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Early 21st century climatology of snow cover for the western river basins of the Indus River System

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Abstract

In this paper we assess the snow cover and its dynamics for the western river basins of the Indus River System (IRS) and their sub-basins located in Afghanistan, China, India and Pakistan for the period 2001–2012. Moderate Resolution Imaging Spectroradiometer (MODIS) daily snow products from Terra (MOD) and Aqua (MYD) have been first improved and then analysed on seasonal and annual basis against different topographic parameters (aspect, elevation and slope). Our applied cloud filtering technique has reduced the cloud cover from 37 % (MOD) and 43 % (MYD) to 7 %, thus improving snow cover estimates from 7 % (MOD) and 5 % (MYD) to 14 % for the area of interest (AOI) during the validation period (2004). Our results show a decreasing tendency for the annual average snow cover for the westerlies-influenced basins (Upper Indus Basin, Astore, Hunza, Shigar, Shyok) and an increasing tendency for the monsoon-influenced basins (Jhelum, Kabul, Swat and Gilgit). Regarding the seasonal snow cover, decrease during winter and autumn and increase during spring and summer has been found, which is consistent with the observed cooling and warming trends during the respective seasons. Sub-basins at relatively higher latitude/altitude show higher variability than basins at lower latitude/mid-altitude. Northeastern and northwestern aspects feature larger snow cover. The mean regional snow line altitude (SLA) zones range between 3000 and 5000 m a.s.l. for all basins. Our analysis provides an indication of a decrease in the regional SLA zone, thus indicating a change in the water resources of the studied basins, particularly for the Upper Indus Basin (UIB). Such results are consistent with the observed hydro-climate data, recently collected local perceptions and glacier mass balances for the investigated period. Moreover, our analysis suggests some potential for the seasonal stream flow forecast as a significant negative correlation has been detected for the inter-annual variability of winter snow cover and value of the North Atlantic Oscillation (NAO) index of the previous autumn.

1 Introduction

Snow is an essential part of the climate system with a large influence on the hydrological cycle as well as on the atmospheric processes due to its high albedo and low thermal conductivity (Hall and Riggs, 2007). Snow is especially important for the hydrological cycle as large amounts of the water supplies come from the seasonal snowmelt in high latitudes and mountainous basins (Barnett et al., 2005). This is particularly true for the Indus Basin where snowmelt runoff provides first handful water availability after a long dry period (October–March, Immerzeel et al., 2010). This is due to the fact that the Indus Basin receives winter precipitation mainly in solid form over the Hindu Kush–Karakoram–Himalaya (HKH) ranges in the north (Rees and Collins, 2006). Such hydro-meteorological phenomena along with the existing cryosphere determine the overall hydrological balance of the basin and the water availability downstream in an otherwise very arid land. Analysis of upstream–downstream hydrographs reveals that the maximum diversion within the Indus Basin takes place during the snowmelt season (Hasson et al., 2013b). The snowmelt contribution to the flows of Upper Indus Basin (UIB), located in the western part of HKH ranges, is not well known. Immerzeel et al. (2009) have reported that the snowmelt contributes almost 40 % of the UIB flows. Such an estimate is based on a modelling study and subject to various uncertainties associated with the modelling approaches. Nevertheless, in view of the importance of snowmelt for the Indus Basin, an accurate quantification of its distribution pattern and its climatic properties is essential. Additionally, snow cover assessment is required for the calibration/validation of distributed hydrological models (Konz et al., 2010), as well as for the seasonal forecast of the freshwater supplies.

Consistent with the unprecedented warming worldwide (IPCC AR4, 2007), Himalayas are reported to experience significant warming during the last decades (Shrestha et al., 1999; Diodato et al., 2012). Consequently, annual average snow cover has decreased by ~ 16 % over the entire Himalayas during 1990–2001 (Menon et al., 2010). A similar snow cover trend has also been observed during 2000–2008

(Immerzeel et al., 2009) and during 2000–2010 (Gurung et al., 2011), though some regional anomalies do exist. In contrast, UIB experiences unique signatures of climate change, featuring cooling temperatures and increasing precipitation (Fowler and Archer, 2005b). Tree-ring-based precipitation reconstruction further confirms that the last century was the wettest in the last millennium in this region (Treydte et al., 2006). Similarly, most of the Himalayan glaciers have been retreating and losing mass since the end of Little Ice Age where current observations show, on the average, an acceleration of such response since 1990. However, glaciers in the Karakoram Range have featured irregular behaviour since a long time, showing balanced budgets during the last decade (Hewitt, 2005; Bolch et al., 2012; Bhambri et al., 2013; Gardelle et al., 2012). Under such contrasting hydro-climatic regime, prevailing snow cover state is largely unknown, leading to uncertainties in present and future management of water resources.

The sparse network of short-length high-altitude meteorological stations, within part of UIB in Pakistan, makes it hard to assess the detailed picture of snow cover dynamics at a sub-basin and regional scales. The regional snow surveys are also not possible in the HKH region, due to its complex terrain and harsh environment. Furthermore, as snow features a high degree of variability, it needs mapping at a fine temporal resolution, unlike glaciers, which require only fine planar resolution. In this regard, integration of remote sensing (RS) data and methods with geographical information system (GIS) techniques has proved its usefulness in mapping snow cover in inaccessible areas (Max, 2001; Tong et al., 2009). Such an approach has been adopted by recent studies performed over the region, focusing the MODIS snow products (Immerzeel et al., 2009; Gurung et al., 2011; Tahir et al., 2011a). Large-scale snow accumulation/distribution processes are generally controlled by synoptic scale meteorological patterns and the larger topography (esp. elevation and aspect). Instead, snow redistribution depends on the local topography (esp. slope) and local meteorological conditions on a small scale (Kelly et al., 2003). In view of the role of topography and lacking snow cover estimates for sub-basins of the Indus Basin having contrasting hydro-climatic regimes

(Archer, 2003), these studies only partially provide, the information about the present snow cover state.

The present study aims at applying rigorous non-spectral cloud filtering techniques on hyper temporal MODIS daily snow products from Terra (MOD10A1) and Aqua (MYD10A1), in order to improve the snow cover mapping accuracy. Our mapping of snow cover for the western river basins (Indus, Jhelum and Kabul) and their six sub-basins against different topographic parameters (aspect, elevation and slope) is unprecedented at such detailed scale. Furthermore, we are able to link our findings to the recent hydro-climatic signals as well as to the socio-economic vulnerability observed in the region over a recent decade to late 20th century.

2 Study area

The study area covers the spatial domain 30–38° N and 67–84° E, comprising three large river basins (i.e. Jhelum, Kabul and UIB) and their six sub-basins, namely, Astore, Gilgit, Hunza, Swat, Shigar and Shyok (Fig. 1). We have restricted our analysis to the western river basins of the Indus River System (IRS) except for the Chenab River basin, but including the Kabul River basin. According to the Indus water treaty, the western rivers of IRS (Jhelum, Indus and Chenab) are under the exclusive control of Pakistan, while the eastern rivers (Ravi, Sutlej and Beas) are controlled by India (Mehta, 1988). The investigated basins are located at the boundary between two large-scale circulation modes: the western mid-latitude disturbances and the south Asian summer monsoon system (Hasson et al., 2013b). The hydrology of the high latitude/altitude (Hunza, Shigar, Shyok and Astore) sub-basins is dominated by the precipitation regime of the western mid-latitude disturbances during the winter and spring seasons (Wake, 1987; Rees and Collins, 2006; Hasson et al., 2013a). Such high latitude/altitude sub-basins, located in the rain shadow of the western Himalayas, receive negligible precipitation from the summer monsoon (Ali et al., 2009), which is mostly restricted to the lower latitude/altitude (Swat, Jhelum, Kabul and Gilgit) sub-/basins.

The UIB features unique patterns of the observed climate change. Since 1960s, almost half of the observational record within the UIB shows a cooling tendency of the mean annual and seasonal temperatures except during the winter season (Fowler and Archer, 2005b). Further, the diurnal temperature range (DTR) is widening in the UIB throughout the year (Fowler and Archer, 2005b) while it has been narrowing worldwide since 1950 (Karl et al., 1993; Easterling et al., 1997). In contrast to the observed cooling, the CMIP3 general circulation models (GCMs) project instead an increase in temperature over northern Pakistan (part of the UIB) throughout the 21st century, which is higher than the projected increase over the surrounding lowlands areas as well as the global projections for IPCC SRES A2 and A1B scenarios (Islam et al., 2009). For the precipitation, however, both the observational records and GCMs projections are in agreement, suggesting the observed increase during the second half of the 20th century (Archer and Fowler, 2004) and projected increase for the 21st and 22nd centuries (Hasson et al., 2013b) on an annual timescale.

