Climatic Change (2011) 108:391–400
DOI 10.1007/s10584-011-0181-y

LETTER

An analysis of snow cover changes in the Himalayan region using MODIS snow products and in-situ temperature data

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Received: 23 February 2011 / Accepted: 26 July 2011 / Published online: 9 August 2011

Abstract Amidst growing concerns over the melting of the Himalayas' snow and glaciers, we strive to answer some of the questions related to snow cover changes in the Himalayan region covering Nepal and its vicinity using Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover products from 2000 to 2008 as well as in-situ temperature data from two high altitude stations and net radiation and wind speed data from one station. The analysis consists of trend analysis based on the Spearman's rank correlation on monthly, seasonal and annual snow cover changes over five different elevation zones above 3,000 m. There are decreasing trends in January and in winter for three of the five elevation zones (all below 6,000 m), increasing trends in March for two elevation zones above 5,000 m and increasing trends in autumn for four of the five elevation zones (all above 4,000 m). Some of these observed trends, if continue, may result in changes in the spring and autumn season river flows in the region. Dominantly negative correlations are observed between the monthly snow cover and the in-situ temperature, net radiation and wind speed from the Pyramid station at 5,035 m (near Mount Everest). Similar correlations are also observed between the snow cover and the in-situ temperature from the Langtang station at 3,920 m elevation. These correlations explain some of the observed trends and substantiate the reliability of the MODIS snow cover products.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-011-0181-y) contains supplementary material, which is available to authorized users.

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1 Introduction

The Himalaya and surrounding high-altitude regions are the source of major river systems in Asia including Indus, Ganges, Brahmaputra, Yangtze, Yellow and Mekong and provide freshwater resources to over 1.4 billion people in the region (Immerzeel et al. 2010). As vast areas over the Himalaya are covered by snow and glaciers, these regions are very susceptible to climate change, in particular to global warming. The ice mass in the region is third largest on Earth, after Arctic/Greenland and Antarctic regions (Barnett et al. 2005). Some studies pointed out that warming in the Himalayan (Bhutiyani et al. 2007; Shrestha et al. 1999) and Tibetan (Hu et al. 2011; Liu and Chen 2000; Qin et al. 2009) regions has been much greater than the global average (Trenberth et al. 2007) over the last century. Glaciers' shrinking in the Himalayas received a wide coverage in international news media, mostly portrayed as an alarming sign, notably since the beginning of this century (BBC 2009; Cyranoski 2005, 2008; Nayar 2009) including a IPCC report of the Working Group II (WG II) (Cruz et al. 2007, p 493). The IPCC report however has been a subject of intense criticism (Bagla 2009; Leake and Hastings 2010; Schiermeier 2010), particularly triggered by a discussion paper (Raine 2009) (see, e.g. Cogley et al. 2010).

The fact that the area is so vast and largely inaccessible for researchers, any attempts in predicting the fate of Himalayan glaciers will remain anything but undisputable. What could be unanimous however, is that changes in glaciers and snow balance in the world's largest and highest mountain system will have impacts on water resources and the ecosystems of the densely populated region downstream, although the scale of the impacts varies significantly in different river basins. Any changes in hydrological regimes also have direct impact on agriculture and water based developments like hydropower plants, and therefore timely assessment of any short- and long-term changes in the snow/ice dynamics in the Himalaya is of critical importance. However, the assessment of a continuous and long-term change in the Himalayan snow cover extent, which inevitably contributes to the sustainability of glaciers in the long run, has not yet received enough attention.

In this study we investigate trends and variability of snow cover changes in the Himalayan region at different temporal scales (monthly, seasonal and annual) and at different elevation zones above 3,000 m. Such an investigation is expected to provide some information about long-term sustainability of the glaciers in the Himalayas despite the limitations related to the short-term nature of the data sets. We used Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover products (Hall et al. 2007) from 2000 to 2008 covering the Himalayan range in and around Nepal from 80° E to 89° E longitude (Fig. 1). In-situ temperature measurements from two high altitude stations (5,035 m and 3,920 m) and net radiation and wind speed data from one of the stations are used to substantiate the results.

