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Long-term analysis of snow-covered area in the Moroccan High-Atlas through remote sensing

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ABSTRACT

The High-Atlas mountainous region in Morocco is a true water tower for the neighbouring arid plains, where the water resources are intensively and increasingly subjected to exploitation for agriculture and tourism. In order to manage this resource sustainably, it is necessary to describe accurately all the processes that contribute to the hydrological cycle of the area, and, in particular, to know the respective contributions of liquid and solid precipitations to runoff. In this context, a seven-year time series of SPOT-VEGETATION images is used for mapping snow-covered areas. The spatial and temporal variations of the snow cover are analyzed for the entire High-Atlas region as well as by altitudinal zones. The spatial distribution of snow-covered areas appears logically controlled by elevation, and its temporal fluctuations can be clearly used to identify dry and wet seasons. In addition, a possible control of snowfalls by the Northern Atlantic climate variability, and, in particular, the North Atlantic Oscillation, is highlighted. Finally, this study shows how satellite remote sensing can be useful for the long-term observation of the intra- and inter-annual variability of snowpacks in rather inaccessible regions where the network of meteorological stations is deficient.

1. Introduction

Snowfall and snowmelt are fundamental processes of the hydrological cycle. The space–time dynamic of snowpacks is an indicator of the climatic change (Bloschl, 1999). Its knowledge is necessary for hydrological modelling (Liston, 1999).

In arid and semi-arid regions, mountainous areas are important water sources, not only for upland regions, but also for adjacent lowlands where rivers supply water for irrigation, industrial or other water uses. In some Mediterranean regions, an important percentage of the available water is accumulated in the form of snow before the melting season. In Lebanon, for example, water from snowmelt contributes roughly to two-thirds of the annual volume of water supplies (Shaban et al., 2004). In the surrounding of High-Atlas mountains in Morocco, the irregular nature of precipitations, combined with a high evaporation rate, makes the monitoring and management of water resources difficult (World Bank, 1995). Consequently, it is important to thoroughly understand the processes and variables which control the hydrological cycle in these areas. In particular, previous studies show the importance of the contribution of snowmelt to the stream flows for the main wadis in the region (Abidi, 1989; Schulz and De Jong, 2004; Chaponnière et al., 2005, 2008; Boulet et al., 2008). In this context and within the framework of the SudMed project (Chehbouni et al., 2008), we investigate the possibility of using remote sensing data to quantify the spatial and temporal dynamics of snow-covered areas (SCA) in the Moroccan High-Atlas mountainous region.

Satellite imagery provided by low spatial resolution sensors is a tool specifically adapted to regional studies. It allows the acquisition of observations regularly distributed in time and space (NOAA-AVHRR since 1980, TERRA-MODIS and SPOT-VEGETATION since the late 1990s). The optical domain of the electromagnetic spectrum is well suited for the identification of SCA because the optical properties of snow are very specific. Snow and ice are characterized by a high reflectance in the visible and near infra-red parts of the electromagnetic spectrum, and a high absorption in the middle infra-red part. These properties have allowed the mapping of SCA from various optical sensors (Rosenthal and Dozier, 1996; Simpson et al., 1998; Salomonson and Appel, 2004; Chaponnière

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et al., 2005). Monitoring the dynamics of SCA requires high frequency data coverage such as those coming from large field-of-view sensors, which allow almost daily observation of the Earth. This is the case of the SPOT-VEGETATION observations used here.

The main question addressed in this research is how long time series of satellite observations can be used for the reconstruction of the intra- and inter-annual variability of snow-covered areas in mountainous semi-arid regions? To address this question, we used a seven-year archive (1998–2005) of SPOT-VEGETATION data acquired over the High-Atlas region. After describing the study area, we present the methodology used to monitor SCA from SPOT-VEGETATION images. The space–time variability of the snow extent is studied at the scale of the High-Atlas, both globally and by altitudinal zones. A first attempt to link the inter-annual variability of SCA with the Northern Atlantic Oscillation is finally presented.