Runoff from these basins is comprised of a slow (snow and glacier melt) and a fast (rainfall) component in the higher and lower altitude sectors, respectively (Archer, 2003; Ali and De Boer, 2007). It is confined to the summer months (June–September) and primarily depends upon the slow runoff component (Hasson et al., 2013a). The historical discharge climatology of the Kabul, Jhelum and UIB basins shows that these three basins provide almost 80 % of the annual surface water available within Pakistan through IRS (Ali et al., 2009).

Generally, the whole Indus Basin can be divided into three major categories on the basis of their hydro-meteorological characteristics according to Fowler and Archer (2005a):

- High altitude basins with a large percentage of glacier cover (glacier-fed basins). Their hydrology mainly depends upon the glacier melt runoff during the melt season, which correlates with concurrent summer temperatures. The snow distribution significantly affects the timing and magnitude of the glacier melt runoff from these basins.

- Mid-altitude basins, with lower elevation (and latitude as well) than the glacier-fed basins and having smaller percentage of glacier cover (snow-fed basins). The hydrology of these basins is mainly dominated by the snowmelt runoff component, which in turns highly correlates with the previous winter season solid precipitations.

- Low-altitude foothill catchments, which mostly receive precipitation in a liquid form (rain-fed basins).

We have divided all the nine considered basins into only two categories, i.e. glacier-fed and snow-fed basins. According to this division, Hunza, Shigar and Shyok basins are mainly glacier-fed while Jhelum, Kabul, Gilgit, Astore, and Swat are mainly snow-fed basins (Fig. 1). Table 2 shows the total area of these basins. Keeping in view the dependency of river flows from these snow- and glacier-fed catchments on previous winter precipitation and concurrent temperatures, respectively, and the observed conflicting signals of increased precipitation and cooling temperatures over HKH region of Indus Basin, one can expect significant changes in the snow cover at spatio-temporal scale with climate change, impacting in turn water availability and glaciers' nourishment in the region.

3 Data

We have chosen the MODIS daily snow products from both Terra and Aqua (MOD- and MYD-10A1) Version 5 (Hall et al., 2006) for the period 2001–2012 for our analysis, available at 500 m resolution. The MODIS snow cover products have been generated through the automated snow-mapping procedure using bands 1 (0.659 µm), 2 (0.865 µm), 4 (0.555 µm) and 6 (1.64 µm). Normalized difference snow index (NDSI) using bands 4 and 6 is used to detect snow (Hall et al., 1995) as it has high reflectance value in visible band (band 4) and low reflectance value in the short-wave infrared band (band 6). A surface temperature filtering has been included in the version 5 of the snow products in order to prevent mapping of the warm surfaces as snow, which have their spectral features similar to the snow (Riggs et al., 2006).

The MODIS snow cover products range from a swath level to the composite global climate modelling grid (CMG) products at 0.05° resolution after spatial and temporal transformations (Riggs and Hall, 2011). Each higher level snow product, therefore, assimilates the accuracy and errors from its preceding product (Riggs and Hall, 2011). MODIS snow products are produced and distributed by the NASA Distributed Active Archive Centre (DAAC) located at the National Snow and Ice Data Centre (NSIDC). The MODIS daily snow tiles of h23v5, h24v5 and h25v5 for both Terra and Aqua are downloaded from NSIDC online archive in order to cover the study area.

As MODIS is on-board both the Terra and Aqua satellite, each of them passes over the same area in the morning and afternoon, respectively, providing twice a daily temporal resolution. Such high temporal resolution is desirable for our applied cloud filtering technique to reduce the cloud cover. Their spatial resolution of 500 m is also considered highly suitable for estimating the snow cover of the basins with an area of about 10 000 km^2 or larger (Hall et al., 2002); however, it can still be useful for relatively smaller basins. The overall absolute accuracy of the MOD10A1 and MYD10A1 products has been reported to be ~93 %, which may vary with land use/land cover type and particular snow conditions (Zhou et al., 2005). Clouds are a major problem of remotely sensed data set in the optical wavelength regions. Such a problem is even worse in the mountainous regions where the occurrence of clouds is instantaneous and hard to predict. The errors in the accuracy of the MODIS snow products are due to the resemblance in snow and cloud covers. For example, while analysing the MODIS daily snow product (MOD10A1) for Upper Rio Grande river basin for the period 2000–2004, Zhou et al. (2005) found less than 10 % omission error as misclassification of snow as a land and vice versa. However, they have found high omission error of around 50 % as misclassification of snow or land as a cloud. The presence of cloud cover in scenes prevents adequate quantitative assessment of snow, introducing uncertainty in the analysis (Hall et al., 2002). Although the cloud problem has been overcome to the extent possible by MODIS cloud masking procedure (Hall and Riggs, 2007), these snow products are not cloud free. This emphasizes the need of further cloud filtering application over the considered snow products prior to their use in the analysis.

Additionally, the station-based seasonal mean North Atlantic Oscillation (NAO) index (Hurrell, 1995) was downloaded from an online archive (http://climatedataguide.ucar.edu/sites/default/files/cas_data_files/asphilli/nao_station_seasonal_1.txt) of the Climate Analysis Section, National Centre for Atmospheric Research (NCAR), Boulder, USA, to analyse the statistical relation between snow cover and intensity and position of the storm track and of the ensuing mid-latitude disturbances. These are mainly responsible for the precipitation input over the studied basins (Wake, 1987; Archer and Fowler, 2004; Hasson et al., 2013b). The gap-filled Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) Version 4 (Jarvis et al., 2008) at 90 m resolution, from CGIAR – Consortium for Spatial Information (http://srtm.csi.cgiar.org/), was used to define the topography and to delineate the watershed boundaries. The same SRTM DEM V4 was interpolated using the nearest neighbour method to 500 m resolution, in order to match the resolution of MODIS data and to unambiguously calculate snow cover with reference to the aspect, slope and altitude, based on the underlying terrain.

4 Methodology

The MODIS Re-projection Tool (MRT) (Dwyer et al., 2001) jointly with MODIS Snow Tool (MST) (Gurung et al., 2011) was used in batch processing mode to

1. mosaic the same-day tiles h23v05, h24v05, h25v05 for Aqua and Terra separately
2. re-project the twice-a-day tiles to Geographical Coordinate System (GCS)
3. sub-set the area of interest (AOI) from the full extent of the projected mosaic tiles covering all the study basins.

In order to minimize the data gaps due to clouds from the MODIS snow products, we have additionally applied rigorous non-spectral techniques, partially following Gafurov and Bárdossy (2009) and Gurung et al. (2011). The functionality of various steps of the adopted cloud filtering techniques is briefly discussed here.

Combining Terra and Aqua data

If a particular cloud-covered pixel in the Terra image was cloud-free (snow/no-snow or any other class) in Aqua image, a cloud-covered pixel was replaced by the cloud-free pixel in the output image (logical OR function). In case a particular pixel was present as a cloud in both same-day acquisitions, it remained as a cloud pixel and processed in the following cloud filtering steps. After applying this step, we had a single snow image for each day.

Temporal filter and analysis

We applied this step only in specific situations where the present-day cloud pixel was snow on the previous day but cloud on the next day. In this situation, the present-day cloud pixel was replaced by snow pixel, keeping in mind that snow cover has high spatial correlation and that snow permanence time is usually much longer than one day. In the temporal analysis step, we replaced the present-day cloud pixel with the class of corresponding pixels on the previous and next days, if such a class was the same among the pixels.

Spatial filter

Through a spatial filtering technique, we removed cloud pixels by filling in a value as decided by the majority data filter based on a spatial window size. We chose 7 × 7 as the size of a spatial window.

Basin-cover snow < 10 % cloud cover

Even though an applied cloud filtering technique considerably reduced the cloud cover from the snow product, our data showed that cloud was not completely removed. This was due to the reason that cloud persisted longer than the timescale considered by the temporal filter and/or the cloud cover was larger in extent than accounted for by the window size of the adopted spatial filter. Such cases were especially found during the accumulation period (winter and spring seasons), substantially restricting the quantification of snow cover variability. In order to avoid the influence of remaining cloud cover, daily snow cover estimates of each basin with cloud cover of less than 10 % were considered for further analysis.

We investigated the performance of the applied cloud filtering technique for the whole AOI by estimating the snow and cloud cover before and after the cloud removal process for the validation period. The year 2004 is chosen as validation period, as it was the first wet year after the long drought (1998/1999–2002/2003) over the Indus Basin (Levinson and Waple, 2004; Baig and Rasul, 2009). The year 2004 experienced the maximum cloud cover conditions. In order to investigate the spatial performance of our applied cloud filtering algorithm, we have taken a pair of same-day snow images, each from Terra and Aqua with large cloud cover difference. For such images, our cloud filtering process generated a completely cloud-free image. We have chosen day 96 of the year 2004 with 18 % difference of cloud cover between Terra (12 % cloud cover) and Aqua (30 % cloud cover) snow images. In order to make Terra image cloud free, its cloud cover has been masked out from both the Terra image itself and the Aqua image. Then all the cloud filtering steps, except the first one, are performed to remove the rest of the 26 % cloud cover from the Aqua snow image.

