Shifting mountain snow patterns in a changing climate from remote sensing retrieval

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Article history:
Received 30 April 2013
Received in revised form 14 April 2014
Accepted 21 April 2014
Available online 16 May 2014

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1. Introduction

Mountain regions provide water for drinking purposes to about half the world's population; in addition, water resources originating in mountains are also managed in reservoirs for hydropower production and/or irrigation purposes. In many mountain watersheds, snow accumulation and melting contribute widely to their water budgets. In these regions, the snow pack seasonal evolution is a key parameter for understanding stream-flow dynamics in mountains, foothills and lowlands. While the impacts of climate change on water resources is a process now widely accepted by the scientific community (IPCC, 2007, 2013; Bernstein et al., 2008; EEA, 2012; Beniston and Stoffel, 2014), mountains are particularly sensitive to the recent temperature increase and their impact on snow cover duration and depletion (Beniston et al., 2003, 2010; Barnett et al., 2005; Scherrer and Appenzeller, 2006; Gobiet et al., 2013). Recent studies also show that at altitudes below 1200 m above sea level (asl.), a winter time continuous snow-pack is becoming increasingly rare in Alpine catchments (Hantel and Hirt-Wielke, 2007; Bavay et al., 2009). Water budget modeling for mountain river basins that include snow and ice cover, in a context of short-time climate change impacts, requires improved knowledge of the different mechanisms governing water storage/release and the subsequent hydrological regimes in order to improve water resource management and use (Gottardi et al., 2012; Warscher et al., 2013). These issues are the central focus of the EU-FP7 "ACQWA" project, funded by the European Commission for the period 2008–2013 (www.acqwa.ch/).

In this context, the assessment of snow cover changes based on satellite snow cover data is, particularly in mountain regions, an efficient alternative to sparse ground-based snow depth observations, an essential parameter for hydrological modeling purposes.

This paper describes the contribution of remote sensing tools for a temporal and spatial analysis of the snow regimes in mountain areas. Two case study areas were selected from watersheds investigated in the ACQWA project: one in Europe consisting of the upper Po (Italy) and upper Rhone (Switzerland), both well documented (Beniston, 1997; Braun et al., 2000; Burlando et al., 2002) and where long term weather data are available. The second study site is located in Central Asia (Kyrgyzstan) where information related to glaciers and snow cover monitoring in this area exists for the last 50 years (Aizen et al., 1997), but which are difficult to access mainly from former Soviet-Union archives. More recently, a number of peer-reviewed publications have begun to focus on Kyrgyzstan and its glaciers and watersheds (Sorg et al., 2012; Dietz et al., 2013).

The objective of the remote sensing process is to contribute new information, such as snow cover extent maps (SCE) and maps of deviations from average values, in order to better analyze shifts in mountain snow patterns under changing climate conditions. The interest of the study is then to compare the remote sensing methodology applied at different scales studies, from the medium scales (European river basins) to the larger scales (Central Asia), in order to overcome the limits of the methodology and improve its performance.

2. Case-study areas

Snow is a major contributor to runoff in hydrological basins such as the Rhone (97,800 km^2) and Po (71,000 km^2) in Europe and the Syr Darya in Central Asia (453,000 km^2) where the melting mountain snow-pack adds much water to these rivers during the spring and summer months. As previously mentioned, three headwater catchments that are part of the ACQWA project were selected for our study: the upper Rhone in Switzerland (5340 km^2), the upper Po in Italy (37,875 km^2) and the Syr Darya forming zone in Kyrgyzstan (111,895 km^2); those basin subsets represent respectively the 5.4%, 53% and 24.7% of their entire hydrological basins. These watersheds are located in regions of complex topography where elevation and aspect govern the snow melt processes, with strong local variation.

Table 1
Watershed description.

Watershed	Upper Rhone[a]	Upper Po[b]	Syr Darya[c]
Area (km^2)	5338	37,874	111,895
Min elev (m asl.)	318	32	402
Max elev (m asl.)	4237	4810	5457
Mean elev (m asl.)	2074	925	2531
Glaciers%	14.3	0.5	2.9

[a] Corresponds to the Swiss Canton du Valais administrative region.
[b] Part of the Po hydrological basin that includes the Piedmont and Val d'Aosta regions.
[c] Corresponds to the upper Syr Darya forming zone: Naryn and Kara Darya rivers.

Moreover, many parts of the river flows in the Alps and Kyrgyzstan are heavily influenced by hydropower operations and irrigation/derivation networks (prior water management in Central Asia), and as a consequence regimes at their outlet are highly influenced by upstream infrastructure (Rahman et al., 2011; Sorg et al., 2012; Dietz et al., 2013).

2.1. Topography

Topographic data were retrieved from the SRTM digital elevation model (DEM) at a 90-m scale (http://srtm.csi.cgiar.org/) and extracted from the database for the shape files of the different river basins studied. An overview of their main characteristics is given in Table 1.

The first study site (Europe) is centered on the European Alps (45°.5′ N, 07° 5′ E; Fig. 1) and consists of two adjacent headwater areas separated by the highest peaks of the Alps as Mont-Blanc (4,8010 m asl., France), Matterhorn (4478 m asl., Switzerland) and Monte Rosa (4237 m asl., Italy). The upper Rhone (5338 km^2) is located on the north side of the range in the Swiss canton of Valais. The upper Po (37,875 km^2) basin is located in the Valle d'Aosta and Piedmont regions of Northern Italy, on the south side of the Alps. The sub-area "Dora Baltea" basin included in Fig. 1 corresponds to the Valle d'Aosta administrative region (3620 km^2), and its elevation and slope characteristics are more similar to the upper Rhone case study than the large lowland (Piedmont) part of the Po watershed.

The upper Rhone and Po basins offer contrasted elevation profiles (Fig. 2). The upper Po catchment presents a large part of lowlands with 58% of its territory below 1000 m asl., which is in contrast to the upper Rhone where highlands dominate; only 11% of the area is located under 1000 m asl. Fig. 3 offers a regularly distributed orientation for each catchment but highlights, however, that the Po basin is more E-SE facing than the Rhone basin. These two catchments are influenced by contrasting weather patterns (i.e., the Rhone is primarily influenced by Atlantic air masses, while those in the Po basin originate more in the Mediterranean). Such configurations are useful for a comparison of the behavior of the snow cover, using a single remote sensing database for two catchments on the opposite sides of the same mountain range.

The second study site is located in the Kyrgyz Republic (or Kyrgyzstan), consists of the headwater basins of the Syr Darya (Fig. 4), represents a total surface area of 111,895 km^2 (63% of the national territory) and is centered at 41° N, 74° E. The main basin is the Naryn (68,400 km^2), while the Kara Darya river (43,600 km^2) is located in the South-East part of the studied area. Both are the headwater basins of the Syr Darya and they merge downstream in Uzbekistan, just beyond the Kyrgyzstan border. The Naryn river basin contains an important artificial reservoir built at the end of the 1970s during the Soviet era (the Toktogul lake; 285 km^2, 19.5 km^3 volume). This reservoir provides water resources for numerous areas of irrigated agriculture downstream (Uzbekistan, Tajikistan and Kazakhstan), as well as for hydropower generation (Kyrgyzstan). The Kyrgyz Republic is of special interest for the entire Central Asian region because of its water resources: it generates an annual total flow of about 51 km^3 via the Syr Darya and the total hydropower capacity is 150 billion kWh each year with medium water availability. So far, only about 10% of the hydro potential had actually been developed (World Bank (WB), 2004).

