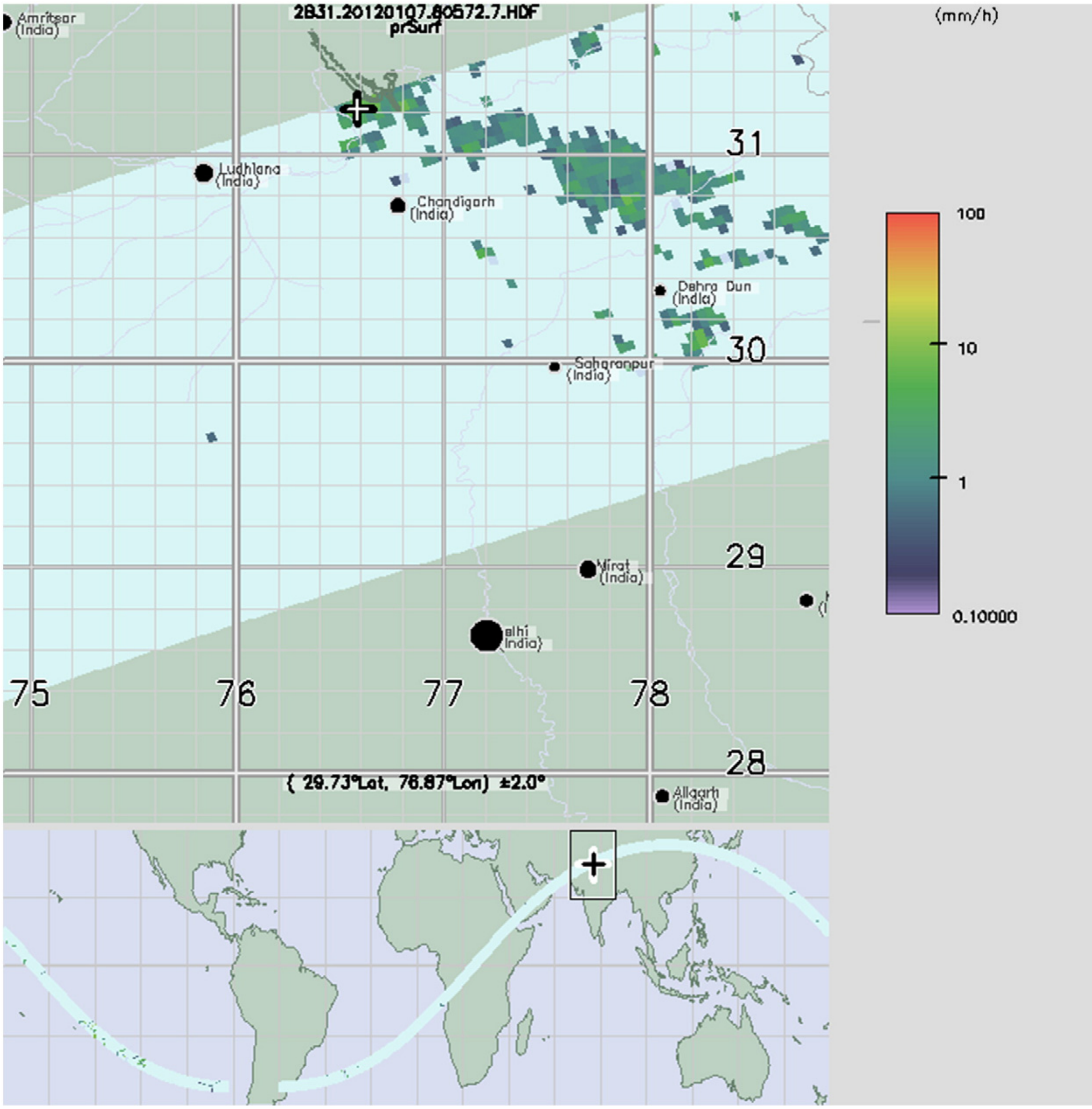

Fig. 5. Precipitation estimate from the only active Precipitation Radar in space (TRMM-PR) for 7 January 2012. TRMM-PR provides a highly resolved picture of precipitation distribution, but only for a rather narrow swath area. The snowfall of 7 January 2012 was the strongest in Himachal Pradesh for many years.
Source: NASA.

are incorporated. We conclude that the more accurate TRMM products are less coherent spatially and temporally in mountainous environments, whereas grid-oriented TMPA products have a relatively coarse spatial resolution and considerable inaccuracies at daily or sub-daily time scales.