2. Materials and methods

2.1. Study area

The High-Atlas is a Moroccan mountainous chain of approximately 60 km in width and 800 km in length organized along a NE–SW axis. It culminates at an altitude of 4167 m at the Jbel Toubkal, the highest summit of North Africa (Fig. 1). The vegetation is generally sparse and is growing mainly at the bottom of the valleys. This makes easier the identification of snowy areas.

The study area is located several ten kilometres at the southeast of the Marrakech city (Fig. 1), between latitudes 30°52′12″ and 31°39′36″ North, longitudes 7°13′12″ and 8°40′12″ West, and at altitudes higher than 1000 m. This is the central part of the Moroccan High-Atlas, which is the water tower for the arid plains of the Haouz in the north and of the Souss in the southwest, as well as the valleys of Drâa and Dadès in the southeast. For the 1989–2007 period, the annual average precipitation is 610 mm in the Oukaimden CAF station at 2650 m altitude, whereas it is only 200 mm at the Marrakech station in the plain (elevation of 450 m). The proportion of precipitations that falls as snow is significant: at the CAF station, rainfall and snowfall are around 240 and 370 mm, respectively.

2.2. SPOT-VEGETATION data

The VEGETATION sensors, launched onboard the SPOT-4 and -5 satellites, include an imaging system in four spectral bands from the blue (~0.45 μm) to the middle infra-red (~1.67 μm). The field-of-view is 0–55° on both sides of the satellite tracking path, allowing the acquisition of data on a swath of approximately 2200 km. The pixel size is 1.15 km × 1.15 km at nadir. The SPOT satellites follow a polar heliosynchronous orbit at an altitude of approximately 830 km. Their period of revolution is 101 min and their orbital repeat cycle is 26 days. These technical characteristics allow the VEGETATION instrument to see the High-Atlas region almost each day.

In this study we used the SPOT-VEGETATION P product ("Primary Product", see Maisongrande et al., 2004), which includes data as seen by the sensor at each orbit pass. The recorded radiations are calibrated and standardized from incident light energy. The digital counts represent the apparent reflectance at the top of the atmosphere. The images are corrected for geometrical effects and presented in a geographical projection where each pixel corresponds to a square with a side measuring 1/112°.

More information on the data and their pre-processing is available in Duchemin and Maisongrande (2002), Maisongrande