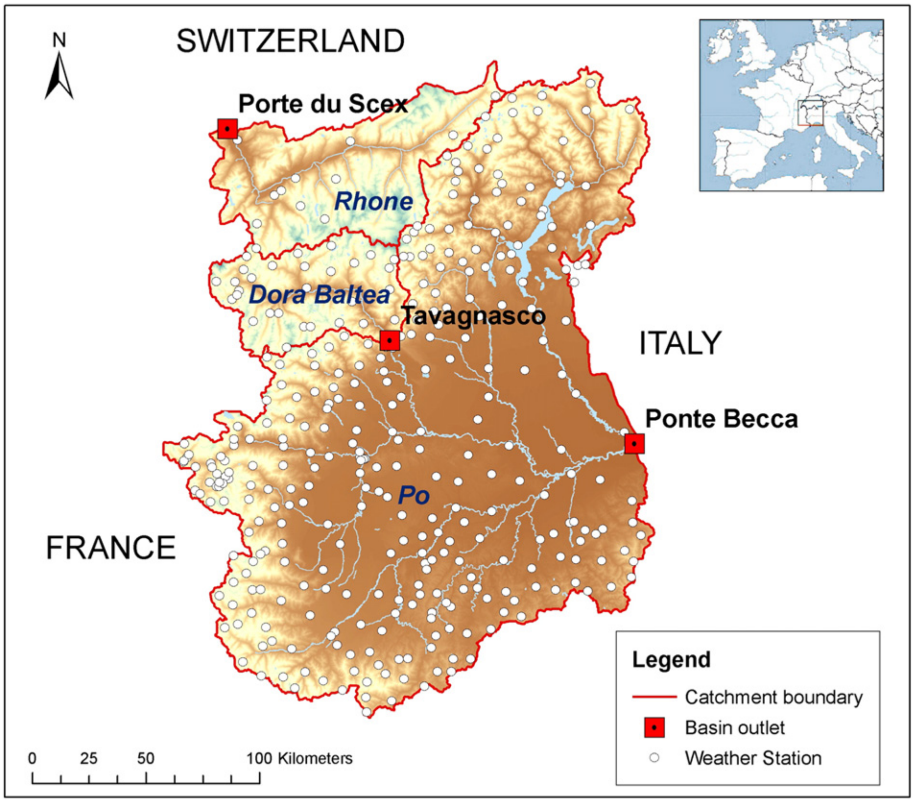

Fig. 1. Study area location in Europe including the catchments and spatial distribution of the 340 weather stations used in this paper.

Fig. 5 highlights the main topographic features of the area, with elevations ranging from 400 m to 5500 m asl.; about 40% of the territory lies above 2500 m asl., because of the presence of the Tien Shan mountains located on the SE of the watershed. Two dominant areas can be observed around 2200 m and 3000 m respectively, corresponding to extensive high elevation plateaux. This point will be of interest for the climate analysis of the remote sensing snow maps. Fig. 6 shows a distribution of slope aspects, mostly consisting of NW-facing orientations, where slope aspect could be a dominant controlling factor of snow patterns.

2.2. Climate data

Mountain topography and atmospheric circulation patterns lead to a high natural variability of climate parameters within the different watersheds, according to their specific orientation. This local variability is related to the global meteorological trends, such as those that exist at the European scale (Jacobeit et al., 2006; Brunetti et al., 2009). As a result of climate change, climate model results suggest that differences between current climate and that of the 1960s include shorter duration and higher elevation for the snow cover and also an annual decrease of the snow mass (i.e., water equivalent) (Marty, 2008; Beniston, 2009, 2012; Magnusson et al., 2010).

Long-term series of meteorological data are provided by the archives of national weather services (Switzerland, Italy, Russia). Automatic and manual snow depth measurements are generally more limited in mountain areas than lowland networks. In our case study, it was possible to retrieve 6 long-term recording stations

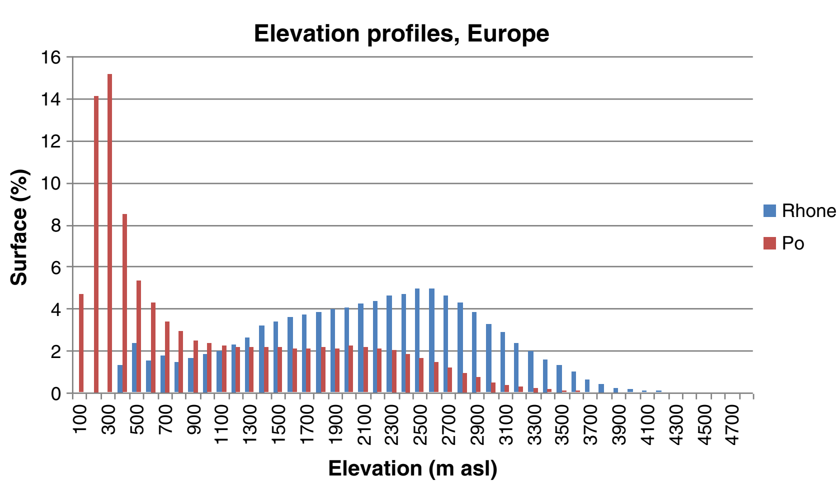

Fig. 2. Elevation profiles for the upper Rhone and Po basins, ranging from 32 m to 3807 m asl.

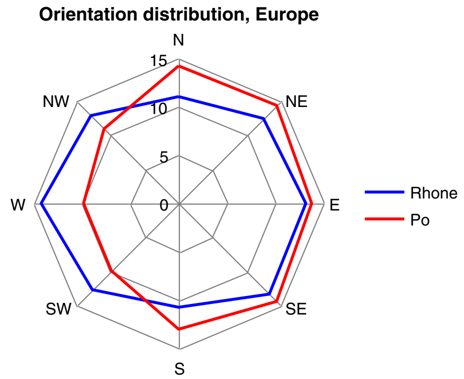

Fig. 3. Orientation distribution (%) for the upper Rhone and Po watersheds.

for the Rhone area (Valais) and 30 sites for the upper Po. Unfortunately such data are not accessible in Central Asia (Kyrgyzstan).

Due to this imbalance and because temperature (T) and precipitation (P) are the principal weather determinants for snow regimes, we decided to limit the study to these two parameters. Moreover, it has been shown that T and P need to be analyzed in a complementary manner, and not separately, in order to achieve a better understanding of the behavior of snow and its occurrence as a function of general atmospheric circulation and weather types (Beniston and Goyette, 2007). Temperature and precipitation parameters will be useful for the statistical analysis of the remote sensing database.

Fig. 7 illustrates the mean monthly temperatures and precipitation measured over the selected river basins during the MODIS 2001–2010 time period. Six measurement sites were used in Switzerland for the upper Rhone, ranging from 381 m to 2472 m asl. (Aigle, Grand St. Bernard, Montana, Visp, Sion, and Zermatt). For the upper Po, a total of 340 stations were used, including 28 measurement sites for the Valle d'Aosta. Concerning Kyrgyzstan, only 4 recording stations were available: Jalal-Abad, Naryn, Toktogul, and Tien Shan, located between 821 m for Toktogul and 3684 m for Tien Shan (Fig. 4).

For the Alps, it is observed that precipitation increases with height, as in the Valle d'Aosta compared to the entire upper Po basin. In contrast, temperatures logically decrease with elevation. Concerning the 2001–2010 time-period, the mean yearly temperature and precipitation for the Po are 9.2 °C and 1030 mm, respectively (average elevation of 925 m asl.). The corresponding figures for the Rhone are 7.6 °C and 593 mm (mean altitude of 2074 m asl.). For Kyrgyzstan, drier conditions representative of the semi-arid climate of Central Asia are observed, with a mean annual temperature of 6.3 °C and 390 mm of precipitation (mean elevation of 2531 m asl.).