Precipitation can also be estimated from climatic reanalysis products — such as the NCEP/NCAR reanalysis (Kalnay et al., 1996). In contrast to air temperature, however, precipitation measurements are not assimilated, meaning that precipitation estimates will be produced by the forecast model only, which is based on temperature and humidity data derived from assimilated observations (Dee et al., 2011). Therefore, precipitation values tend to differ substantially from observations, even at the scale of monthly means and over larger regions (Janowiak et al., 1998), and in particular in mountain regions (Dee et al., 2011). The skill can be improved substantially if precipitation time series are used to correct forecast model output, as demonstrated recently in the case of the 'MERRA LAND' reanalysis, where modeled SWE corresponded reasonably well with observations (Reichle et al., 2011).

When deriving snow-cover accumulation from gauge precipitation measurement, the type of instruments used needs to be taken into account as well. The under-catch of new snow can be up to 50% between heated tipping buckets or unheated Hellman type gauges because of heating losses or snow hat formation (Fig. 6). As a consequence, the apparent overestimation of ERA-interim reanalysis – as compared to APHRODITE data for winter precipitation (DJFMA) in the Karakoram and NW Himalayas – might be less important in reality than recently postulated (Palazzi et al., 2013), simply because APHRODITE is not based on SWE but merely on precipitation gauges.

5.2. Snow cover ablation, satellite information and degree day value

Snow cover ablation is controlled by the energy balance, which can be expressed as the sum of the following fluxes (Loth et al., 1993):

$$Q^* = Q_S^* + Q_L^* + Q_H + Q_{ES} + Q_B + Q_{HPR} \quad (1)$$

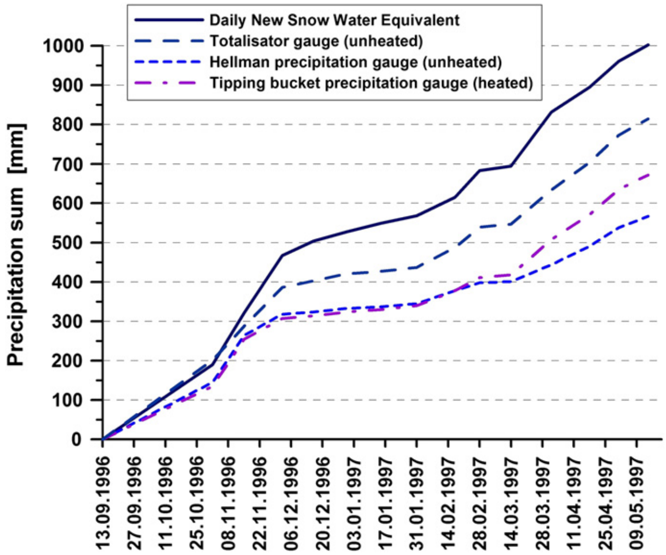

Fig. 6. Summed precipitation as derived from daily new snow water equivalent sum, totalisator precipitation sum, summed Hellman gauge precipitation (unheated) and tipping bucket gauge precipitation sum at Weissfluhjoch-Davos, Switzerland (2560 m asl).
Data: SLF, 1999.

where Q_S^* is the short wave radiation balance, which can be calculated from global radiation Q_S and albedo a; Q_L^* is the long wave radiation balance; Q_H and Q_{ES} represent the sensible and latent turbulent heat fluxes, respectively; Q_B is the ground heat flux; and where Q_{HPR} is the energy input by rain. As in-situ station measures of radiation and/or air temperature, humidity and wind gradients are very scarce in the Greater Himalayas, ablation is typically derived from temperature indices or degree-day models, for which a relationship between ablation and air temperature is assumed and usually expressed in the form of positive temperature sums. The basic formulation of these models relates the amount of ice or snow melt M (mm) to the sum of positive air temperatures of each day T^+. The factor of proportionality is the degree-day factor DDF expressed in mm day^{-1} °C^{-1} (Hock, 2003).