We have considered the performance of our cloud filtering technique as satisfactory, if it has reduced the cloud cover to less than 10 % of AOI during validation period. The cloud free snow products were then used to estimate the snow cover of the study basins. In order to estimate snow cover against different topographic parameters, such as elevation, slope and aspects, the basin areas were divided into equal zones of 500 m elevation, 10° slope and 16 aspects, respectively. All the processing was performed using MODIS Re-projection Tool (MRT) (Dwyer et al., 2001), MODIS Snow Tool (MST) (Gurung et al., 2011) and ArcGIS 9.3 spatial analyst package.

Our analysis presents the snow cover climatology along with its inter-annual variability for the MODIS record. In addition to that, it is worthwhile addressing the intra-annual variability of the snow cover, which may of course have a greater impact on the timely availability of the water within a year. For this purpose, we have analysed the seasonal snow cover for the four time slices, namely, autumn (September–November), winter (December–February), spring (March–May) and summer (June–August) seasons and have ascertained the mean seasonal snow cover trends, in addition to mean annual trends for all the studied basins.

5 Results

5.1 Cloud filtering results

The applied cloud filtering technique has reduced the overall cloud cover from 37 (MOD) and 43 (MYD) to 7 %, improving snow cover estimates from 7 (MOD) and 5 (MYD) to 14 % for the whole area of interest (AOI) during the validation period (i.e. year 2004). In the individual steps, combining the MODIS Terra and Aqua same-day images, the temporal filter, the spatial filter and temporal analysis have reduced the average cloud cover to 29, 9, 8 and 7 % and have improved the snow cover to around 8, 12, 13 and 14 % of the whole AOI respectively. Hence, the cloud cover has been reduced and the snow cover results have been improved significantly (cf. Figs. 2 and 3).

The spatial scale performance of our applied cloud filtering algorithm showed that the Aqua image cloud cover has been reduced from 26 % to about 5 %. Its snow cover has been improved from about 10 % to about 13 %, which was comparable to MODIS Terra snow image (Table 1). Figure 4 illustrates the spatial performance of the applied technique. The applied cloud filtering technique suggested almost 0.3 % overestimation of the snow cover in the resultant Aqua image relative to the snow cover of the same-day Terra image. This may partly be attributed to the spatial cloud cover differences among the same-day Terra and Aqua images and partly due to the fact that the first step of combining both same-day images has been skipped during this validation process.

One should consider that our analysis was based on the snow cover estimates for the days experiencing cloud cover less than 10 % of the respective basin areas. Such days accounted for 65–85 % of the total number of days over the whole period for all basins, except Shigar and Hunza sub-basins. We have observed that winter (30–65 %) and spring (60–80 %) seasons have experienced a minimum number of days with less than 10 % cloud cover, whereas for summer and autumn seasons, numbers of such days were always higher (i.e. 60–90 %). The Shigar and Hunza (high latitude/altitude glacierized) sub-basins have experienced only 45–50 % days of less than 10 % cloud cover for the whole period, whereas such days during winter season were about 15 % for the Shigar sub-basin and about 25 % for the Hunza sub-basin.

5.2 Basin-wide snow cover estimates

Snow cover

Shigar has the highest annual average snow cover percentage followed by the Hunza, Astore and Gilgit (Fig. 5, Table 2). These sub-basins have shown large year-to-year variation as compared to other lower latitude/altitude basins. On the other hand, the Shyok sub-basin has the lowest snow cover mainly due to its large extent at lower latitude in the south east.

The snow cover for the Astore and Gilgit sub-basins of UIB ranges from 2 ± 1 and 3 ± 1 % during the summer to 98 ± 1 and 90 ± 4 % during spring season, respectively. These basins experience relatively low cloud cover but high variability in both accumulation and ablation seasons. The sharp drop of the snow depletion curve implies that both of the basins have low glacier melt contribution so that their hydrology mainly depends upon the snowmelt (Fig. 5a and b). This is further clarified by the minute minimum snow cover (near to 0 %) and small glacier cover reported for these basins.

For the Hunza and Shigar sub-basins of UIB, the snow cover extent ranges from 17 ± 6 and 25 ± 8 % as the minimum during summer to 83 ± 4 and 90 ± 3 % as the maximum during spring season, respectively. We can observe the relative smooth drop of the snow depletion curve during the ablation period (Fig. 5c and d). Conversely to what we have observed in the Astore and Gilgit sub-basins, here the sub-basins feature large reservoirs of the perennial snow and permanent ice and have relatively low snow cover variability throughout the year.

The snow cover for the Jhelum and Kabul basins ranges from about 1 % for both basins during the summer to 75 ± 8 and 67 ± 5 % during spring, respectively. These two basins exhibit high snow cover variability in the accumulation period like other snow-fed sub-basins, such as Astore and Gilgit (Fig. 5e and f). On the other hand, they feature low snow cover variability during the ablation period. This results from the fact that these mid-altitude basins, lying at relatively lower latitude than the other high altitude/latitude basins, experience relatively low cloud cover throughout the year. We have observed great similarity for the Jhelum and Kabul river basins in terms of their minimum and maximum snow coverage and snow depletion patterns (Fig. 5e and f). This observation is further reinforced by the fact that both river basins give similar contribution (about 16 %) to the average annual surface water available in Pakistan, as calculated from the long-term record (Ali et al., 2009). Swat, a comparatively smaller sub-basin of the Kabul Basin, receives snow coverage ranging from 1±1 to 72±9 %. Its snow accumulation/ablation patterns and other snow cover characteristics are similar to those of the Kabul and Jhelum basins (Fig. 5i).

Mean annual cycle of the snow cover percentage for the UIB and its major sub-basin Shyok has been found to be quite different from that of the other basins. Figure 5g and h shows that the snow cover of these basins ranges from 4 ± 1 and 3 ± 1 % in the summer to 54 ± 7 and 44 ± 9 % in spring season, respectively. Both of the basins showed high snow cover variability in both the accumulation and ablation seasons which was substantially pronounced for the Shyok sub-basin, except during the winter season (Fig. 5g and h). This was caused probably by the large and persistent cloud cover during the season, which has restricted the assessment of their snow cover variability. A large portion of the northeastern Shyok sub-basin, characterized by low precipitation rate, has neither permanent snow nor glacier cover. Instead, the part of the Shyok sub-basin lying in the Karakoram Range features high concentration of ice (Hewitt, 2007; Bhambri et al., 2013). Hence, its contribution to the stream flows mainly comes from the glacier melt. For the UIB, the minimum snow cover corresponds to the estimates of its sub-basins Gilgit, Hunza, Shigar, Shyok and UIB itself, so it exhibits the average effect of the contrasting hydrological regimes of its sub-basins. Interestingly, our extracted mean annual minimum snow cover extent for all basins except Astore and Hunza, generally corresponds to the areal extent of the existing glaciers, with a slight systematic underestimation (Table 2). Such underestimation is larger for the Hunza Basin, which features large glacier areas under debris cover. However, inconsistent estimates for the Astore Basin (snow-fed basin) could also be due to an overestimation of the available glacier outlines from the Randolph Glacier Inventory (ICIMOD, 2007; Arendt et al., 2012).

Most of the mid-altitude basins, namely, Jhelum, Kabul and UIB including Swat and Shyok sub-basins show high variability in their mean maximum snow cover (i.e. greater than equal to 5 %) as compared to their mean minimum snow cover. But the Astore and Gilgit sub-basins show high variability in their mean snow cover. Among high altitude basins, only Shigar sub-basin shows high variability in its mean minimum snow cover. A large spread is found during the snow accumulation and ablation seasons. Such variability is typically higher for the snow-fed basins than for the glacier-fed basins. High variability in the minimum, maximum and the annual average snow coverage directly affects the melt-water runoff contribution on yearly basis, which may further contribute to the inter-annual variability of the IRS flows.