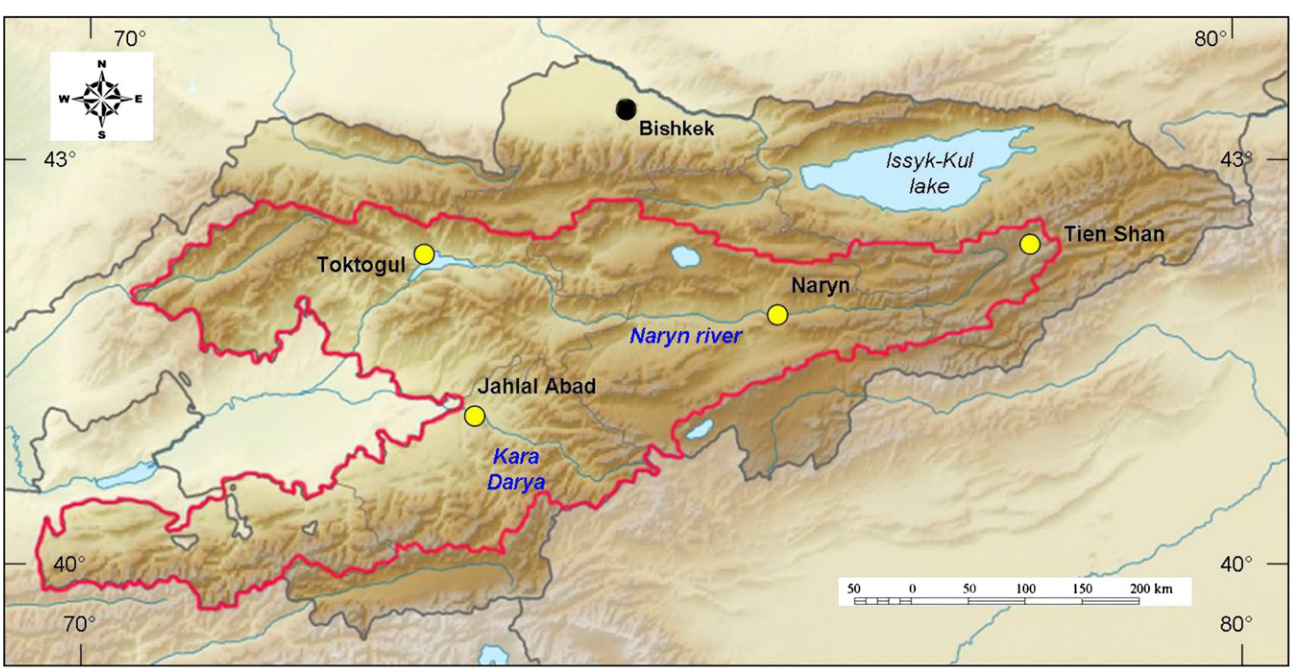

Fig. 4. Kyrgyzstan location map; showing the Syr Darya forming zone and weather stations used in this study. Red line shows the borders of the river basin.

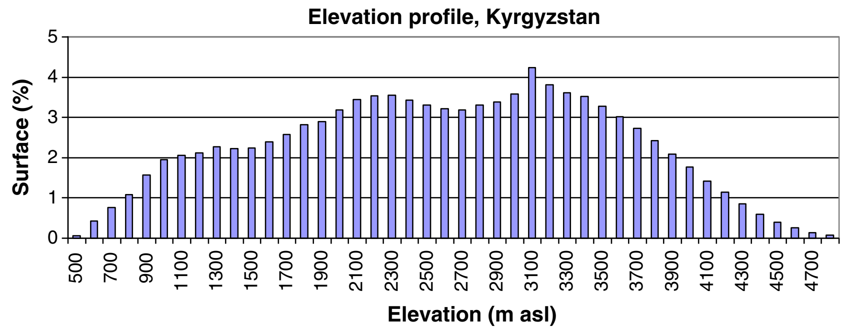

Fig. 5. Elevation profiles for the Syr Darya forming zone (Kyrgyzstan).

3. Remote sensing

Remote sensing provides a unique opportunity to address the question of snow cover regime changes at a regional scale adapted to the local topography of Alpine watersheds. Since the availability of daily optical satellite data at the global scale (NOAA-AVHRR) at end of the 1980s, and at the regional scale (MODIS) since the year 2000, different methods have been developed to compute changes in terms of snow cover area (SCA) expressed in km^2 and snow cover duration (SCD) expressed in days (Chokmani et al., 2005, 2013; Parajka and Blösch, 2006; Flueraru et al., 2007; Foppa et al., 2007; Ertürk et al., 2008; Sirguey et al., 2009; Notarnicola et al., 2013a, 2013b; Zhang et al., 2012; Hüsler et al., 2012, 2013). The main parameters analyzed are the timing and duration of the melting season under current and future climate conditions. Maps and statistics retrieved are useful for hydrology and climate applications.

The objective of this work within the ACQWA project was to elaborate a remote sensing database of snow cover dynamics over a time period of 10 hydrological years (i.e., October 1–September 30 for the period 2000–2010) and to apply such to the three selected watershed: The satellite data were provided by the MODIS Terra MOD-09 images and the MOD-10 snow products (NSIDC).

The results discussed here rely on previous studies already conducted in different regions to reconstruct time series of snow cover at regional scales and to analyze snow regime trends in the context of climate change (Wang and Xie, 2009; Zhang et al., 2012; Dietz et al., 2013). However, the specific added value of this work conducted in the context of the ACQWA project in regard to the existing literature includes: (i) an alternative remote sensed method for the detection of climate trend impact on snow cover dynamics and (ii) scientific results over regions with a crucial lack of information (Kyrgyzstan).

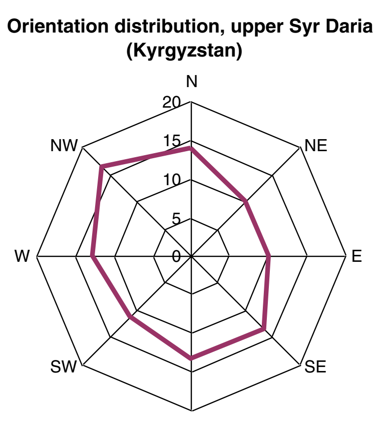

Fig. 6. Orientation distribution (%) for the upper Syr Darya (Kyrgyzstan).