$$\sum M = \mathrm{DDF}\sum T^+ \tag{2}$$

As a further result of virtually non-existent in-situ snow measurement stations in the Greater Himalayas, snow cover ablation modeling is widespread and usually based on satellite information. Numerous studies on snow cover recession use MODIS products at weekly time steps to analyze the evolution of snow cover ablation since 2000 (http://modis-snow-ice.gsfc.nasa.gov/). The MODIS snow product suite starts with a 500 × 500 m resolution, and yields a 2330-km swath snow-cover map which is then gridded to a sinusoidal grid. The sequence proceeds to climate-modeling grid (CMG) products on a latitude/longitude grid (Hall et al., 2002). MODIS products have been demonstrated to be reasonably accurate provided that imagery is free of clouds (Hall and Riggs, 2007; Parajka and Blöschl, 2006). By way of example, Pu et al. (2007) have used MODIS data to derive seasonal variations in snow cover fraction over the Tibetan Plateau by comparing the MOD10A2 product with in-situ snow-depth measurements of 115 stations of the Chinese Meteorological Administration (CMA). The authors report an overall accuracy of ca. 90% and a decrease of the false alarm ratio from 7% to almost zero with the snow cover persistent days going from 1 to 8. For snow-cover depths >10 cm, the detection rate was even >95%. Immerzeel et al. (2009) used the MOD10C2-product in combination with a digital terrain model to assess the seasonal snowline in different basins of the Himalayas (Table 1), and stated that the undesired effects of potentially misclassified snow pixels can be avoided by defining the 5% percentile of the elevational distribution of snow covered pixels in the basin. Other sensors or products used in the field include AWiFS (Kulkarni, 2010), where WE data has to be estimated by derivate variables in this case and by using a degree day relation (Snowmelt Runoff Model; Martinec and Rango, 1987). In this case, degree day values are calibrated based on either existing time series or prefixed values, often defined as 4 or 5 mm day^{-1} °C^{-1}. For their assessment of changes in runoff, Immerzeel et al. (2010) have chosen a degree day factor of 4 mm day^{-1} °C^{-1} for current climate and an uncertainty of 1 mm day^{-1} °C^{-1} for future climatic conditions.

Table 1
Mean seasonal snowline (in m asl.) for different basins and for the March 2000 to February 2008 period. Data is derived from the Shuttle Radar Topographic Mission (SRTM) digital elevation model and the MODIS snow cover product MOD10C2.
(Source: Immerzeel, 2009).

	Indus	Brahmaputra	Ganges	Yangtze	Yellow
Winter	2336	2932	3330	3240	3220
Spring	3035	3749	3866	3673	3202
Summer	4109	4433	4573	4580	4598
Autumn	3712	4137	4189	4213	3205

Past work on snow cover runoff from Himalayan basins has been based primarily on remotely sensed snow cover data, related snow cover recession and assumed degree day factors to estimate WE of snow melt. When applied to the entire melting season and over larger basins, these predefined values yield fairly robust results (Lang and Braun, 1990). In the case of smaller headwater catchments of the Greater Himalayas, however, the use of maximum daily temperature values might be, however, more appropriate, as daily mean temperatures are often close to zero, or even below, despite the fact that melting still occurs in reality during the day. Also, for shorter time intervals, degree day values may differ considerably from the prefixed values of 4–5 mm day^{-1} °C^{-1}, especially during particularly dry or wet periods (Hock, 2003). Along this line of thinking, Fig. 7 illustrates quite impressively that snow cover ablation can occur even with constantly negative air temperatures, especially at the end of the ablation season. In this case, ablation of a ca. 10-cm thick snow cover was driven clearly by a positive radiation balance. Ablation will be mostly in the form of sublimation whereas a smaller fraction might refreeze before reaching the river. Had analysis been based on the degree day factor and mean daily air temperatures, the degree day sum over the period covering mid-January to late March 2005 would have been zero at this location where snow cover was in fact more than 50 cm in reality.

Taking into account some of the pitfalls presented above, Shrestha et al. (2012) recently presented a snow-cover model for the Dudhkosi region (Nepal) for which they simulated snow cover accumulation with corrected precipitation, temperature and snow-cover ablation data and a simplified energy balance approach. Based on a verification of their results with MODIS data, the authors demonstrated that snow cover accumulation and ablation can be simulated accurately, but that the accumulation modeling would have been virtually impossible without a correction with measured precipitation values and in-situ snow cover data (Shrestha et al., 2012). As a matter of fact, results of this study are very clearly in concert with the purpose of this paper and our plea for more in-situ measurements of snow cover in the Greater Himalayas.