Snow cover trends

There is a slight negative trend change for the annual average snow cover for UIB and for its all sub-basins except Gilgit sub-basin (Table 2). These basins are mainly influenced by the westerlies. On the other hand, a slight positive trend exists for the rest of the studied basins, which are mainly influenced by the monsoon. However, no trend was found to be statistically significant. The analysis of annual data depicted consistency with the worst drought in Pakistan, which spanned from 1998/1999 to 2002/2003 and weakened in 2003–2004 due to heavy winter precipitations (Levinson and Waple, 2004; Baig and Rasul, 2009). Similar drought indications were observed during 2006 to 2009. Seasonal average snow cover shows that winter and autumn feature decreasing trends for most of the studied basins. Instead, there was a positive snow cover trend for the Gilgit Basin in autumn season and for the Jhelum Basin throughout the year. Most basins show an increasing snow cover trend in the rest of seasons except Shyok and UIB, which have shown a decreasing trend for the spring season. However, a statistically significant trend was found only for the Jhelum Basin in summer season. The decrease in winter and autumn season snow cover and the observed increase in spring and summer season snow cover are consistent with the observed cooling and warming trends (Fowler and Archer, 2005b) in the respective seasons. While there is no significant systematic change in the snow cover, a large variability is indeed present. This can affect the timely availability of melt water downstream. Since we have data only for 12 yr, it is clear that it is extremely hard to make proper deductions about the long-term trends.

Tele-connections

It is worth noting that the inter-annual snow cover variability is well explained by the inter-annual variability of the snow cover during the melt season only (not shown here). This critically depends on the input of solid precipitation by the mid-latitude westerly disturbances during the previous winter season. As the strength and track of the synoptic disturbances is controlled by NAO index (Hurrell, 1995), it is interesting to analyse how the index explains the winter season snow cover variability. The station-based NAO index is based upon the normalized sea level pressure differences among Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland. The index shows pronounced variability at quasi-decadal (6–10 yr) timescale and during the winter season (Hurrell, 1997), allowing its correlation analysis possible with the short-length (12 yr) snow cover time series. Our analysis suggested a negative correlation between NAO index (autumn season) with the winter season snow cover of all the studied basins, which was particularly significant for UIB (Table 3). On the other hand, there was a positive correlation between NAO (winter season) and the winter season (DJFM) snow cover for the Jhelum and Kabul basins. These findings suggest the possibility of a winter season snow cover forecast with a lead time of up to a season. It can subsequently be related to the availability of snowmelt runoff during the summer season.

Height dependence of snow cover estimates

We have found high seasonal variation of the height-dependent snow cover for the snow-fed basins as compared to the glacier-fed basins throughout the year (Fig. 7). The maximum snow cover for the high-altitude/latitude basins is during winter, while for lower latitude/mid-altitude basins, it occurs during the spring season (Fig. 7). In most of the basins, a disproportionally large fraction of the snow cover comes from high altitude zones, which include very small surface areas, such as zones above 5000 m a.s.l. for the Astore, Swat and Jhelum, above 5500 m a.s.l. for the Kabul, above 6000 m a.s.l. for the Gilgit, Shyok and UIB, and above 6500 m a.s.l. for the Hunza and Shigar basins. Conversely, the Jhelum, Kabul and Swat basins have considerable surface areas below 2000 m a.s.l. which have a negligible snow cover percentage (Fig. 7). On the basis of our height dependent snow cover time series, we have also estimated the end of summer regional snow line altitude (SLA) zone. Variations in SLA zone provide a good approximation of the prevailing local climatic conditions (e.g. precipitation input and concurrent temperature regime) and the mass balance variation signal of the existing water resources. The rise of SLA zone indicates enhanced melting and increased exposure of the snow-free glaciers' area to retreat. On the other hand, its drop indicates the opposite, implying positive mass balance of the existing glaciers. Under the observed cooling (Fowler and Archer, 2005b) and increasing snow cover in summer, we have conjectured a falling tendency of the regional SLA zone. In order to test our hypothesis, we have compared the inter-annual variability of the end-of-summer regional SLA zone with the median elevation of basin-hosted glaciers. Glaciers' median elevation is a reasonable proxy for the long-term equilibrium line altitude (ELA – the altitude where net mass gain/loss is zero) of the present glaciers based on their topographic data (Braithwaite and Raper, 2009). Our analysis has shown that the estimated regional SLA zones within all basins are situated well below the glaciers' median elevation (Fig. 8). Such facts imply the positive mass balance of existing glaciers during the analysis period. Table 4 shows the estimated end-of-summer climatic regional SLA zones for each studied basin.

Exploring the relationship of snow cover with respect to slope, we expect that the high altitude basins experience relatively low snow cover at higher slopes due to the mass release of accumulated snow. Instead, for the mid-altitude basins, low snow cover is expected at lower slopes as their large areas extend at hotter, less mountainous regions. Our findings are consistent with such hypotheses, as the Gilgit, Hunza, Astore, Shigar basins have experienced a low snow cover over higher slopes, whereas the Jhelum, Swat, Kabul, Shyok and UIB basins have experienced a low snow cover over lower slopes (Fig. 7).

Aspect-wise snow cover estimates

Each of the studied basins has different morphometric characteristics, which play a significant role in defining the distribution pattern of the snow cover. Aspect is also a major topographic parameter which influences the snow cover distribution. South facing slopes were expected to feature relatively faster depletion of snow cover than the north facing slopes in Northern Hemisphere. This fact raised further interest to deduce the influence of aspect to the snow cover area distribution within study basins. For this purpose, we have estimated the snow cover percentage for 16 aspect zones (Fig. 9). Obviously, we expect that the north facing slopes have comparably more snow than slopes facing south, because of the reduced melting due to small direct solar insolation. Nonetheless, the quantitative dependence of snow cover on the aspect is far from trivial. It differs from location to location because, for example, precipitation is impacted by the relationship between the aspect and the prevailing wind direction. Hence, we have calculated north to south (N–S), northwest to southeast (NW–SE), northeast to southwest (NE to SW) and west to east (W–E) ratios of seasonal snow cover for all the basins (Table 5). It is found that N–S ratios are high during all seasons with the maximum during autumn. Such ratios are also higher than other aspect-ratios during all seasons. Only Shigar and Shyok sub-basins experience maximum N–S ratio of snow cover during winter season. Similarly, NE–SW ratios are high for all the basins and during all the seasons, except for the Jhelum and Kabul during spring and only for the Jhelum during summer season. Except Astore in summer, all other basins have either high or similar NW–SE ratios. Shyok sub-basin and UIB experience low W–E ratios of the snow cover in spring and winter seasons, whereas similar low ratio is found for the Hunza sub-basin only during the winter season. By combining the information contained in Table 5 and in Fig. 9, we have derived that the N–S, NE–SW and NW–SE ratios of snow cover tend to be higher when the overall snow cover was lower. It points to the fact that aspect is not a very strong limiting factor for snow persistence in high, well snow-fed basins during colder seasons. The snowmelt due to direct sunlight becomes more relevant when climate conditions are milder and/or snow precipitation is weaker. Overall, the aspect-wise snow cover analysis shows that the Astore, Gilgit, Hunza, Shigar, Shyok, Jhelum and UIB basins have relatively larger basin areas in the NE and SW aspects while they experience larger snow cover at the NE to the NW aspects during all seasons.

6 Discussion

Understanding of the statistical properties of snow cover, of its seasonal and inter-annual variability, and its slow trend dynamics is crucial for understanding the hydrological system and also concerning socio-economic importance of snowmelt runoff within Indus Basin. The present study is an attempt in such regards.

The MODIS instrument provided a good opportunity in assessing the snow cover dynamics over the study region, mainly due to its high-temporal resolution. Dealing with cloud cover is however a major problem in the adequate snow cover assessment. It has been observed that the Aqua snow product has relatively more cloud cover as compared to Terra snow product for the AOI. Although the overall performance of the applied cloud filtering technique is satisfactory, we note that it is unable to completely remove the cloud cover from the input snow products. Generally, this happens when cloud persists longer than the window size of a temporal filter or the clouds are larger in extent as compared to the window size of applied spatial filter. Such conditions are observed over the study region during winter and spring season. The conditions during summer and autumn seasons mostly feature clear sky with similar cloud coverage percentage. Therefore, our cloud filtering technique does not perform well during winter season, particularly for the high-latitude/altitude glacierized sub-basins (Hunza and Shigar). Nevertheless, as the overall performance of this technique has been found satisfactory, we encourage application of such approach before use of snow products in the analysis. In this regard, our findings based on the cloud-filtered hyper-temporal snow images for the major and minor sub-basins of the Indus Basin against various geophysical parameters (Slope, Aspect and Height) are unprecedented. A few modelling studies (Akhtar et al., 2008; Immerzeel et al., 2009; Tahir et al., 2011b) using 8-daily MODIS snow products, without adequately reducing cloud cover, provide river flow estimates under climate change conditions. Such estimates, from our point of view, may be prone to larger uncertainties in order to derive the snow cover–runoff relationship and to ascertain the impacts of climate change on melt water runoff quantitatively.