2 Data and methods

The MODIS snow cover data are based on a snow mapping algorithm that primarily employs a Normalized Difference Snow Index (NDSI). An NDSI value is calculated using the at-satellite reflectance in MODIS band 4 (0.545–0.565 μm) and band 6 (1.628–1.652 μm). The classification of a cell as snow or non-snow is based on the NDSI value, the reflectance in MODIS band 2 (0.841–0.876 μm) as well as the Normalized Difference Vegetation Index (NDVI) value for forested area (Hall et al. 1998, 2002). The NDVI values are calculated in the similar manner as the NDSI using the reflectance in visible red and

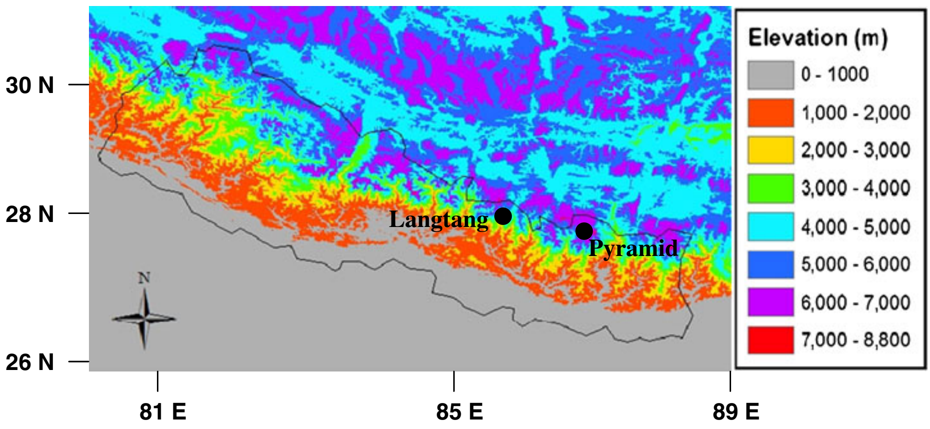

Fig. 1 Location and the extent of the study area; the *black line* indicates the border of Nepal. The *point symbol* indicates the locations of the meteorological stations

near-infrared bands (Running et al. 2004). The snow product used in this study is MODIS/Terra Snow Cover 8-Day L3 Global 500 m Grid (MOD10A2), Version 5 (Hall et al. 2007), which is available from 24 February, 2000 to present. MOD10A2 comes in a spatial resolution of 500×500 m^2 in every 8-day period that begins on the first day of each year and extends to first few days of the next year. This product represents the maximum snow extent in the given 8-day period.

A number of publications reported the validation of MODIS snow products and showed very good to reasonably good agreement with the ground observation data from various regions (Klein and Bernett 2003; Parajka and Bloeschl 2006; Simic et al. 2004; Wang et al. 2008). For example, Klein and Bernett (2003) showed an overall accuracy of 94% by comparing MODIS snow product with in-situ Snowpack Telemetry (SNOTEL) measurements at 15 locations in the Upper Rio Grande Basin (Colorado and New Mexico) during the snow season of 2000 and 2001. They also reported that in the majority of the days when MODIS fails to map snow occurs at snow depth of less than 4 cm. Parajka and Bloeschl (2006) presented an extensive validation using daily in-situ observations of snow depths from 754 climatic stations over Austria from 2000 to 2005. They showed that the accuracy of MODIS snow products is very high with an average of 95% on cloud free days. Similarly, Wang et al. (2008) evaluated the accuracy of MODIS snow products using ground observed snow depth data at 20 climatic stations in Northern China from 2001 to 2005. They also showed 94% accuracy of MODIS snow product on snow free days at snow depth $\geq$4 cm. More detailed coverage of published results of the MODIS snow product validation is found in Riggs and Hall (2007).

Monthly snow cover areas are derived from the 8-day snow cover maps taking average of the spanned 8-day periods in each month for five elevation zones covering the study area. The five elevation zones used are 3,000–4,000 m, 4,000–5,000 m, 5,000–6,000 m, 6,000–7,000 m and above 7,000 m. The areas of these elevation zones covered in this study are approximately 21,920, 122,480, 131,460, 4,070 and 250 km^2, respectively. The effect of clouds is an important issue in the study using MODIS snow products. Some studies (e.g. Gafurov and Bardossy, 2009; Gurung et al., 2011) applied different techniques for filtering cloud obscured pixels from the MODIS snow cover products. In this study, we observed that the percentage of cloud covers and its timing varies significantly at different elevation zones. For example, in the 3,000–4,000 m elevation zone, the cloud presence is mainly notable during the monsoon (summer), whereas in above 7,000 m elevation zone the cloud presence is notable during winter. The cloud presence is mostly minimal for elevation zones 4,000–5,000 m and 5,000–6,000 m. In the analysis of trends, we presented the results only for the periods in which the cloud cover is less than or equal to 10%.