6. Modeling snow cover runoff in the Greater Himalayas in a climate change context

As a result of the general scarcity of in-situ measurements, precise determination of snow cover parameters is hardly possible for present climatic conditions in the Greater Himalayas. Under a changing climate, it will be even more difficult to predict these values due to their altered individual contribution or function compared to past conditions. The projected increase in greenhouse gases, for instance, is likely to increase net long wave input for snowmelt significantly. This

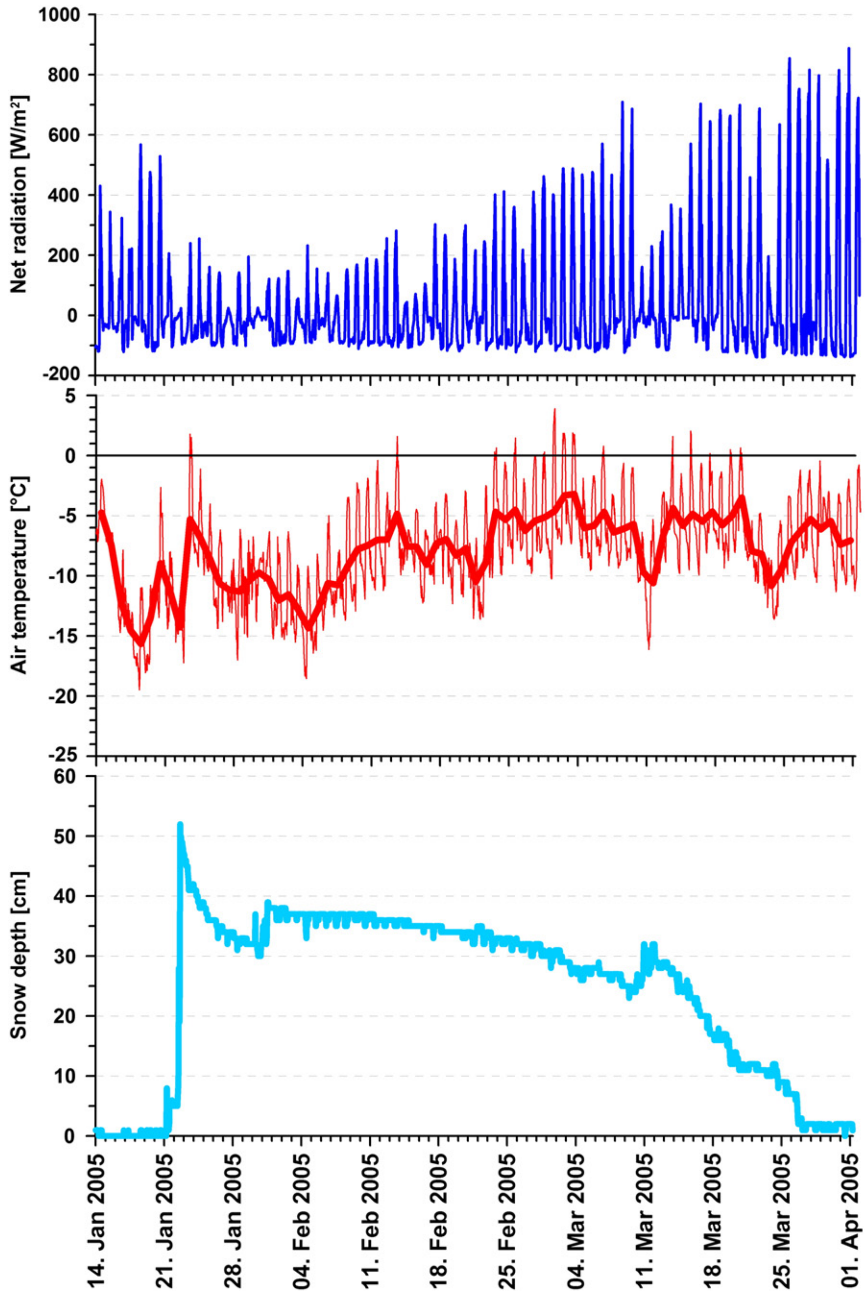

Fig. 7. Hourly observations of specific humidity, net radiation, air temperature and snow depth at Pyramid station in Khumbu Valley (Nepal) at 5050 m asl. Note that daily mean air temperature (bold) was never above 0 °C between 14 January and 31 March 2005, but that snow depth decreased mainly due to positive net radiation sums.
Data: EVK2R-SHARE.