We note that, generally, estimated minimum snow cover slightly underestimates the areas given by the available glacier outlines (ICIMOD 2007; Arendt et al., 2012). One of the main reasons for such underestimation could be the areas of debris-covered glaciers in the region (Bolch et al., 2012) which are not detectable by MODIS (Painter et al., 2012). Such effect has been most prominently seen for Hunza Basin. On the other hand, Astore Basin also shows large inconsistency between its MODIS minimum snow cover and the total glacier area. Reasons for such disagreement may be due to the fact that the observation dates of the available glacier data used in Randolph Glacier Inventory and the extracted minimum MODIS snow coverage do not necessarily coincide, plus the unavoidable issues associated to the quality of data in a complex terrain (Painter et al., 2012). Coarser resolution of MODIS as compared to the data used in GLIMS inventory may also be responsible for underestimation of snow cover as compared to glacial extent.

We have found that basins under monsoon influence behave differently than the basins under the westerlies influence. On annual average timescale, westerly-influenced basins show decreasing snow cover trends while monsoon-influenced basins show the opposite behaviour. In the context of increasing winter precipitation (Archer and Fowler, 2004), such decreasing trends indicate: (1) enhanced melting due to observed warming during winter (Fowler and Archer, 2005b; Khattak et al., 2011); (2) transformation of solid precipitation into liquid (Hasson et al., 2013b). On seasonal timescale, we found a negative snow cover trend during winter and autumn seasons but positive trends during summer and spring seasons. These findings are in agreement with Immerzeel et al. (2009) and Gurung et al. (2011) and consistent with reports of cooling and warming trends during the respective seasons by Fowler and Archer (2005b) and Khattak et al. (2011). Consequently, these trends suggest reduced melt water availability for agriculture production and hydro-power generation downstream and shift in solo-season cropping pattern upstream. Such reduction of stream flow has been reported by Khattak et al. (2011). Moreover, placement of regional SLA zone well below the median-elevation of existing glaciers – a proxy of ELA (Braithwaite and Raper, 2009) – also confirms the indication of a positive mass balance of these glaciers. This is consistent with recently reported possible slightly positive mass balance of Karakoram glaciers (Gardelle et al., 2012).

The changes discussed above have vital importance when the socio-economic effects of environmental pressures are considered. A comprehensive community/household level survey conducted in the Yasin and Hunza valleys of Gilgit–Baltistan during May–June 2012 (Gioli et al., 2013) suggests that there is among locals a widespread perception of an increase in annual precipitations and of cooling of the hot season, and a decrease in the summer river flows, despite the increase in the summer rain. Note that the local agriculture depends critically on melt water, as the fields are irrigated and not rain fed. Summer water scarcity, the shift of/reduction in the duration of the growing season and other factors like population growth and the consequent reduction of per capita landholding have decreased drastically the yields in the last 10 yr, with very serious impacts on food security and livelihood of these communities. Such pressures can increase differences between the socio-economic status of different classes and groups, and diffuse political instability in the region. Interestingly, most of these climate change perceptions are in disagreement with local perceptions on climate change and variability collected in the Central and Eastern Himalayas (Eriksson et al., 2009). This mirrors the special nature of the observed hydro-climatic changes in this region.

Projecting in the future the changes in the snow cover dynamics is far from being a trivial task. Rees and Collins (2006) suggest an initial increase in flows, followed by a subsequent reduction, due to the decrease in glaciated area under the warmer climate. Other studies (Immerzeel et al., 2009; Tahir et al., 2011b) suggest similar tendencies. In our opinion, such findings are not necessarily relevant for the study area discussed here, as the region in the last decades has not followed the climate change signals of neighbouring regions, and climate models have proved unable to describe such anomalies (Hasson et al., 2013a, b). Most commonly adopted scenarios – temperature increase (Fowler and Archer, 2005b; Khattak et al., 2011; Minora et al., 2013), glacier area decrease (Minora et al., 2013) seem presently inappropriate, but may be relevant for the long-term future. Under such scenario we encourage the modelling community to consider additionally the observed hydro-climatic scenario for near-future assessment of the melt runoff contribution.

It is well accepted that the present-day state-of-the-art climate models can be used to project future changes in the hydrological cycle over the region under warmer climate (Hasson et al., 2013a). However, in contrast to the observed historical trend, CMIP3 climate models foresee increase in temperatures for the region (Islam et al., 2009). Likewise, with high inter-model agreement, a negative change is projected for winter and spring precipitation by the end of 21st and 22nd centuries (Hasson et al., 2013b). If this occurs in the future, reduction in the snow cover and the glacier nourishment will cause certain changes in the melt water contribution.

Our results show large inter-annual snow cover variability. Together with an erratic behaviour of monsoon, such variability can exacerbate the water management problem for Pakistan. To counter this effect, increased water storage capacity is needed. Unfortunately, the original Pakistan water storage capacity was 13 % of the available average annual flows, when the main basins were engineered. Now, this portion has been reduced to 9 % and continues to decrease further due to the heavy load of sedimentation from the young HKH Mountains (Ali et al., 2009). This on one hand requires the adequate adaptation measures to be taken and on the other hand emphasizes the need for further investigating the future changes in water resources considering scenarios relevant for the study region.

Our finding about the significant negative correlation between NAO index (autumn) and the winter snow cover for UIB, suggests the possibility of winter season snow cover forecast with a lead time of up to a season. Furthermore, this can be related to the availability of snowmelt runoff during the summer season as suggested by Forsythe et al. (2011). Based on their correlation analysis between the stream flow observations and the MODIS snow cover data, they clearly describe a great potential of the snow cover variability in providing indicators of quantitative runoff during melt season in the region. Based on these relationships, we can postulate that the region has a good potential for the summer season water availability forecast. This will provide great opportunities for the water resources management in the region well in advance.

7 Conclusions

The data set covers a too short time frame for being able to draw robust conclusions about the general behaviour and long-term changes of snow cover dynamics. However, this study has provided the opportunity to understand the present state of snow-cover regime and its dynamics and its temporal and spatial variability, taking into account different geophysical parameters in the region. The results of this study will also be useful in driving the hydrological models and improving their validation procedures. On the other hand, findings about the link between snow cover and NAO index, suggest the possibility of short-term forecast of water resources. The main findings of our study are summarized here

- the annual average snow cover analysis has revealed that the westerlies-influenced basins (UIB, Hunza, Shigar, Shyok and Astore) have decreasing snow cover tendency. On the other hand, monsoon-influenced basins (Jhelum, Swat, Kabul and Gilgit) have increasing snow cover tendency. The seasonal analysis shows downward snow cover trends for all basins during winter and autumn seasons except for the Gilgit during autumn. The Jhelum Basin features an increasing trend of snow cover throughout the year, whereas all the other basins show an increasing trend of snow cover for spring and summer seasons (except Shyok and UIB). However, only the summer snow cover trend for the Jhelum is found to be statistically significant.
- high variability is found in the snow accumulation and ablation seasons. This variability is relatively higher for the snow-fed than for the glacier-fed basins and

higher during the winter and spring seasons than during the summer and autumn seasons. An east–west gradient is not present in terms of snow cover and its variability. However, sub-basins at higher latitude/altitudes show more snow cover variability than basins at relatively lower latitude/mid-altitudes.

- high seasonal variation with respect to elevation is observed for the snow-fed basins as compared to the glacier-fed basins throughout the year. Average regional SLA zone for the Hunza and UIB basins ranges from 3000 to 3500 m a.s.l., for the Gilgit, Shigar, Jhelum and Kabul basins from 3500 to 4000 m a.s.l., for the Astore and Shyok basins from 4000 to 4500 m a.s.l. and for Swat Basin from 4500 to 5000 m a.s.l.

- the aspect-wise snow cover analysis shows that the Astore, Gilgit, Hunza, Shigar, Shyok, Jhelum and UIB basins have comparatively larger basin area in NE and SW aspects, and larger snow cover at NE aspect than other aspects. Northern aspects, as expected, have in general more snow cover than southern aspects. Such discrepancy becomes larger when considering warmer seasons or basins at lower altitude, where temperature is a stronger limiting factor for the snow persistence.

- the slope-wise snow cover analysis shows that the Gilgit, Hunza, Astore, Shigar basins have low snow cover over the higher slopes, whereas the Jhelum, Swat, Kabul, UIB and Shyok basins have low snow cover over the lower slopes.

- an indication of a positive change in the UIB frozen water resources was found under prevailing climate conditions. This was evident from the facts: (1) observed increase in winter precipitation (Archer and Fowler, 2004), (2) possible positive mass balance of the central Karakoram glaciers (Gardelle et al., 2012), (3) decreasing summer flows (Khattak et al., 2011), falling end-of-summer regional SLA zone and increasing snow cover due to cooling trends for summer season. In contrast to the summer season, increasing winter flows (Khattak et al., 2011) and warming trends during such season indicated a possible seasonal shift in the snow distribution. Such a shift depends partly on the precipitation input during accumulation season and partly on the prevailing seasonal temperature regimes. The observed trends agree with the local perception of climate change in the region (Gioli et al., 2013).