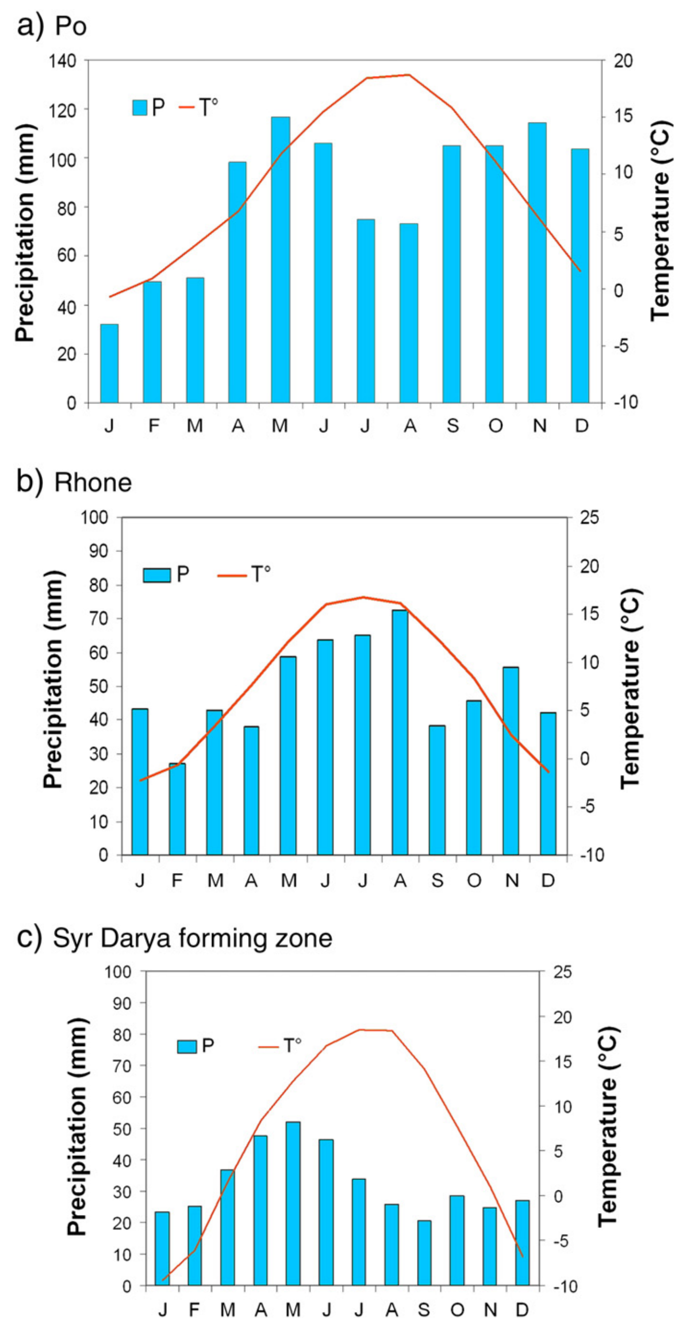

Fig. 7. Monthly average distribution of precipitation and temperature (2001–2010) for: (a) Po, (b) Rhone, and (c) upper Syr Darya watersheds.

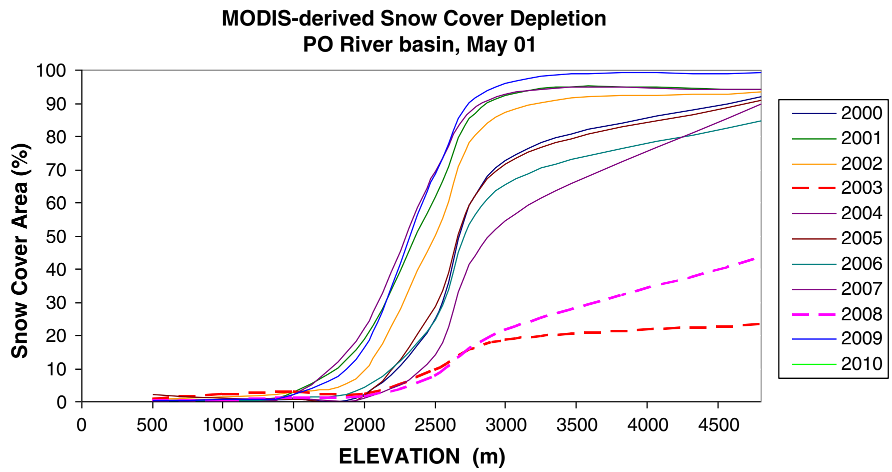

Fig. 8. Yearly snow cover depletion (2000–2010) for the upper Po watershed retrieved from MODIS data on the 1st of May. In dotted line are the snow-scarce winters of 2003 (red) and 2008 (pink). Other years are in solid line.

Concerning the method, the specificity here is based on a particular use of common statistical tools, such as the standard deviation (STD) of the snow cover inter-annual snow cover variability. Maps of standard deviation derived from snow cover duration (SCD) allow the highlighting of sensitive regions where the strong temporal and spatial variability of this duration is indicative of a change in climate trends. The statistical outputs of this study are of interest for watersheds where little or any consistent snow information exists.

3.1. MODIS data

Physical properties of snow retrieved by optical remote sensing is well documented (Rees, 2006; Painter et al., 2009), especially for energy balance or runoff modeling (Seidel and Martinec, 2004; Dozier et al., 2008; Rittger et al., 2013). Numerous applications of the daily MODIS (MODerate-resolution Imaging Spectroradiometer) snow cover products (Hall et al., 2002) have demonstrated their accuracy at a spatial resolution of 500-m spatial resolution with ground-based snow observations and are summarized in Hall and Riggs (2007) and Dietz et al. (2012). The MODIS instrument is implemented on two space-borne platforms, namely Terra (since 1999; equatorial crossing at 10:30 a.m.) and Aqua (since 2002, equatorial crossing at 1:30 p.m.). In this study, only the Terra platform was used because images are acquired early in the morning and are therefore better correlated with a dry snow surface. Furthermore, the cloud cover masks derived from Terra/MODIS database are generally smaller than on the Aqua snow cover products, as indicated by Xie et al. (2009) and Zhang et al. (2012). In addition, the 1.6-micron channel of the Aqua platform, related to the difference between snow and clouds, was unfortunately out of order shortly after launch (unreliable data registration).

3.2. Image processing

The MODIS satellite image database was extracted from the MODIS/NSIDC website archive (http://nsidc.org/index.html) for SCA maps: MOD10_A1 daily product and MOD10_A2 8-day product of maximum snow cover. These input data were complemented with the snow fraction (FRA) calculation where data were loaded from the U.S. MODIS/NASA website (http://modis.gsfc.nasa.gov/) for reflectance images (MOD09_B1 product). Snow percentage at the sub-pixel size is useful for sensitivity analyses of the homogeneity of the snow cover, especially during the melting season, whether it is continuous or not. All data were acquired for pixel sizes of 500 m × 500 m, and the main steps of our methodology can be summarized as (i) the re-projection of all data from sinusoidal to UTM using the SRTM DEM, (ii) radiometric correction of local sun illumination within the DEM (Teillet et al., 1982; Corbari et al., 2009), (iii) snow cover area (SCA) mapping retrieved from the NSIDC classification (Hall et al., 2002), (iv) fractional snow cover mapping

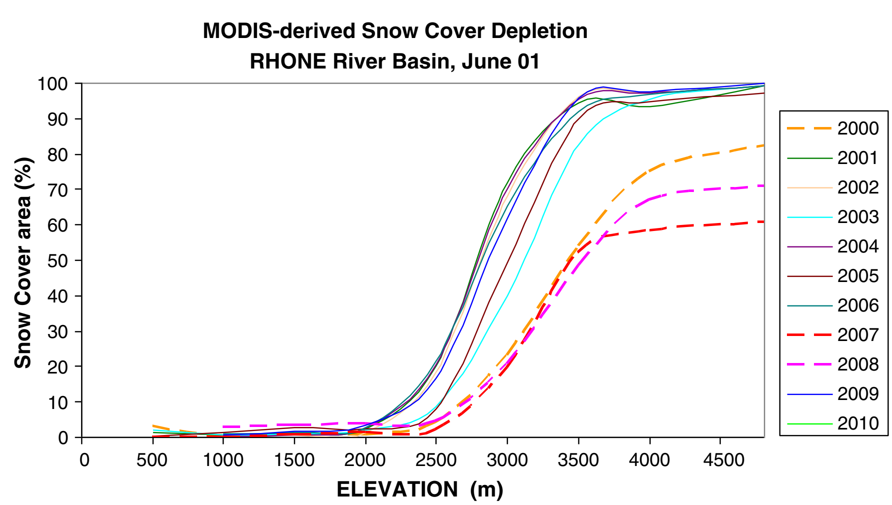

Fig. 9. Yearly snow cover depletion (2000–2010) for the upper Rhone watershed retrieved from MODIS data on the 1st of June. In dotted line are the snow-scarce winters of 2000 (orange), 2007 (pink) and 2008 (red). Other years are in solid line.