long wave incoming radiation has been demonstrated to have increased at an average global rate of 2.2 W m^{-2} per decade between 1973 and 2008 (Wang and Liang, 2009). With the projected further increase of greenhouse gas concentrations, long wave incoming radiation is expected to grow even further. At melting conditions of snow, long wave emission will remain unchanged, but the down-welling long wave radiation can be expected to increase, as water vapor partial pressure might also increase, in parallel will latent heat and the long wave balance, as shown by Sicart (2005) for the Andes. In addition, the ongoing emission of light scattering aerosols in SE Asia has been reported to cause solar dimming, which may in fact have masked partly the global warming by anthropogenic greenhouse gases (Wild, 2012) as well as some of the warming effects induced by light absorbing aerosols ('brown cloud'; Ramanathan et al., 2007). As a further result of aerosol emission and black carbon deposition, snow albedo might decrease even further in the future (Flanner et al., 2007; Yasunari et al., 2010; Lau et al., 2010; Flanner et al., 2012).

Fig. 8 illustrates the total down-welling long wave radiation for the Himalayas and its projected increase of ca. 30 W m^{-2} between 2010 and the end of the 21st century assuming the Representative Concentration Pathway (RCP) 8.5. In the case of a melting snow cover, the upwelling long wave radiation will correspond to a black body radiation at 0 °C which is 316 W m^{-2}, a value that will not evidently change in the future. Assuming that the mean annual long wave incoming radiation was ca. 314 W m^{-2} in 2010 for the same geographical domain and according to ERA-interim reanalysis, the long wave net balance of a melting snow cover is expected to increase considerably. We therefore argue that degree day factors are likely to change significantly over the next few decades, even more so as the radiative effects of black carbon – in terms of short wave albedo lowering of the snow cover –

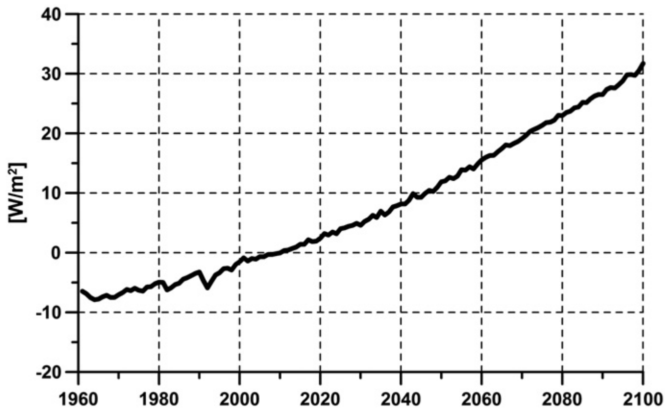

Fig. 8. Changes in surface incoming longwave radiation as projected by 37 models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) for RCP 8.5 with respect to the reference year 2010. The annual mean values are averaged for all models of the of IPCC AR5 over the domain 65°E to 105°E and 25°N to 45°N.

will have an additional effect on the energy balance of the melting snow cover. The driving forces are unlikely to have identical effects on snow cover runoff and temperature increase, and thus more data from in-situ monitoring of snow cover and runoff in headwater catchments of the Greater Himalayas will be required.

7. In-situ monitoring of Himalayan snow cover

The Global Terrestrial Observing System (GTOS, 2009), as part of the Global Climate Observing System (GCOS, 2010), declares snow depth and SWE as Essential Climate Variables (ECV) in addition to snow cover extent. Whereas snow cover extent can be monitored remotely (see Table 1), snow depth and SWE are difficult to measure with satellite-based methods.

Some research projects, such as the Marsyandi valley project in the Annapurna region (Nepal; Barros et al., 2000), have maintained station networks for short periods, and thereby gathered valuable data on precipitation, snow cover or SWE. Nevertheless, a lack of long-term series of in-situ measurements of snow cover related variables still persists, with the exception of the data compiled by SASE at Dhundi (Himachal Pradesh, India). Using data from SASE, Tahir et al. (2011) concluded that the coupling of satellite-based snow cover data with ground data (e.g. snow pits) or information based on snow cover runoff models might be an appropriate approach to overcome the poor gauging of precipitation data in the higher-elevation regions of the Indus basin.