- there is a significant negative correlation between NAO index (autumn season) with the winter season snow cover, suggesting the possibility of a winter season snow cover forecast. Furthermore, it suggests a great potential of snowmelt runoff forecast, providing opportunities for effective and timely water resources management.

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Table 1. Performance of cloud filtering technique for day 96 of year 2004.

S. no.	Snow image	Cloud cover %	Snow cover %
1.	Terra after cloud removal	0.0	12.5
2.	Aqua after masking out terra cloud	26.5	9.8
3.	Aqua after temporal filter applied	5.7	12.7
4.	Aqua after spatial filter applied	4.8	12.8
5.	Aqua after spatial analysis applied	4.8	12.8

Table 2. List of 9 Basins with total area along with snow coverage (SC) % and trend slope (2001–2012). Values in bold are statistically significant, values in italic show variability greater than equal to 5 %. Note: glacier areas are derived from RGI Glacier Inventory (www.glims.org, Arendt et al., 2012).

S. no	Basin at gauging site	Area (km^2)	Snow cover %				Snow cover % trend slope				
			Glacier area	Mean min ± Stdev	Mean max ± Stdev	Avg. ± Stdev	DJF	MAM	JJA	SON	Ann.
1.	Astore at Doyian	3897	14	2 ± 1	98 ± 1	*47 ± 5*	−0.79	+0.49	+0.76	−0.72	−0.29
2.	Gilgit at Gilgit	12 652	7	3 ± 1	90 ± 4	41 ± 4	−0.58	+0.50	+0.77	+0.02	+0.16
3.	Hunza at Dainyor Bridge	13 705	28	*17 ± 6*	83 ± 4	49 ± 3	−1.07	+0.09	+0.38	−0.30	−0.12
4.	Jhelum at Azad Patan	27 291	1	0.2 ± 0.2	*77 ± 8*	22 ± 2	+0.16	+0.47	**+0.33**	+0.23	+0.30
5.	Kabul at Nowshera	88 676	2	1 ± 0.3	*67 ± 5*	18 ± 2	−0.05	+0.11	+0.19	−0.01	+0.12
6.	Swat at Chakdara	6080	3	1 ± 0.5	*72 ± 9*	27 ± 3	−0.04	+0.39	+0.37	−0.09	+0.15
7.	Shigar at Shigar	6974	30	*25 ± 8*	90 ± 3	58 ± 3	−0.76	+0.30	+0.37	−0.17	−0.02
8.	Shyok at Yugo	138 836	6	3 ± 1	*44 ± 9*	14 ± 2	−0.21	−0.63	+0.09	−0.16	−0.17
9.	UIB at Besham Qila	271 359	7	4 ± 1	*54 ± 7*	21 ± 2	−0.74	−0.07	+0.21	−0.13	−0.15

Table 3. Correlations between NAO index and the snow cover (SC) of the studied basins. Correlations significant at 90 % level are marked with italic only, at 95 % level are marked with bold only and at 99 % level are marked with bold and italic.

S.No.	Basin	SC(DJF) -NAO(DJF)	SC(DJFM) -NAO(DJF)	SC(DJF) -NAO(ASO)	SC(DJF) -NAO(SON)	SC(DJF) -NAO(OND)
1	Astore	0.18	0.13	−0.39	**−**0.62	−*0.52*
2	Gilgit	0.22	0.13	−0.19	−0.45	−*0.58*
3	Hunza	−0.10	−0.04	−0.41	**−0.66**	**−0.67**
4	Jhelum	*0.54*	**0.70**	0.07	−0.18	−0.15
5	Kabul	*0.52*	**0.59**	0.30	−0.01	−0.20
6	Swat	0.43	0.35	−0.03	−0.27	−0.40
7	Shigar	0.06	0.11	−0.28	−0.50	−0.34
8	Shyok	−0.45	−0.22	−0.59	***−0.74***	−0.51
9	UIB	−0.33	−0.25	−0.55	***−0.79***	**−0.67**

Table 4. Estimated end-of-summer mean regional snow line altitude (SLA) zone for each studied basin.

S. no.	Basin	Climatic regional SLA zone
1	Astore	4100–4200
2	Gilgit	3900–4000
3	Hunza	3400–3500
4	Jhelum	3600–3700
5	Kabul	3900–4000
6	Swat	4500–4600
7	Shigar	3800–3900
8	Shyok	4200–4300
9	UIB	3200–3300

Table 5. Seasonal aspect ratios of snow coverage for all studies basins.

S. no.	Basin name	DJF				MAM				JJA				SON			
		N/S	W/E	NE/SW	NW/SE	N/S	W/E	NE/SW	NW/SE	N/S	W/E	NE/SW	NW/SE	N/S	W/E	NE/SW	NW/SE
1.	Astore	1.2	1.0	1.1	1.1	1.2	1.0	1.1	1.1	1.3	1.0	1.1	0.9	1.7	1.0	1.3	1.2
2.	Gilgit	1.2	1.0	1.2	1.1	1.3	1.0	1.1	1.1	1.2	1.1	1.1	1.1	1.5	1.1	1.2	1.3
3.	Hunza	1.3	0.9	1.3	1.1	1.3	1.0	1.2	1.1	1.4	1.0	1.2	1.1	1.4	1.0	1.3	1.2
4.	Jhelum	1.2	1.1	1.0	1.1	1.3	1.1	0.9	1.2	1.5	1.3	0.9	1.4	1.9	1.2	1.1	1.7
5.	Kabul	1.2	1.2	1.0	1.2	1.2	1.3	0.9	1.2	1.3	1.3	1.0	1.1	1.5	1.4	1.0	1.5
6.	Shigar	1.1	1.0	1.2	1.1	1.1	1.0	1.1	1.1	1.0	1.0	1.1	1.0	1.1	1.0	1.2	1.1
7.	Shyok	1.8	0.9	1.5	1.1	1.6	0.9	1.4	1.1	1.3	1.0	1.2	1.1	1.7	1.0	1.4	1.3
8.	Swat	1.2	1.0	1.1	1.1	1.2	1.0	1.1	1.1	1.2	1.2	1.0	1.2	1.4	1.1	1.1	1.4
9.	UIB	1.5	0.9	1.3	1.1	1.4	0.9	1.2	1.1	1.3	1.0	1.2	1.1	1.6	1.0	1.3	1.4

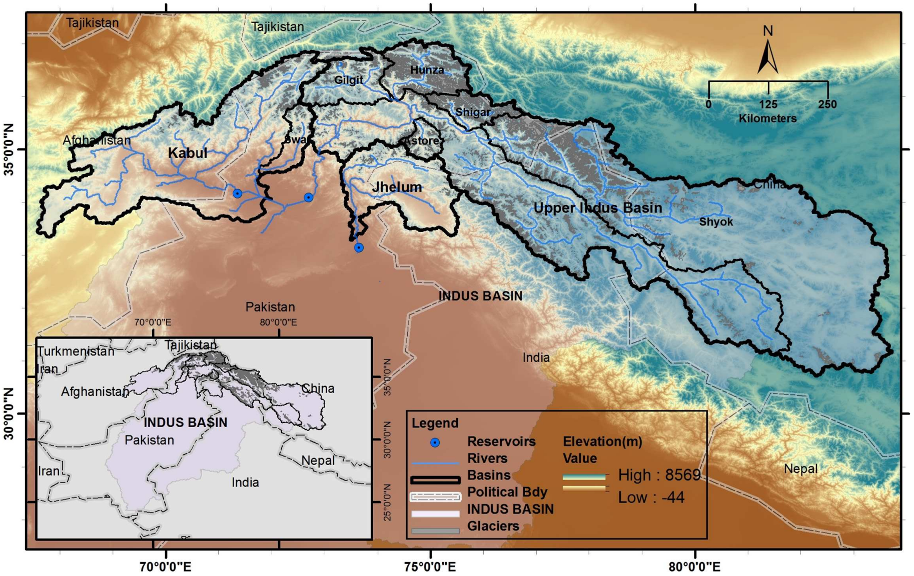

Fig. 1. Study area for snow cover mapping showing three major western river basins namely Indus, Kabul and Jhelum and their six sub-basins. Swat is a sub-basin of Kabul Basin, whereas the Gilgit, Hunza, Shigar, Shyok and Astore are the sub-basins of UIB. The political boundaries are tentative only.