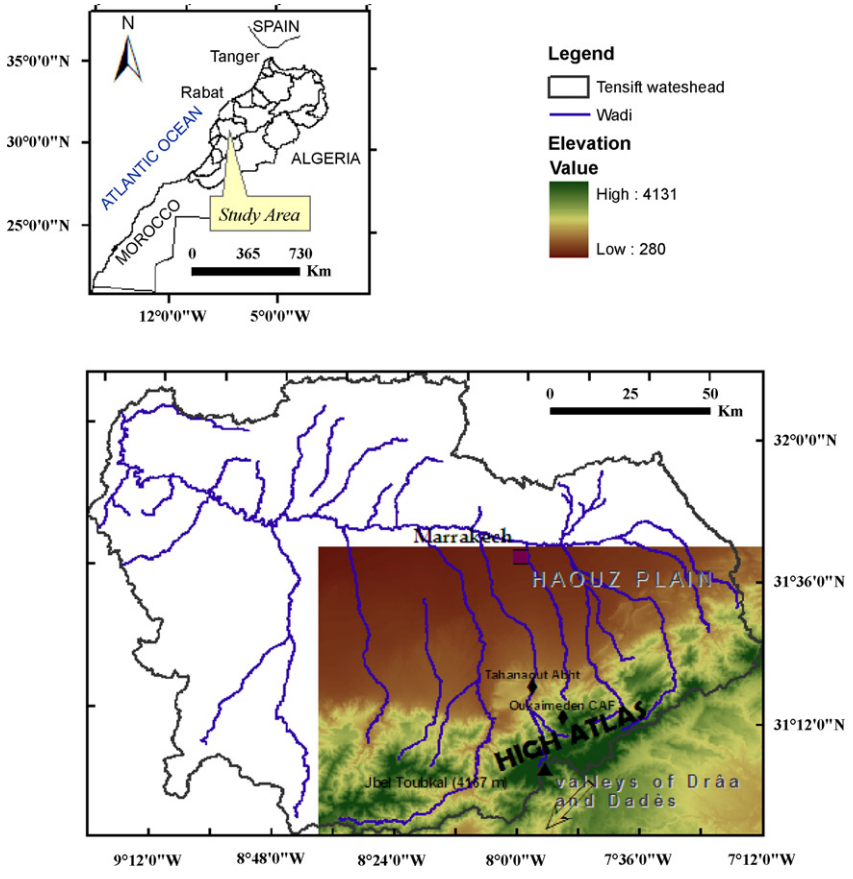

Fig. 1. Location and topography of the study area.

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et al. (2004) and Hagolle et al. (2005), as well as the following website: www.spot-vegetation.com, www.vegetation.cnes.fr, and www.spotimage.fr.

2.3. Selection of cloud-free images

The archive of SPOT-VEGETATION P products covers the hydrological years between 1998–1999 and 2004–2005 from September 1 to June 30, which means approximately 300 images per season. For the study area, the size of the images is 191 lines by 280 columns (~53,000 km^2).

The remarkably irregular relief of the High-Atlas Mountains causes difficulties in the interpretation of the images acquired with large viewing angles. We have therefore only kept images acquired with a view zenith angle less than 23°. This leads to selection of 8 images every 26 days and limits both geometrical (change in the observed surfaces depending on exposures and slopes) and directional (change in reflectances according to the sun-target-sensor geometry) effects.

To select cloud-free data, we initially eliminated the images showing high reflectances over the lower-lying areas close to High-Atlas mountains. A threshold of 20% was applied after averaging blue reflectances on approximately 5000 pixels snow-free, i.e. 10% of the study area with altitude lower than 1000 m. High reflectances are due the presence of clouds on the Atlas foothills, and therefore, almost certainly, on the Atlas mountains as well. In a second phase, we performed a visual examination to identify partial or thin clouds on the remaining images.

The number of images retained after passing through the two phases of selection is 36, 34, 23, 24, 35, 37 and 34 for years 1998–1999, 1999–2000, 2000–2001, 2001–2002, 2002–2003, 2003–2004 and 2004–2005, respectively. The number of useful observations is, on average, the equivalent of 1 image every week, albeit strong disparities regarding their temporal distribution.

2.4. Estimate of snow-covered areas

The calculation of the snow-covered areas is based on a Snow Index (SI, Eq. (1)) which uses reflectances from the blue (B_0), red (B_2) and medium infra-red (MIR) channels of the VEGETATION sensor (Lissens et al., 2000). This index has been retained following a comparison of several other algorithms over the Moroccan High-Atlas (Hanich et al., 2003; De Solan et al., 2002). It was subsequently improved to reduce the influence of the variations of the spectral signature of the ground through the calculation of a Modified Snow Index (MSI, Eq. (2), after Chaponnière et al., 2005). The MSI limits this influence using the snow indices of totally snow-free surfaces (SI_0, computed, for each pixel, from images acquired in summer) and of pixels totally covered with snow (SI_{100}, one single value computed as the maximum of SI on images acquired during winter).

$$SI = \frac{B_0 + B_2}{2} - MIR \quad (1)$$

$$MSI = SI - SI_0 \frac{SI_{100} - SI}{SI_{100} - SI_0} \quad (2)$$

The area covered with snow (S_{HOR}, Eq. (3)) in each pixel was calculated by applying the exponential relationship established by Chaponnière et al. (2005) after combining the analysis of SPOT-VEGETATION data with high-resolution spatial (Landsat-TM) images. The factor 0.84 in Eq. (3) converts the area in km^2; without this correction, Eq. (3) provides the relative percentage of the surface covered by snow in each pixel, expressed between 0 and 1.

$$S_{HOR} = 0.84\left[1 - 0.49\exp\left(-0.69\frac{MSI}{100}\right) + 1\right]^{20} \quad (3)$$