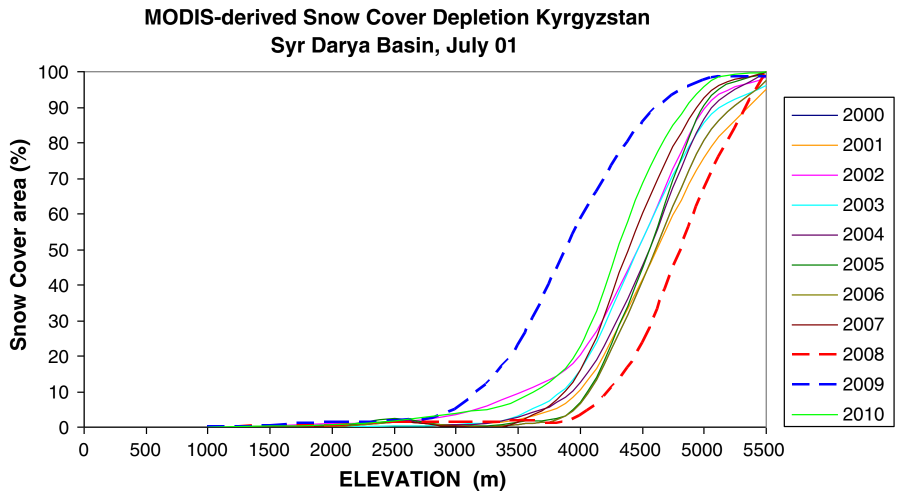

Fig. 10. Yearly snow cover depletion (2000–2010) for the upper Syr Darya watershed retrieved from MODIS data on the 1st of July. In red dotted line is the snow-sparse winter of 2008 (bottom), and in blue dotted line the snow-abundant season of 2009 (top). Other years are in solid line.

derived from the linear regression method of Salomonson and Appel (2006), and finally (v) database compiling of the two output products.

Cloud cover essentially reduces the capability of optical remote sensing for snow cover mapping, especially in the winter season and in mountainous regions (Tong et al., 2009). The MOD10A1 products are not clear of clouds in the current v.5 process (Hall and Riggs, 2007). So, we applied a threshold from the "NDSI" normalized snow ratio index (Dozier, 1989) in the objective to create cloud masks (40% of the complete database), but some misclassifications were still remaining in the lower segments of the watersheds. For this reason, we applied a second cloud filtering by an inverse elevation correlation method, using the SRTM DEM at 90-m scale (http://www.cgiar-csi.org) for the correction of snow classification errors (Derrien et al., 1990; Parajka et al., 2010). In this manner, lowland clouds (fog), misclassified as "snow" by the automatic NSIDC process, were removed from the snow cover maps that mainly occurred on the large Po valley images. This spatial filter reduces the cloud coverage by about 10% in the MODIS "NDSI" output products.

Following this step, a forest mask from the Globcover 2009 Land-use Classification (http://due.esrin.esa.int/globcover/) was applied to the complete database to avoid problems of non-continuous snow cover under densely-forested areas where snow cover less than 30% cannot be detected (Klein et al., 1998; Abbott and Kahn, 2009).

The final output products are (i) daily snow cover area (SCA) maps, defined as the number of pixels classified as "snow" in the watershed and (ii) snow cover duration maps (SCD), defined for each pixel of the watershed as the number of days with snow cover throughout the year.

4. Results and discussion

4.1. Snow versus topography

Mapping the duration and variability of snow cover can help identify regions with highly variable conditions, due to both shifts in climatic conditions and local topographic conditions. In mountain areas, the main control on snow duration is the elevation of the terrain. There is a clear altitudinal dependency of snow cover added to the basin orientation behavior (i.e., NW versus SE). Figs. 8, 9 and 10 show that during the melting season, a clear relationship can be observed between topography and snow cover for the three watersheds, resulting from the temperature gradient. Table 2 indicates the snowmelt season for each basin. Snowmelt is here considered as the last day of a pixel classified as "snow", before its disappearance until the onset of the next snow season. Obviously, the snow cover melting date will occur earlier in lowlands (Feb–March) than for the higher territories (June–July).

Table 2
Snowmelt period of the selected river basins and mean snow depletion rate for the 2000–2010 time period.

Watershed	Time period	Days	Surface loss (%/day)
Upper Po	March 1st–July 31st	~150	0.66
Upper Syr Darya	April 1st–July 31st	~120	0.81
Upper Rhone	April 1st–July 31st	~120	0.74

Snow melting rate was calculated over the snow melting periods defined in Table 2 as percentage decrease per day of the extent of basin occupied by snow.

The duration and rate of snow melting were derived from all the SCA maps versus the DEM and using altitudinal bands (Tong et al., 2009). During the melting season snow depletion is respectively of 0.3% per day (16 km^2) of surface loss for the upper Rhone catchment, 0.4%/day (450 km^2) for the Syr Darya headwater basins, and 0.6%/day (227 km^2) for the upper Po. The value is higher for the Po, due to the lower mean elevation of the watershed and its larger surface of lowlands compared to the two other catchments.

Following this, the snow melting start-dates versus elevation class retrieved from the DEM have been calculated for each year and summarized to retrieve a mean timing value: this yields May 1 for the Po, June 1 for the Rhone and July 1 for upper Syr Darya.

Particularly interesting are the warm winters of 2000, 2003, 2007 and 2008 with snow-sparse conditions in Europe, and 2007 in Central Asia (dotted lines). A snow cover reduction is observed from 30% (Rhone) to 50% (Po). These specific years may foreshadow a more common situation in the near future, in case of climate change persistence, and could be used as examples for long term changes (i.e. years 2003 and 2008 for the Po).

In contrast, the cold winter of 2009 in Central Asia is clearly visible with snow-abundant conditions (blue dotted line). Temperature gradients and precipitation both seem to exert a more important impact on snowpack variability at low- or mid-altitudes, e.g., between 1500 and 2000 m than above, as shown by Moran-Tedeja et al. (2013).

4.2. Snow maps and deviation

Annual snow cover duration (SCD) was calculated as the number of snow covered days (*Nsnow*) throughout the year by using the following

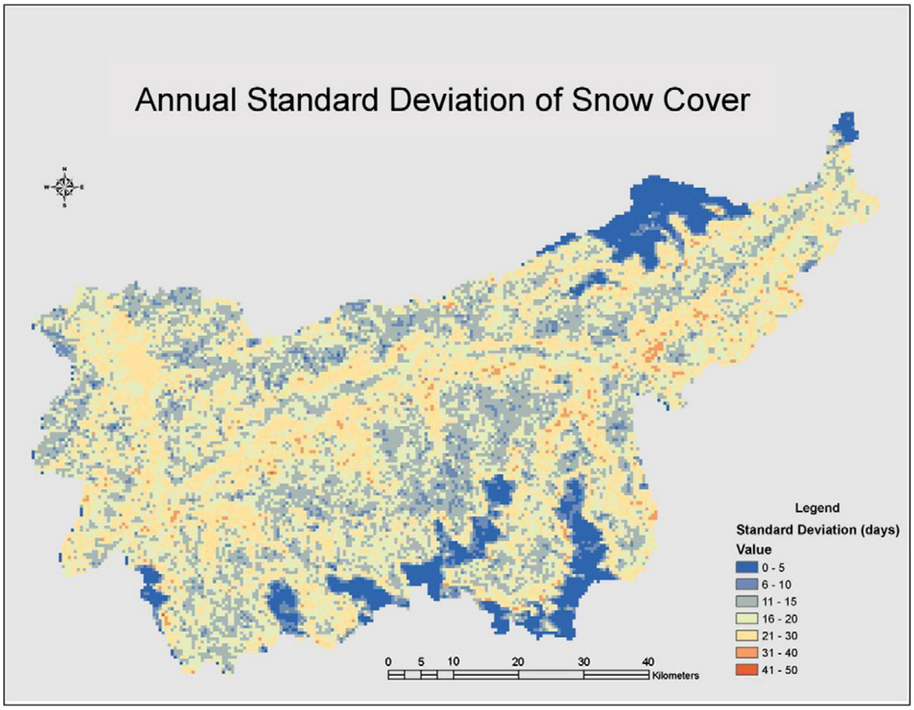

Fig. 11. Annual standard deviation of snow cover (days) for the period 2000–2010, for the upper Rhone watershed. In blue are the glaciated areas with regular snow regime.

relation:

$$Nsnow = \frac{Nsnow_{Modis}}{Nsnow_{Modis} + Nosnow_{Modis}} \times 365 \text{ days}$$

where $Nsnow_{modis}$ is the number of the snowy day through the year and $Nosnow_{modis}$ is the number of the days without snow through the considered year (365 days).