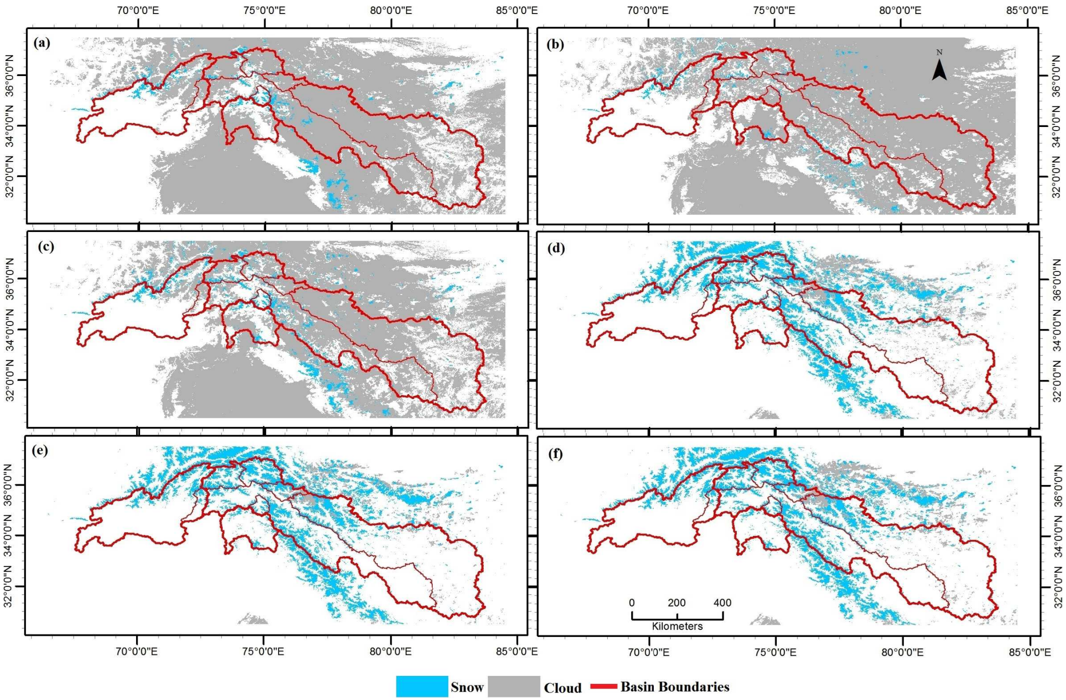

Fig. 2. Cloud and snow cover of original MODIS Terra and Aqua Images and after implementation of five steps for day 144 of year 2004 over the whole AOI, **(a)** original MODIS Terra, **(b)** original MODIS Aqua, **(c)** after combining Terra and Aqua, **(d)** after temporal filtering, **(e)** after spatial filtering, and **(f)** after temporal analysis.

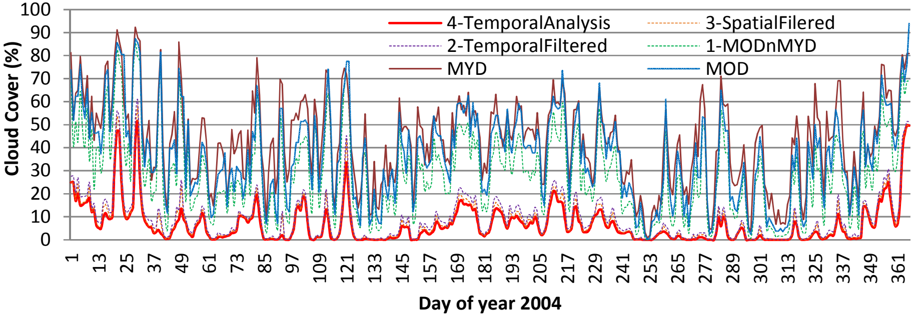

Fig. 3a. Cloud coverage from the MODIS Terra (MOD), Aqua (MYD) and after each step of the cloud filtering technique for the validation period of year 2004.

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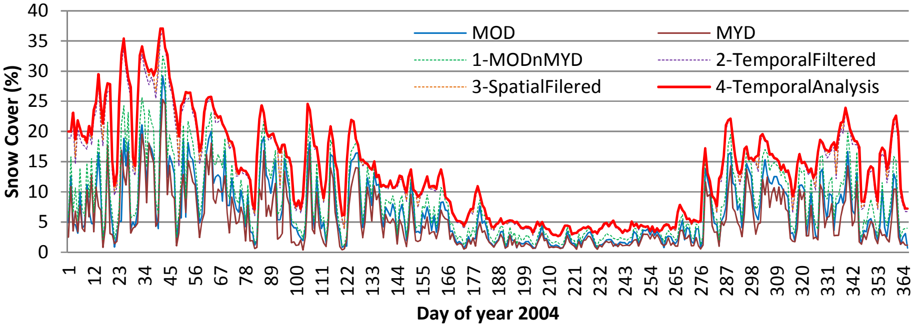

Fig. 3b. Snow cover from the MODIS Terra (MOD), Aqua (MYD) and after each step of the cloud filtering technique for the validation period of year 2004.

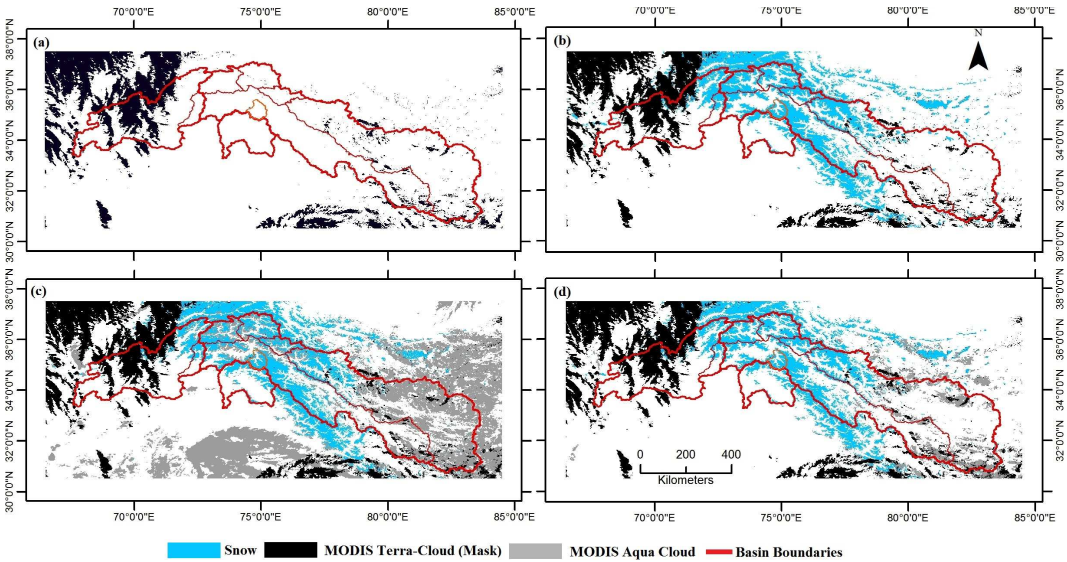

Fig. 4. Spatial performance of the cloud filtering technique over aqua snow image with respect to terra snow image for day 96 of year 2004 over the whole AOI (terra cloud mask in black, snow cover in blue and aqua cloud cover is shown in grey); **(a)** terra cloud cover, **(b)** terra snow image after masking out terra cloud cover, **(c)** aqua snow image after masking out terra cloud cover, **(d)** aqua snow image after applying all cloud filtering steps except combining it with terra same-day image.

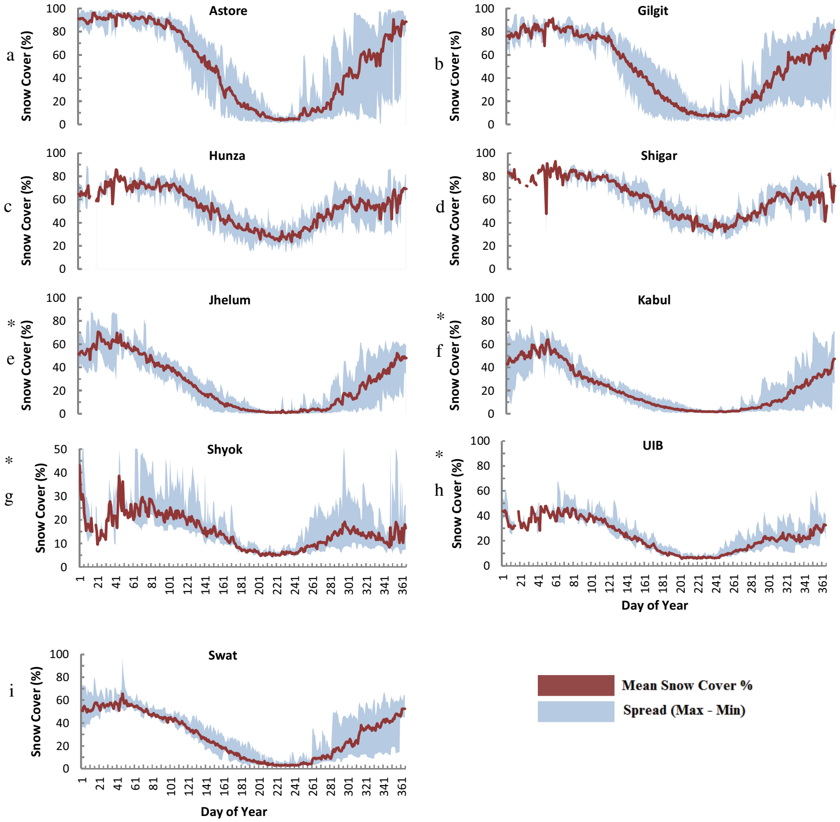

Fig. 5. (a)–(i) Snow cover climatology and its variability over the period 2001–2012 for all basins. Blue shaded area shows the spread (mean minimum and mean maximum), whereas red line shows the mean of the snow cover percentage over the whole period. Note: (*) indicate major basins.