Spearman's rank correlation method, a nonparametric test, was used for trend analysis on monthly, seasonal and annual snow cover. The annual snow cover is based on the periods from July to June as the snow cover is the lowest in July on average. The nonparametric method was chosen due to the small sample size. The magnitude of the trend (slope) where exists was estimated using a liner regression method. The error bounds on the estimated slope at 95% confidence level are also provided.

In-situ observation data for a number of meteorological parameters (such as temperature, radiation and wind speed) were obtained for the Pyramid station (which is close to Mount Everest) at 5,035 m elevation. In addition, in-situ temperature data were also obtained from the Langtang station at 3,920 m elevation. Correlations between the monthly snow cover for selected elevation zones and the in-situ temperature, net radiation and wind speed were also analysed.

3 Results and discussion

3.1 Inter-annual variability of the snow cover

Figure 2 shows the snow cover and cloud cover as fractions of the total area in each 8-day period for all five elevation zones. The values presented in the figure are averages of 9 years from 2000 to 2008. The clouds are particularly significant during the monsoon in the lower (3,000–4,000 m) elevation zone and during winter in the >7,000 m elevation zone. The analysis shows that the change in the snow cover extent is not always monotonously increasing with the increasing elevation. This result leads to the construction of snow depletion curves, which are commonly used as an input for snow-runoff modelling. The figure shows a clear separation of elevation zones to a lower range up to 6,000 m and a upper range above 6,000 m, such that the snow cover in the lower range is less than 40% with the exception of few months in winter for elevation range 3,000–4,000 m and more

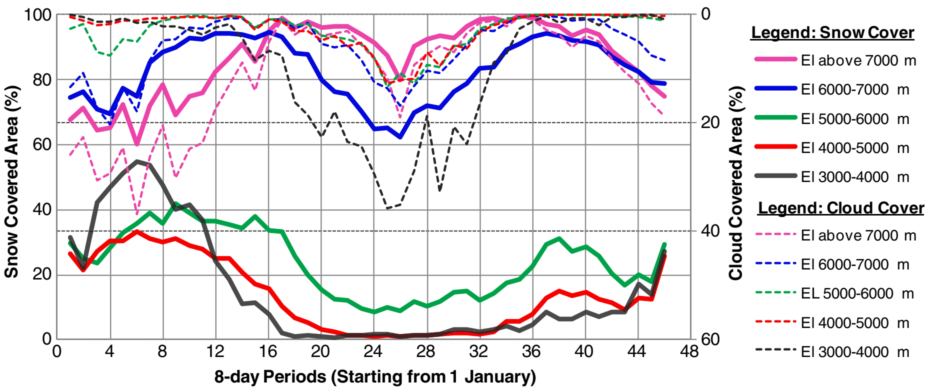

Fig. 2 Variations of the snow cover expressed in percentage of the total area at given 8-day periods of the year in various elevation zones. The values are averages of 9 consecutive years from 2000 to 2008

than 60% throughout the year in the upper range. During the winter months, particularly in February and March, the snow cover is higher in 3,000–4,000 m zone than in the 4,000–5,000 m and 5,000–6,000 m zones. For the rest of the year in these three elevation zones, the snow cover extent is monotonously increasing with increasing elevation. It is to be noted that for the >7,000 m elevation zone the figure shows more snow cover during the summer than in winter. This seems to be due to the high percentage of cloud cover in this elevation zone during winter. At this high elevation zone, large part of the cloud covered pixels could be expected to be snow in winter. Also in the 6,000–7,000 m elevation zone, the cloud cover is reasonably high during Jan–Feb and Jul–Aug.