In-situ monitoring of SWE is also important because rain gauge data are usually underestimating snow precipitation (see Fig. 6), mainly if precipitation is measured with unheated tipping buckets or traditional Hellman gauges. These instruments often largely underestimate snow precipitation. SWE measurements would also be of great use as a benchmark for satellite estimated rainfall products such as TMPA.

In principle, snow albedo reduction by black carbon can be detected by remote sensing techniques (Painter et al., 2012), but the reduction of black carbon in snow is difficult to detect (Warren, 2013) as (i) surface albedo inferred from satellite measurements has typical errors of a few percent and (ii) the inference of albedo values based on nadir radiance measurement can be biased low because of undetected thin clouds or blowing snow altering the angular reflectance pattern. We thus strongly recommend to measure albedo reduction by soot or dust with in-situ methods.

8. Runoff monitoring in the Himalayas

Although some runoff measurement sites exist in the Greater Himalayas (e.g., Braun et al., 1993, Arora et al., 2010, Prasch et al., 2012), upstream runoff gauges remain either scarce or hardly accessible to the international research community. As a consequence, coverage of Himalayan rivers in the Global Runoff Data Centre of the German Hydrological Survey (www.grdc.bafg.de) remains fairly limited, and even more so for recent data series. Since in-situ data of snow cover and precipitation are also rare, an adequate scientific assessment of Greater Himalayan water resources proves to be very difficult. In consequence, upstream runoff data should be made freely available to the international research community to allow data-based scientific discussions and provide robust information to decision makers regarding possible impacts of climatic changes and related adaptation measures in a context of changing water resources. National and regional authorities, with the support of international agencies, furthermore need to plan and to implement an enhanced and much denser network of Greater Himalayan runoff stations. Data from these stream gauges located in Greater Himalayan headwater catchments would enable the scientific community to have a better basis to estimate impacts of future climatic changes. For the time being and in absence of freely accessible long-term runoff data, calibration and validation of runoff models will remain extremely difficult. Moreover, free data accessibility will be the only way to guarantee true scientific discussion of model results and ultimately lead to higher quality assessments of climate change impacts.

In summary, future estimations of the contributions of snow and ice melt to runoff in Greater Himalayan rivers will primarily depend on the construction and maintenance of long lasting runoff stations located in headwater catchments where glacierization is above 50%, similar to the one at the snout of Gangotri glacier, which was operational between 2000 and 2003. In addition, more runoff measurement stations should be installed in catchments where snowmelt is important. At these future stations, reading water levels could be done in a conventional manner twice or three times a day and level-discharge curves calibrated by regular salt-dilution procedures if the installation of automated gauging stations is considered too expensive. Stations of this type have been operational in the Langthang Khola headwater catchment (Nepal) for more than 20 years now (Braun et al., 1993; Konz et al., 2007), and still provide very valuable results.

9. Conclusions

This contribution has aimed at providing a summary of existing snow and snow cover data from the Greater Himalayas and at discussing consequences that a lack of exhaustive, longer-term and/or in-situ measurements have (and will have) on future runoff studies. In this sense, this paper also is a clear advocacy for the development and maintenance of a permanent, high-altitude network for the measurement of snow-related variables in the Greater Himalayas, even more so as the contribution of snowmelt (and its possible changes) has been demonstrated to have more far-reaching consequences than the wasting of Greater Himalayan glaciers.

At the international level, snow cover has been declared an Essential Climate Variables (ECV) for the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO), and remote sensing monitoring of snow cover clearly needs to be complemented with in-situ data series (GCOS, 2010). In addition, many global climate models (GCM) and regional climate models (RCM) project a significantly larger temperature increase for high-altitude regions as compared to lower altitudes. In the case of the 'Third Pole', the Tibetan Plateau, CMIP5 models project an increase of 2-m winter (DJF) air temperatures of up to 11 K under RCP8.5 and 6 K under RCP 2.6 around the year 2100 and as compared to 1961–2005 (Su et al., 2013). If these extreme scenarios come true, the impacts for montane and alpine livelihoods would be very severe. In this line of thinking, and in view of the scarce weather stations above 3000 m asl., the monitoring of cryospheric feedbacks on temperature or snow cover at medium and high altitudes of the Greater Himalayas clearly seems to be of fundamental importance.