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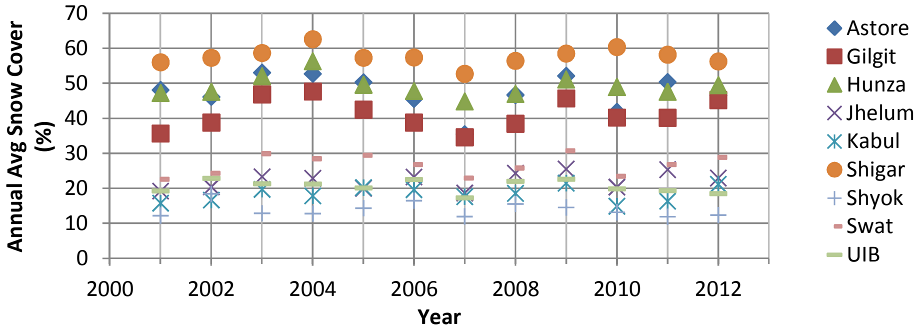

Fig. 6. Annual average snow cover for all basins for the period 2001–2012.

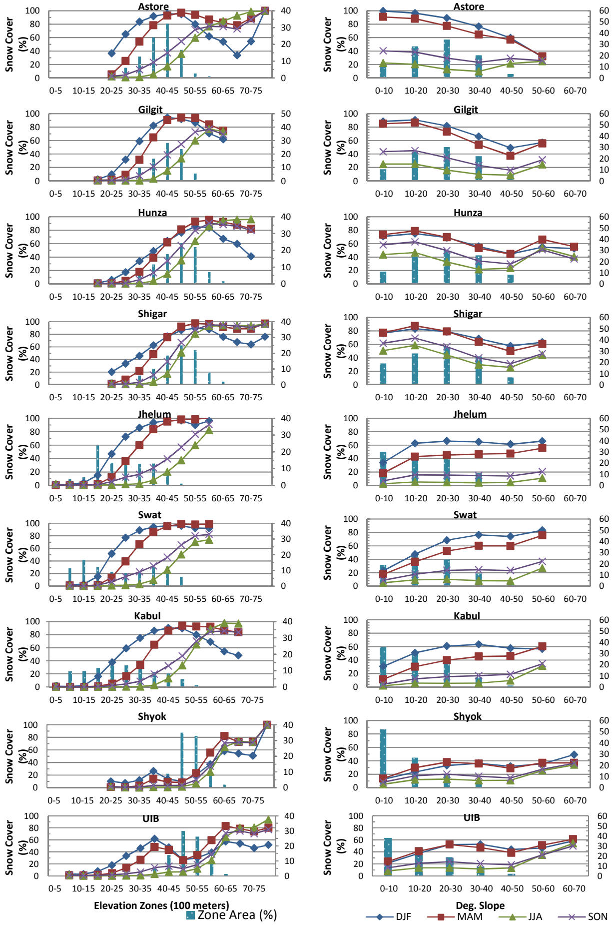

Fig. 7. Snow cover with regards to elevation (left panels) and slope (right panels) zones along with area within each zone.

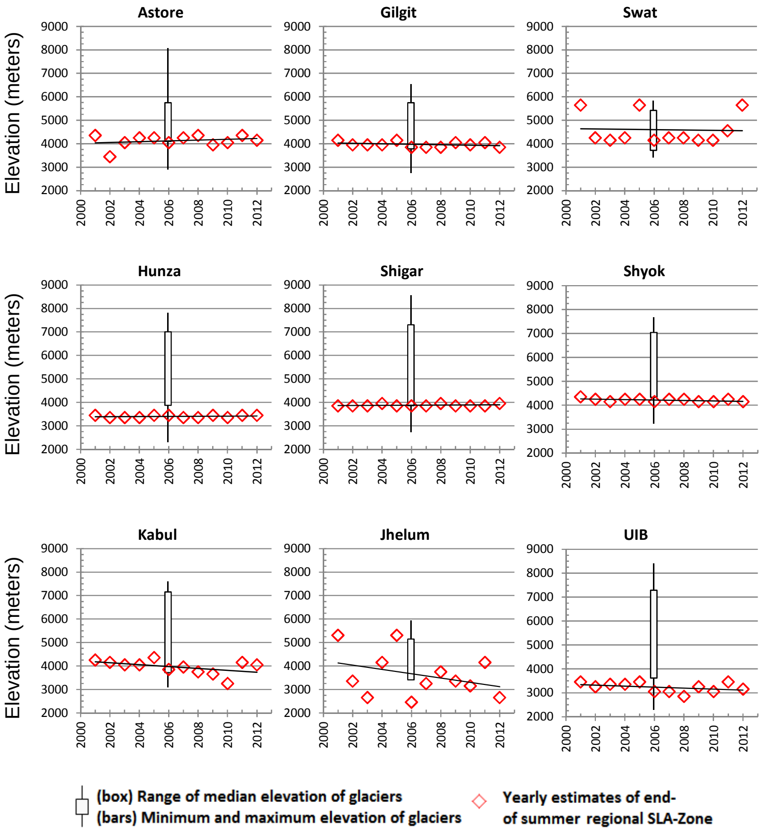

Fig. 8. Median-elevation of glaciers and inter-annual variability of the end-of-summer regional SLA zone for each studied basin. Note: median elevation of glaciers along with minimum and maximum elevation shown in box plot is time independent.

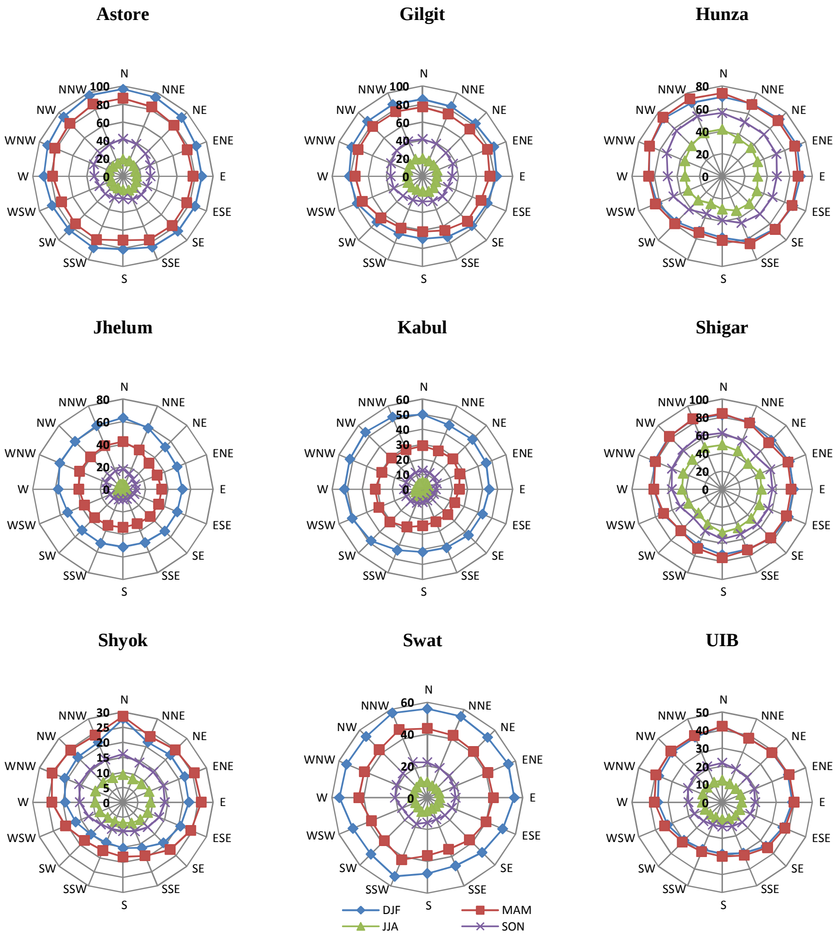

Fig. 9. Aspect wise distribution of snow cover (in percentage) during winter (DJF), spring (MAM), summer (JJA) and autumn (SON) seasons for the nine study basins.