Then, the standard deviation (STD) of the annual mean value of snow cover was computed for the complete time-period 2000–2010 and retrieved into maps for each watershed, as presented in Figs. 11 to 13.

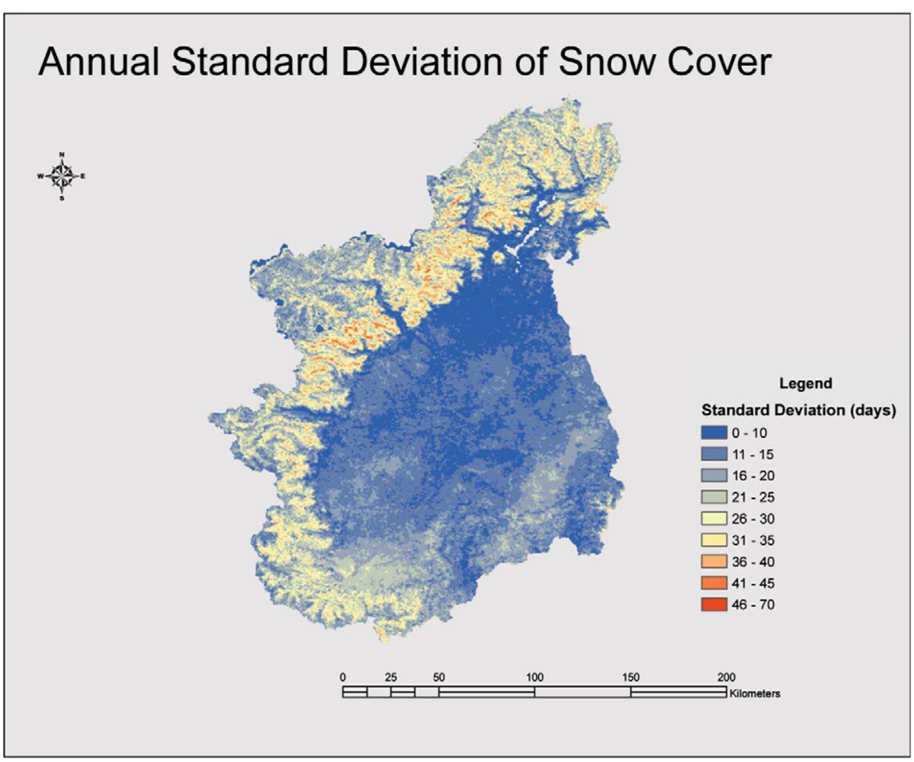

Fig. 12. Annual standard deviation of snow cover (days) for the period 2000–2010, for the upper Po watershed. In red are the foothills of Piedmont with non-inter-annual regular snow regime.

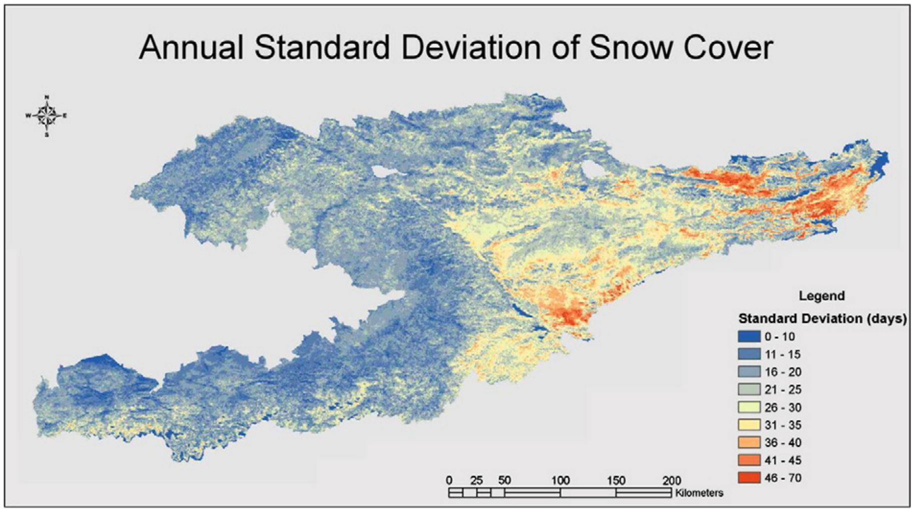

Fig. 13. Annual standard deviation of snow cover (days) for the period 2000–2010, for the upper Syr Darya river basin (Kyrgyzstan). In red are the high plateaux of Tien Shan area (east part of the watershed) and Alabuga area (south part), with non-inter-annual regular snow regime.

The red areas correspond to a high variability of snow cover duration with more than 40 days of variation from the mean snow cover value. As a reminder, if the number of days is more than 1 STD above the mean frequency, then the year is snow-sparse with a strong decline in snow duration. On the contrary, if the STD is less than the average value, then the winter can be considered to be snow-abundant. These trends were analyzed by Beniston et al. (2010) in Switzerland by assessing the influence of weather types on snow behavior.

In this present study, it is observed for the Rhone that there are few deviations from the average values, globally no more than 40 days of deviation. The glaciated areas (above 3000 m) remain constant over

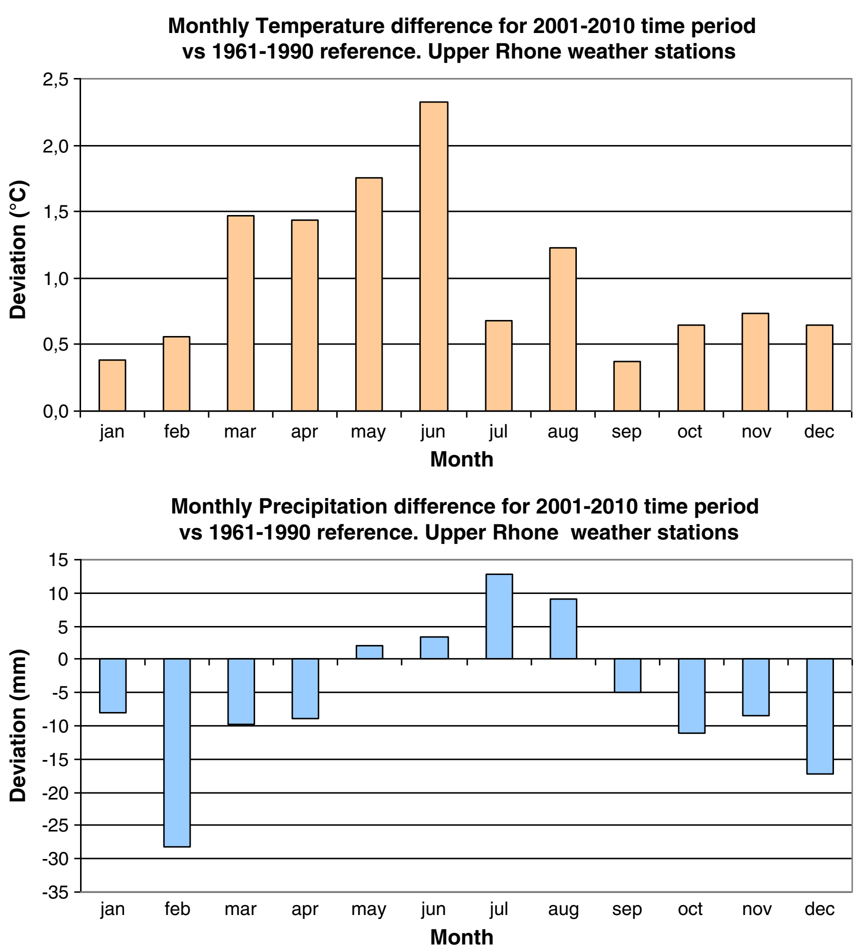

Fig. 14. Monthly deviations of temperature and precipitation for the upper Rhone river basin: 2001–2010 versus the 1961–1900 baseline.