2.5. Topographic correction

To approximate the actual extent of snow-covered areas, we performed an additional correction using a digital elevation model (DEM) to account for the slopes in the calculation of the snow-covered areas (Eq. (4)). The DEM came from the radar interferometry data gathered during the 10 day mission of the Endeavour Space Shuttle (freely available at http://seamless.usgs.gov/Website/Seamless/, with a spatial resolution of 90 m). The correction was made using a mean slope, degraded from 90 m to the resolution of SPOT-VEGETATION data by simple averaging. The DEM was also used to partition the study area into 400 m elevation zones from 1000 to 4200 m.

$$S = \frac{S_{HOR}}{\cos(\text{mountain slope})} \quad (4)$$

where S is the actual snow-covered area.

3. Results and discussion

3.1. Spatio-temporal variability of snow-covered areas

Fig. 2 shows an example of three VEGETATION images acquired during winter 2005 and the resulting snow maps obtained after the application of Eq. (3). Snow-covered areas are clearly identifiable in the VEGETATION images (in blue in Fig. 2a–c). (For interpretation of the references to colour in this text, the reader is referred to the web version of this article.) Snow-covered area increases considerably from February 22 to March 6, 2005 after a snowfall event and decreases thereafter until March 21 during a snowmelt period (Fig. 2d–f). The spatial distribution appears from a first analysis to be primarily controlled by elevation (see the DEM in Fig. 1).

Fig. 3 shows the seasonal variations of the SCA accumulated over the whole study area for hydrological seasons 1998–1999 to 2004–2005. The episodes of snowfall are marked by peaks of snow-covered areas, whereas melting periods are generally characterized by a very important reduction of SCA (e.g. a decrease from 2600 to 350 km^2 from January 17 to 27, 2003). Table 1 summarizes the main features of the snow cover from the satellite observations. These results highlight the strong seasonal and inter-annual variability of snowpacks in the region:

- The presence of snow is always detected in winter, but over markedly variable areas, with a maximum of snow-covered surfaces of 1750 km^2 for the season 1999–2000 against more than 4600 km^2 for the season 2005–2006.
- The number of snowfall episodes detected each season varies between one (1999–2000) and five (2002–2003 and 2004–2005); the melting periods are dominant, including in the very midst of the winter season.
- The period separating the first from the last snowfall (peaks of snow-covered surfaces) is also quite variable; the first snowfalls are observed between the end of September (1998–1999) and the end of December (2000–2001), while the last snowfalls are recorded between the end of January (2000–2001) and the beginning of April (2003–2004).

From these facts, we can also make a distinction between two groups of seasons: three wet winters (1998–1999, 2003–2004 and 2004–2005), marked by a seasonal average snow coverage of about