Monthly variations of the snow extent in various elevation zones from the 9 years data are presented in box-plots in Fig. 3. There exists a large inter-annual variability in the monthly snow cover, particularly in winter. During the winter months the elevation zone 3,000–4,000 m gets the maximum variation, which is close to 60% in February. This high variability can be attributed to the alternation of heavy snowfall periods from Jan and Feb and sometimes even in Dec or Mar in various years at this elevation zone. This is also true for relatively large variability present in the winter period snow cover in elevation zones 4,000–5,000 m and 5,000–6,000 m. Although it is very difficult to quantify, the snow drift due to wind may also have contributed to the high variability observed in the snow cover. The elevation zone 6,000–7,000 m and the highest elevation zone (> 7,000 m) also show

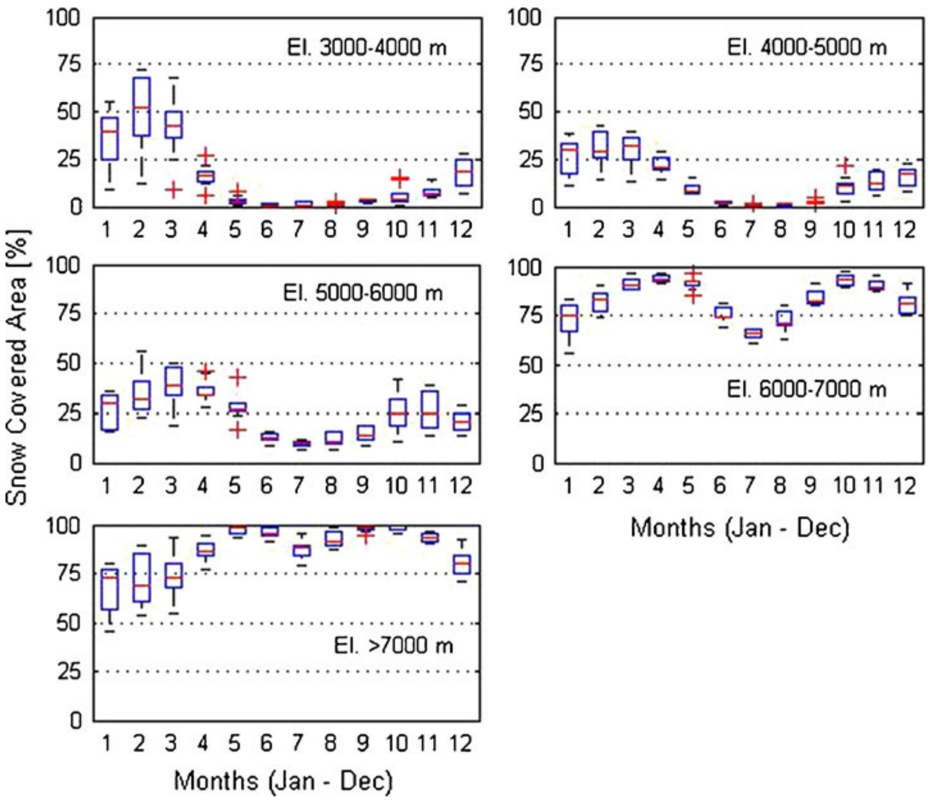

Fig. 3 Monthly variations of snow cover expressed in percentage of total area at various elevation zones presented in box-plots based on 9 years data from 2000 to 2008

large variations in winter, which is as high as 40% in February and March in the latter elevation zone. However for these elevation zones, part of the variation could be due to the presence of relatively large percentage of clouds during this period which could prevent some of the snow pixels to be detected. Interestingly, the elevation zone 6,000–7,000 m sustains least variations in all three seasons, except in summer when the variations are comparable to that of the elevation zones 5,000–6,000 m and >7,000 m.