ten hydrological years (5 days and less of deviation) whatever their orientation (e.g., the south-facing Aletsch Glacier, or the north-facing Arolla Glacier). The snow cover of this area seems to be consistent over the entire period. For the Po basin, it is observed that the foothill range of Piedmont presents more than 40 days of deviation in different parts of the region, in particular from Locana to Cuorgné, Biella to Coggiola, and Verbania (on Lake Maggiore).

These deviations are linked to more to snow-scarce winters than to snow-abundant winters. All local regions are located between 1000 and 1500 m asl. Moreover, the inter-annual anomalies with non-regular snow regimes are observed more in areas with a S or SE orientation (upper part of the foothills), than those with a NE orientation located in the southern part of the hill range (see Fig. 12). As for the Rhone, snow cover over the glaciated areas (Mt Blanc, Mt Rose) is consistent for the entire 2000–2010 time period. High elevation and dominant cold conditions over the full year can explain the persistence of snow cover in these regions.

In Kyrgyzstan, two regions, with elevations around 3000 m asl., can be identified with more than 40 days of deviation, mainly in the form of snow-sparse winters: (1) the southern part of the basin with the upper Alabuga plateau, above the Chatyr-Kul Lake, close to the Chinese border; and (2) two eastern plateaux (Tien Shan) located to the north-west of the towns of Enilchek and Kara-Say. From the Globcover land-use map, these areas are all classified as sparsely vegetated (<15%), mainly grassland, and are in addition included in the inventory of territories that experience seasonal permafrost (Bolch and Marchenko, 2006; Marchenko et al., 2007).

4.3. Climate

As mentioned above, the Rhone and Po catchments are well documented in terms of past climate studies, such as the HistAlp database (Auer et al., 2007), but little information is available concerning past and current climate trends in Central Asia, particularly for the Tien Shan region.

We now try to understand the deviation observed in the preceding section for the Po (Europe) and Kyrgyzstan (Central Asia) and to put forth a hypothesis for relating these deviations to climate trends. Although the time series of 10 years of data is too short to calculate robust trends of snow-cover characteristics, the results can be used to describe the average snow-cover conditions and compare single years with these values. As seen in Figs. 8, 9 and 10, snow-sparse winters in the observed record include 2003, 2007 and 2008 for the Po, 2007 and 2008 for the Rhone, and 2007 for Kyrgyzstan with an increase in the altitude of the snow-line, ranging from 100 m to 150 m depending on the watershed. These observations can be linked to the climate trends during the period, as shown in the following.

Figs. 14, 15 and 16 describe the deviation between the 10-year MODIS time period relative to the 1961–1990 baseline for mean monthly temperature and precipitation for the Rhone, the Po and Kyrgyzstan, respectively. Input data were provided by the same weather stations network as for Fig. 7. Anomalies were calculated by subtracting the current time average data from the 1961–1990 baseline values. For Europe, the winter months (December, January, and February, or DJF) show that for the Rhone, temperatures increase by +0.53 °C and

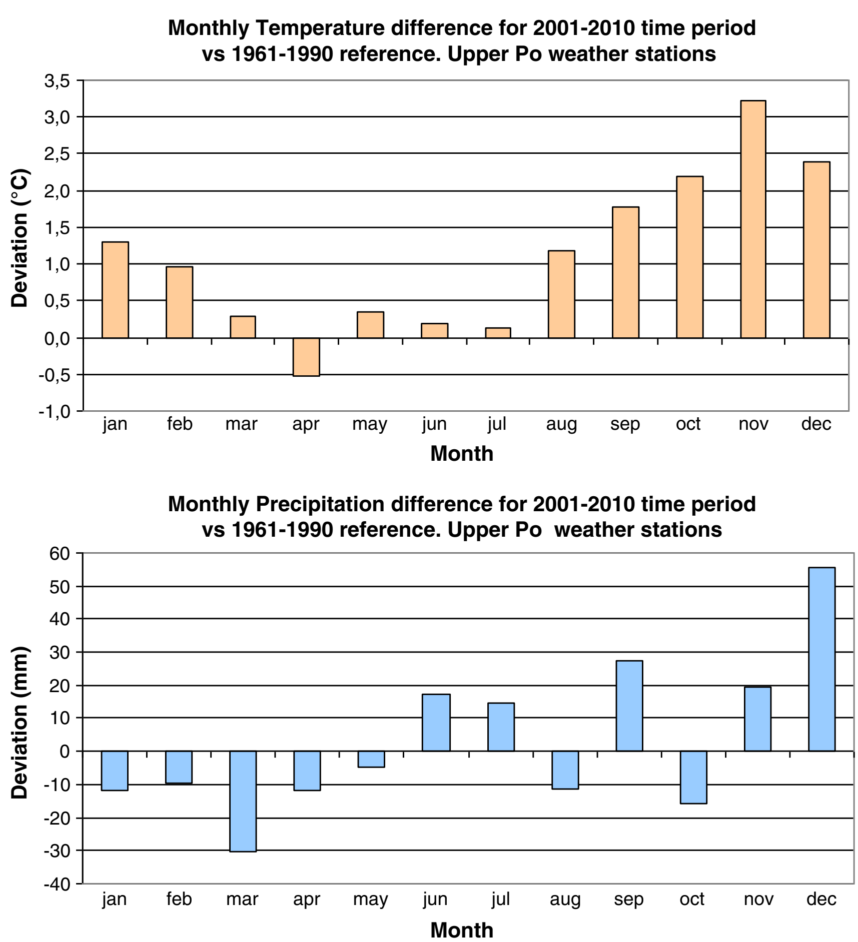

Fig. 15. Monthly deviations of temperature and precipitation for the upper Po river basin: 2001–2010 versus the 1961–1900 baseline.