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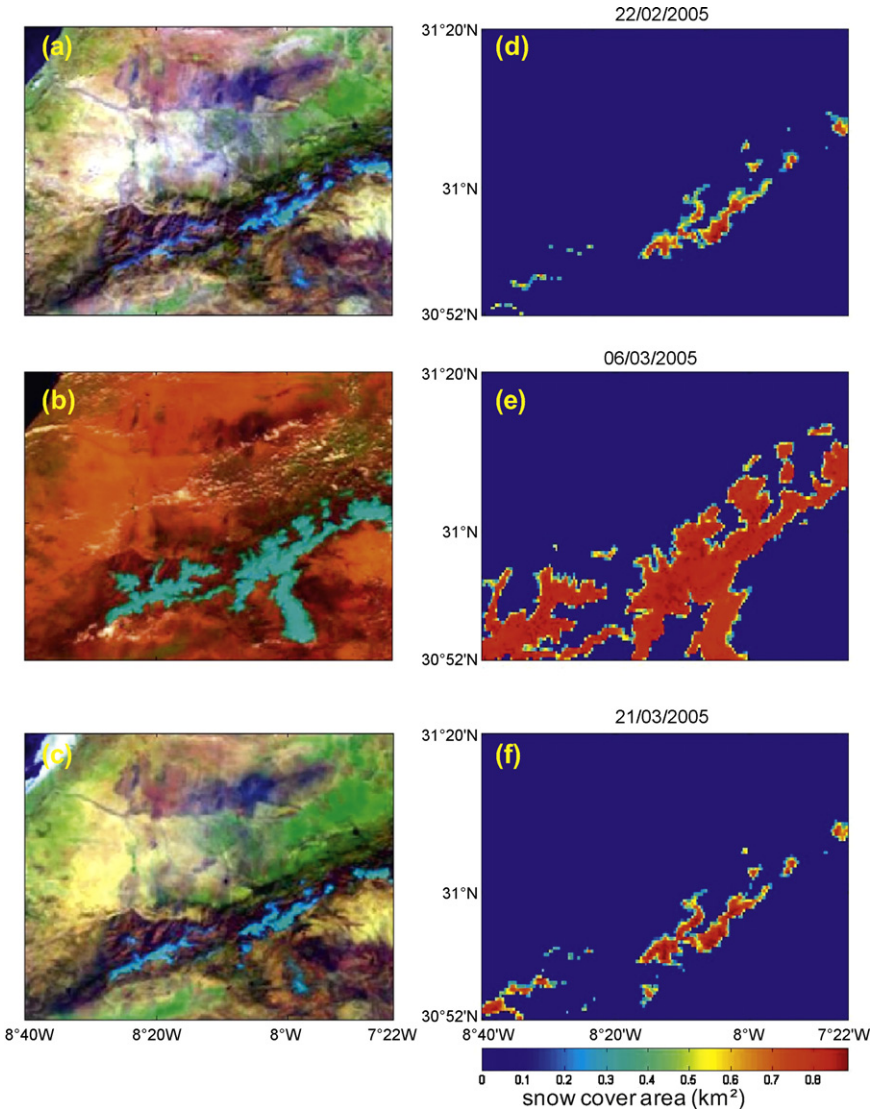

Fig. 2. Examples of SPOT-VEGETATION multi-spectral images (left) and derived snow-covered areas maps (right, in km^2): examples of February 22, 2005 (a and d); March 6, 2005 (b and e) and March 21, 2005 (c and f).

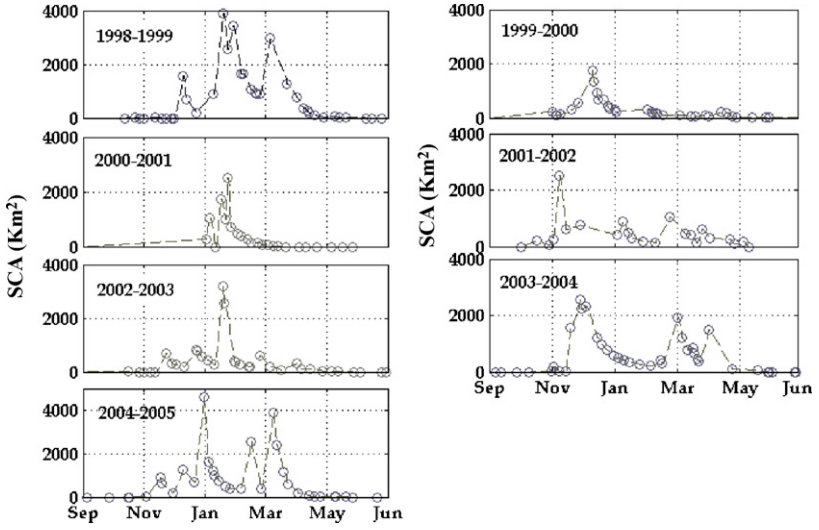

Fig. 3. Dynamics of snow-covered areas at the scale of the High-Atlas from seasons 1998–1999 (top-left) to 2004–2005 (bottom-left).

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Table 1
Main characteristics of snow-covered areas observed by SPOT-VEGETATION at the scale of High-Atlas from seasons 1998–1999 to 2005–2006.