Table 2
Recommended in-situ measurement network of snow parameters in the Greater Himalayas.

Variable	Minimum frequency	Ideal frequency	Recommended instrument	Ideal spatial domain	Altitudinal range
SWE of new snow	1/day	1/day	Snow probe	1000 km^2	3000–5000 m
SWE of snow cover	1/week	1/h	Snow probe/snow pillows	10,000 km^2	3000–5000 m
Precipitation	1/week	1/10 min	Totalizers/weighing instruments	500 km^2	2500–5500 m
Air temperature	3/day	1/10 min	Shielded/actively ventilated thermometers	1000 km^2	2500–6000 m asl.
Humidity	3/day	1/10 min	Psychrometer/dew point mirror	1000 km^2	2500–6000 m asl.
Wind speed	1/h	1/10 min	Vane/sonic anemometer	1000 km^2	2500–6000 m asl.
Global radiation	Hourly mean	10 min mean	Pyranometer 1st class	5000 km^2	2500–5000 m asl.
Albedo	Hourly mean	10 min mean	Albedometer 1st class	10,000 km^2	2500–5000 m asl.
Downwelling long wave radiation	Hourly mean	10 min mean	Pyrgeometer 2nd standard	100,000 km^2	2500–5000 m asl.
Upwelling long wave radiation	Hourly mean	10 min mean	Pyrgeometer 1st class	100,000 km^2	2500–5000 m asl.
Runoff measurements	3/day	1/h	Staff gauges & salt dilution/radar and ultrasonic measurements	Head watersheds of principal tributary rivers of main Himalayan streams	3000–5000 m asl.

In a similar way, most studies focusing on future runoff from heavily glacierized basins are highly parameterized for current and future conditions and often use the same input values. Based on the evidence presented in this paper, stationarity should not be assumed, especially because a future degree day factor could differ significantly from what we typically assume for today's climate. To explore these changes and to reduce uncertainties, a more extensive in-situ network of snow cover, new snow and related variables is more urgently needed than ever.

While the use of remotely-sensed runoff variables is fully justified for mountain chains that are – in horizontal and vertical terms – as extended as the Greater Himalayas, calibration and verification of results are still critically needed. This process can be achieved with on-site based remote sensing such as mobile Doppler radar assessments of precipitation intensity and bright band altitude, but would be more appropriately done by hourly and/or daily in-situ measured time series of snow cover and related variables. Abrupt changes in snow cover albedo, as derived from MODIS images, can be used as well to document recent snowlines of precipitation.

A station concept should be developed including measurement of WE of snow cover and other snow related variables. Such a network used to be operational in the Marsyandi project (Annapurna region, Nepal), but sustainability, maintenance and support have often proven to be difficult. Also, quality control and homogeneity of the data series would need to be guaranteed for the network and for the entire period of operation. Measurements should be at the daily time scale and should at least include WE of new snow and snow cover, and respective energy balance components. Moreover, data series must be made available to the international research community focusing on the consequences of climate change on Greater Himalayan snow cover and related runoff. In this context, satellite-based information on snow cover extent can serve as input not only to runoff modeling from snow cover, but also for the verification of precipitation–runoff modeling based on in-situ datasets (APHRODITE as an example). Table 2 shows a possible station concept to measure snow-related variables in the Greater Himalayas.

This contribution has illustrated clearly that the paucity of in-situ measurements of snow cover and related variables may severely hamper runoff assessments, even more so in a climate change context. The WE of the snow cover, as one of the key elements of the water balance of the alpine and montane zones of the Greater Himalayas, can only be implemented in a realistic manner into runoff modeling if more in-situ measurements are realized, preferably in the form of station networks along valley profiles encompassing an altitudinal range from 2500 to 5500 m asl. In addition, more runoff gauges clearly need to be installed in Greater Himalayan headwater catchments and the data series of existing stations should be made freely accessible to interested scientists to facilitate our understanding of snow accumulation, its melt and related runoff in the Greater Himalayas and in a climate change context.

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