3.2 Trends in snow cover changes

Spearman's rank correlation coefficients (ρ) were computed for analysing trends on changes in monthly, seasonal and annual snow covered areas over the 9 years period for all five elevations zones. The trend results are presented in Table 1. Also shown in the table are the magnitudes (slopes) of the trends in percentage per year based on liner regressions and the estimate of errors in the slope at 95% confidence level. Although the 9 year period is not long enough to make firm conclusions from the trend analysis, some important trends with reasonably high correlations are observed. In particular, there are decreasing trends of snow cover in January for three elevation zones below 6,000 m, two of them with reasonably high correlations and all of them at the rate of 2 to 3% per year. The trends are increasing in March for the elevation zones 5,000–6,000 m and 6,000–7,000 m. At the seasonal level, all the winter trends are negative for elevations from 3,000 m to 6,000 m, and similarly for the spring for 4,000–5,000 m and 5,000–6,000 m elevations. On the contrary, increasing trends are observed in autumn for elevation zones above 4,000 m. If such trends in the snow cover continue, it is likely to result in noticeable changes in the river flows in spring and autumn. These trends are certainly intriguing to study the impact on flow regimes in the region. It is to be noted that the elevation zones between 5,000 m to 7,000 m are likely to be most sensitive to climate change as most of the glaciers exist at these elevations and significant amount of snow cover remains throughout the year. Therefore, slight change in temperature at these elevation zones particularly if it is around the threshold of freezing/melting point could cause significant change in the snowmelt. Also of importance is the dominance of increasing trends of snow cover in the elevation zone above 7,000 m. The analysis by Immerzeel et al. (2009) on the Indus basin (to the west of the present study area) also found significant increasing trends particularly at higher elevation zones in winter.

3.3 Correlations between snow cover and temperature

Online supplemental figures are provided showing the correlations between the monthly snow cover and the in-situ measurements of temperature, net radiation and wind speed. Figures S1 and S2 show correlations between the snow cover and the temperature observed at Pyramid and Langtang stations. In both cases, snow cover in most of the months show negative correlations with the temperature of the same month and/or the previous month, particularly in snow free months, such as January and November for the elevation zones below 6,000 m. Shown in the figures are the results for selected months with reasonably high correlations. The significance of this result is twofold. It not only supports the reliability of the MODIS snow cover products, but also explains some of the trends observed in the snow cover changes. For example, the high negative correlation between the temperature and snow cover means that the decreasing trends observed in snow cover in January for all elevation zones (Table 1) can be attributed to the increasing temperature in December and January. Temperature data from both Pyramid and Langtang stations for the same period as the available snow cover show increasing trends for December (ρ=+0.48

Table 1 Spearman's rank correlation coefficients (ρ) showing increasing (+) or decreasing (−) trends. Coefficients more than or equal to 0.600 and 0.643 are statistically significant at 5% level for 9 and 8 data points, respectively. In the table, coefficient values more than 0.50 are presented in bold letters. 9 data points are used for the months Feb to Dec and the seasons spring, summer and autumn, and 8 data points for the rest. The trend values are presented only for the periods in which the cloud pixels are less than or equal to 10%. The periods in which the cloud covers are more than 10% are represented by "n.a." (meaning "not available"). The no correlation or very low correlation ($-|\rho|<0.05$) are represented by "–" in the table. The slope values are percentage increasing or decreasing rates per year in the fractional snow cover to the total area at different elevation zones based on linear regressions. The error bounds on the slope are based on 95% confidence level

Indicators	Elevations (m)									
	3,000–4,000		4,000–5,000		5,000–6,000		6,000–7,000		>7,000	
	ρ	Slope	ρ	Slope	ρ	Slope	ρ	Slope	ρ	Slope
Jan	−0.24	−3.03±5.98	**−0.57**	**−2.71±3.17**	**−0.55**	**−2.61±2.45**	n.a.	n.a.	n.a.	n.a.
Feb	n.a.	n.a.	–	–	+0.07	+0.84±3.41	n.a.	n.a.	n.a.	n.a.
Mar	−0.22	−0.78±5.45	−0.22	−0.34±2.70	+0.17	+0.11±3.40	**+0.52**	**+0.52±0.89**	n.a.	n.a.
Apr	–	–	−0.35	−0.24±1.55	−0.22	−0.37±1.88	−0.10	−0.12±0.57	n.a.	n.a.
May	n.a.	n.a.	−0.27	−0.43±0.92	−0.30	−0.87±2.08	−0.22	−0.40±0.91	+0.18	+0.19±0.65
Jun	n.a.	n.a.	**−0.52**	**−0.12±0.14**	−0.07	−0.14±0.78	n.a.	n.a.	**+0.55**	**+0.44±0.86**
Jul	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Aug	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sep	n.a.	n.a.	**+0.55**	**+0.18±0.19**	–	–	−0.05	−0.28±1.37	+0.28	+0.09±0.61
Oct	**+0.55**	**+0.51±1.64**	**+0.53**	**+1.06±1.65**	+0.37	+1.37±2.90	–	–	−0.05	−0.12±0.59
Nov	−0.08	−0.20±0.96	+0.13	+0.35±1.62	+0.37	+0.87±3.09	+0.18	+0.12±0.84	+0.10	+0.10±0.76
Dec	–	–	−0.12	−0.25±1.65	–	–	+0.07	+0.11±1.64	n.a.	n.a.
Winter (JFM)	−0.36	−1.36±4.80	−0.41	−1.04±2.62	−0.19	−0.53±2.74	n.a.	n.a.	n.a.	n.a.
Spring (AMJ)	n.a.	n.a.	−0.47	−0.26±0.67	−0.47	−0.46±0.83	–	–	**+0.52**	**+0.47±0.88**
Summer (JAS)	n.a.	n.a.	**+0.55**	**+0.06±0.10**	–	–	–	–	–	–
Autumn (OND)	–	–	+0.18	+0.38±1.28	+0.37	+0.76±2.18	+0.18	+0.15±1.05	+0.12	+0.17±0.45
Annual (Jul–Jun)	n.a.	n.a.	−0.21	−0.16±0.84	+0.12	+0.06±1.34	−0.24	−0.14±0.80	n.a.	n.a.