Season	Number of snowfall events	First and last snowfall event	Maximal snow-covered areas		Seasonal mean snow-covered areas (km^2)
			Surface (km^2)	Date	
1998–1999	4	December 7–April 10	3900	January 16	779
1999–2000	2	September 20–February 18	1745	October 11	312
2000–2001	3	December 30–February 19	2512	January 20	385
2001–2002	4	October 16–April 22	2518	November 7	431
2002–2003	5	November 21–March 29	3168	January 16	379
2003–2004	3	November 2–April 23	2564	November 28	671
2004–2005	5	November 15–April 11	4620	December 28	750

670 km^2, and four dry winters (1999–2000 to 2002–2003) characterized by a lesser extent of SCA (on average 430 km^2). However, these results must be considered with care because they partly depend on the availability of cloud-free images. For instance, there are long periods without any observations, e.g. from September to December, 2000. Thus, because the snowmelt can be rapid, it is possible that some snowfall events have not been detected. On the other hand, these events are only detected if they correspond to an increase of snow-covered areas, which is not the case when it snows on already existing snowpack. Nevertheless, the result of this classification between dry and wet season appears consistent with the regional climatic features. Indeed, for the three wet seasons, the annual precipitation recorded at the Tahanaoute station was around 500 mm/year, while it was lower than 300 mm/year for the four dry seasons.

Fig. 4 shows a more detailed analysis of snow-covered areas during the 2004–2005 season, for which the dynamics of SCA was the most important. We note, very logically, that the rate of snow coverage increases with altitude, as well as the non-permanent character of the snowpack. During the winter period, i.e. from November 15, 2004 to April 1, 2005, snow-covered areas represent more than 30% of surfaces with altitudes between 3000 and 3400 m, and more than 50% for altitudes higher than 3400 m. In contrast, the snowpack totally disappears at altitudes lower than 2600 m (see the estimates from January 18 to February 2, 2005). The melting period can be very short at these lower altitudes: for instance, the snowpack almost totally disappeared in 6 days (from December 28, 2004 to January 2, 2005) for the 1800–2200 m altitudinal section. The snow ablation process (melt and sublimation) may be also important at higher elevations (see the period from December 28, 2004 to January 22, 2005). This analysis also allows identifying differences in snow ablation process at different elevations. As an example from January 7 to 18, 2005, SCA remains stable over the highest elevation (>3400 m) while a general decrease is observed at the lower altitudinal sections.

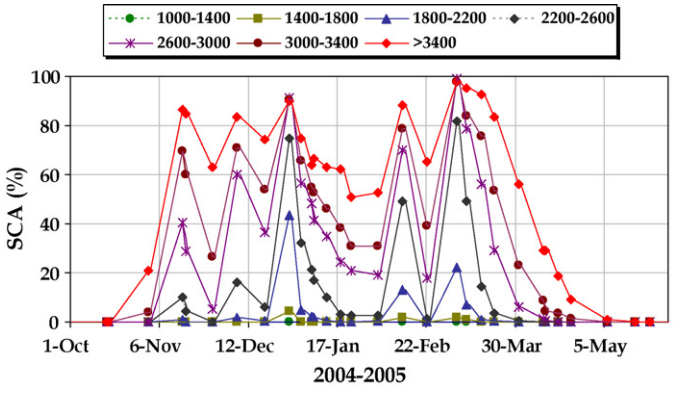

Fig. 4. Variations of snow-covered areas during the 2004–2005 hydrological season at various altitudinal zones from 1000 to 4200 m.

3.2. Possible linkage of SCA with climate

In order to explain the inter-annual variability of snow-covered areas, we carried out a simple composite analysis (Von Storch and Zwiers, 1999) of the Sea Level Pressure (SLP) over the Northern Atlantic. Within this study, data are taken from the NCEP/NCAR reanalysis (Kalnay et al., 1996). This analysis aims to provide with differences of atmospheric conditions between wet and dry years.