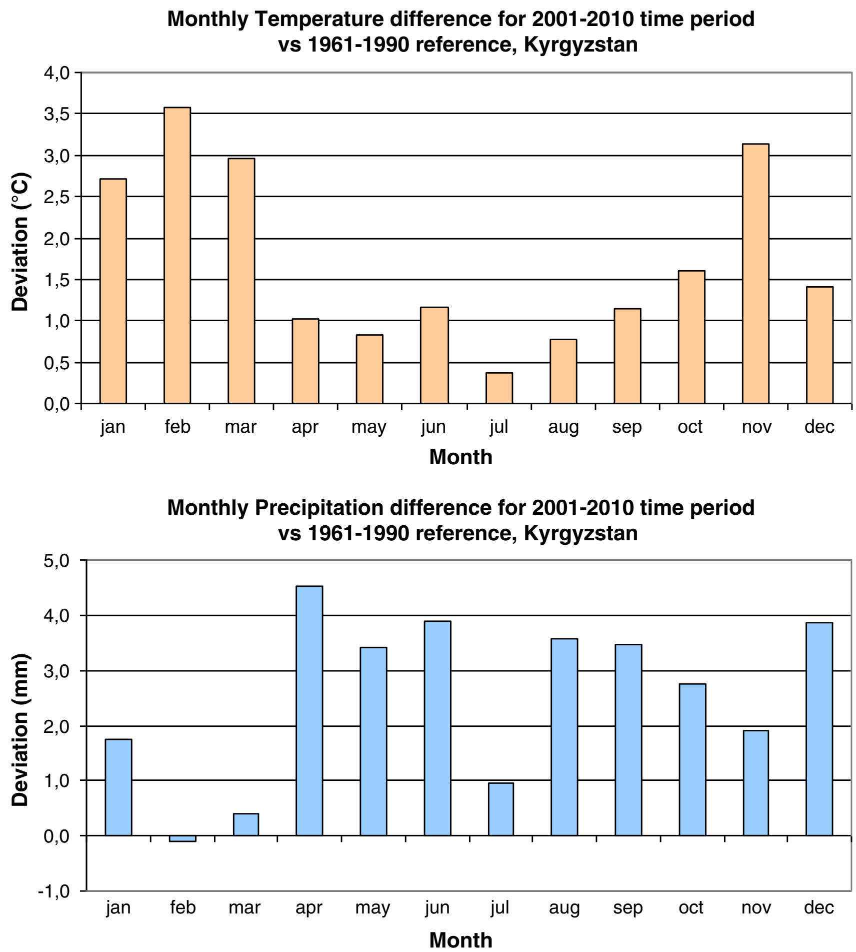

Fig. 16. Monthly deviations of temperature and precipitation for the upper Syr Darya river basin: 2001–2010 versus the 1961–1900 baseline.

precipitation slightly declines by −17.81 mm, with respect to the 1961–1990 baseline. For the Po, a temperature rise of +1.54 °C and an increase in precipitation by +6.44 mm are observed for DJF. Moreover, the summer-time months (June, July, and August, or JJA) exhibit a global average temperature increase compared to the baseline of +1.41 °C for the Rhone and +2.64 °C for the Po, and precipitation increases by +8.39 mm and +20.43 mm, respectively. Temperature increases are also observed in spring and summer, while precipitation has declined in winter.

In central Asia, ΔT of +2.56 °C and ΔP of +1.83 mm for the winter months are observed. The summer months (JJA) exhibit +0.77 °C and +2.81 mm of deviation with respect to the 1961–1990 reference period. Precipitation is quite stable, but temperatures show an increasing trend in winter, that helps to explain the snow cover reduction shown in Fig. 13.

Table 3 summarizes the annual ΔT and ΔP measured between the two time periods. It is seen that the yearly temperatures have increased by more than 1 °C in the 10 years of the record, both in Europe and in Central Asia. The seasonal maximum of temperature deviation is observed in spring for the Rhone, in fall for the Po, and both in winter and fall for Kyrgyzstan (Figs. 14, 15 and 16). Precipitation changes are less marked here, with slight decreases in the Rhone (−23 mm), and small increases in Kyrgyzstan (+30 mm) and in the Po river basin (+38.59 mm). Seasonal behavior shows a precipitation decrease in winter and fall for the Rhone, no significant trend for the Po, and a general precipitation increase throughout the year for Kyrgyzstan (Figs. 14, 15 and 16).

Table 3
Mean deviation (year) of temperature and precipitation for the 2001–2010 time period compared to the 1961–1990 baseline for the three watersheds.

	ΔT°	ΔP_{mm}
Upper Rhone	+1.02	−23.14
Upper Po	+1.12	+38.59
Syr Darya (Kyrgyzstan)	+1.73	+30.38

It is possible to relate these remote sensing snow outputs to the general atmospheric circulation trends at the synoptic scale. In Europe, the North Atlantic Oscillation (NAO) can have a strong influence on the winter snow regime (Hurrell, 1995; Hansen-Bauer and Forland, 2000). A positive index of the NAO can in some instances generate snow-sparse winters over southern Europe, including the Po basin, because of warm temperatures at most elevations. On the contrary, a negative mode of the NAO may generate snow-abundant winters over these regions. Switzerland and the continental Alps such as Austria are more located at a "pivot" situation with respect to these oscillations (Beniston, 1997; Schöner et al., 2009), with some instances of little significant correlations between a given mode of the NAO and the behavior of the winter snow-pack. This may explain why the upper Rhone exhibits few STD days for the decade 2000–2010.

Concerning Kyrgyzstan, the analysis is more complex, because one needs to take into account the lack of consistent information. However, recent shifts in climatic regimes in the Tien Shan seem to be linked to changes in the dynamics of the westerly jet stream (Aizen et al., 1997; Kuzmichenok, 2009).

4.4. Permafrost

In our case study, soils are probably closer to seasonal freeze cycles in winter season than real permafrost. Concerning Kyrgyzstan, trend analyses of weather stations located in northern Tien Shan show a pronounced temperature increase that has become obvious since the 1990s, mainly due to the temperature rise in winter temperatures (Bolch and Marchenko, 2006). Permafrost temperature measurements also indicate that permafrost has been warming and thawing in the recent years, with a measured degradation of extension and thickness (Marchenko et al., 2007). It is possible that the deviation (STD) of the snow duration (SCD) coupled with the positive winter temperatures could both be a proxy that indicates areas of potential frozen soils ("permafrost") degradation. Due to a lack of effective ground validation in this region at the present time, the assessment still remains hypothetical, however.

5. Conclusions

The heterogeneous spatial distribution of snow cover in mountain regions is driven both by the meteorological inter-annual variability of weather (especially temperature and precipitation) and by the local topography conditions (elevation, orientation and slope). In this study we show the improvement of snow cover mapping through the use of optical remote sensing data (Rabuffetti et al., 2006). Three mountain case studies are discussed here, with differences in surface and meteorological characteristics. The obtained results all point in the same direction. Concerning topography, elevation is one of the dominant factors controlling snow cover distribution (SCA) and duration (SCD) in Europe as well as in Central Asia. The MODIS 10-year time period suggests that the standard deviation (STD) of snow duration (days) can be compared to changes in temperature and precipitation for the same time period with respect to the 1961–1990 baseline. Maps of STD highlight the local areas where the maximum of STD occurs during the decade and can be mainly attributed to winters experiencing scarcity of snow. These regions include mid-elevation foothills (1500 m asl., SE facing) for Europe and high plateaux (3000 m) with probable permafrost decline in Kyrgyzstan. Scenarios of future climate, such as those developed by the ENSEMBLES project (www.ensembles-eu.org) for Europe, indicate that the current observed changes of the Alpine snow-pack will amplify throughout this century; indeed, snow could disappear in these sensitive regions (Christensen et al., 2007; Beniston, 2009, 2012).

Acknowledgments

This study was carried out with the support of the EU/FP7 ACQWA project "Assessing Climate impacts on the Quantity and quality of WAter" (Grant agreement no. 212250). MODIS images were provided by the NSIDC (Boulder, Co, USA) online database (http://nsidc.org/). Meteorological data were provided by the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss), by Arpa Piemonte and by Arpa Valle d'Aosta from Italy. Meteorological data of Kyrgyzstan were provided by Annina Sorg (University of Geneva). We are grateful to G. Giuliani from the University of Geneva and UNEP-GRID for his management of the ACQWA Data Warehouse. We thank the anonymous referees for their helpful comments and suggestions. A final thanks to the LTHE trainee engineers (A. Boos and V. Doutreleau) for their technical help.

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