and +0.88, respectively) and January (ρ=+0.23 and +0.52, respectively). Similarly, the positive trend in the snow cover in November can be attributed to the decreasing temperature trends observed for the Pyramid station in October and November (ρ=−0.27 and −0.07, respectively). Both net radiation and wind speed from the Pyramid station show negative correlations to the snow cover of the same or the following month in most cases (Figures S3 and S4). These correlations are also favorable for the reliability of the snow products as more net radiation means more energy for snowmelt resulting in less snow cover. Similarly, the higher wind speed generally gives rise to quicker mixing of the air vertically (the air at skin temperature at the snow/ice surface to the overlying air), which facilitates faster melt if the overlying air is warmer than the freezing temperature.

4 Conclusions

The trend analysis on the alternation of snow cover during the 9 years period from 2000 to 2008 has shown some important results. If the decreasing trend of the snow cover in January and increasing trend in March as observed in this study continue, this may result in significant changes in the river flows and water resources in the region, particularly in spring. This would have implications for aquatic ecosystems that depend on the seasonal melt water pulse, for irrigation dependent agriculture and, last but not least, for water resources in the densely populated downstream areas. At the seasonal level, the negative winter trends for elevation zones 3,000–4,000 m, 4,000–5,000 m and 5,000–6,000 m, and the increasing autumn trends for all elevation zones above 4,000 m are also demanding to study the impact on flow regimes in the region. Some of the trends observed in the snow cover changes can be explained by the high correlations observed between the snow cover and the observed temperature. In particular, decreasing trends observed in the snow cover in January and increasing trend in November can be attributed to the increasing temperature in December and January and decreasing temperature in November, respectively. The negative correlations between the snow cover and the temperature, net radiation and wind speed also substantiate the reliability of the MODIS snow products. Whether these trends will continue as more years of data become available remains to be seen, but these results certainly point to the potential of satellite based snow products and the need to observe changes not only in selected glaciers but also in the regional extent of the snow cover in order to make more justifiable assessment of the destiny of this immensely important freshwater reserve in the Himalayas. With the increasing MODIS snow products every year, these data sets are likely to serve as an invaluable asset for assessing climate change impacts in the highly inaccessible Himalayan regions. It should be noted here that not only snow covered areas but also the snow depth and snow water equivalent will impact the snow melting, which subsequently influence the river flow regimes and water resources availability. Therefore, future studies should attempt to consider these factors for a more comprehensive assessment of the impact of Himalayan snow/glaciers on the river flow regimes.

Acknowledgements Part of this research was funded through the DGIS and UNESCO-IHE Programmatic Cooperation Fund. We acknowledge the Department of Hydrology and Meteorology, Ministry of Science, Nepal, for sharing the temperature data from the Langtang station. We also acknowledge Ev-K2-CNR, Bergamo, Italy for sharing the Pyramid station data, which were collected within the SHARE Project thanks to contributions from the Italian National Research Council and the Italian Ministry of Foreign Affairs. We are very grateful to Ms Roberta Toffolon from the Ev-K2-CNR Secretariat for her generous help in connection to providing these data.

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