Fig. 5 displays the composite difference of SLP anomaly over the northern Atlantic between the wet (1999, 2004 and 2005) and the dry (2000–2003) seasons detected from remotely sensed SCA. The figure is provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado (see www.esrl.noaa.gov/psd). Its analysis points out that the East Atlantic (EA) pattern could be a potential control on winter temperature and precipitation over the Atlas, and thus on SCA. The EA pattern is the second leading mode of low-frequency climate variability over the North Atlantic and displays a north–south dipole of anomaly centers spanning the North Atlantic from east to west (Barnston and Livezey, 1987). It is strongly associated to the North Atlantic Oscillation (NAO). Through east–west oscillation motions of the Icelandic low temperature/pressure and the Azores high temperature/pressure, the NAO controls the strength and direction of westerly winds and storm tracks across the North Atlantic. NAO impacts many parts of the word (Hurrell, 1995). As it is a winter phenomenon, it has a high potential impact on processes that occur in winter such as snowfall in the northern hemisphere. Positive phases of NAO (positive anomaly over the Azores and negative anomaly over the Iceland) lead to increased westerly winds and, consequently, mild and wet winters in Central Europe. In contrast, during negative phases of NAO (positive anomaly over Iceland and negative anomaly over the Azores), westerly winds are suppressed, Central Europe experiences cold winters and storms track southerly toward the Mediterranean Sea. This brings increased storm activity and rainfall to southern Europe and North Africa, and, in particular, over Morocco (Knippertz et al., 2003).

The composite analysis shown in Fig. 5 corroborates the potential control of EA pattern and NAO oscillation over SCA in the Atlas Mountains: wet years (1998–1999, 2003–2004 and 2004–2005) are characterized by higher SLP over Iceland and lower SLP over the Azores region than dry years (1999–2003), thus reinforcing the southern position of the storms track activity to southern Europe and northern Africa. However, the short length of the time series (1998–2005) precludes from carrying out a more in-depth diagnostic analysis.

3.3. Conclusion and perspectives

This study shows the possibility of observing the dynamics of the snowfall and snowmelt cover within the semi-arid High-Atlas Mountains, based on long-term satellite imagery (SPOT-VEGETATION, 1998–2005). In addition to the identification of relatively dry seasons and wet seasons, the interest of such

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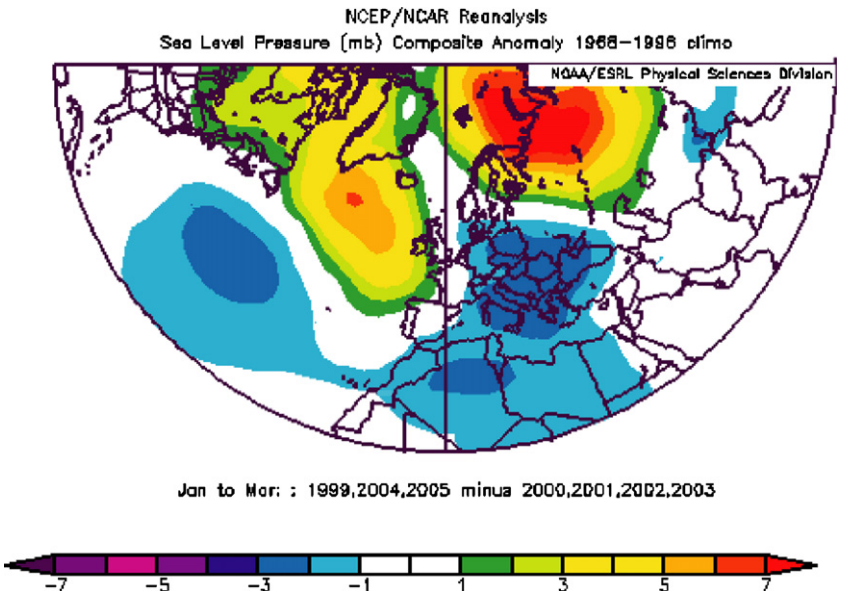

Fig. 5. Composite difference of Sea Level Pressure (averaged from January to March) anomaly over the wet (1999, 2004 and 2005) and the dry (2000–2003) seasons.

observations is even greater given the high spatial and temporal variability of snowpacks. This information may significantly reinforce the information derived from the climatic network, generally not very consistent or reliable in the high mountains, despite the fact that precipitations in such environments are often local and heavy.

In addition, a preliminary study of the linkages between the inter-annual variability of SCA and climate has been carried out. The composite analysis of the Northern Atlantic SLP points out to the East Atlantic Pattern and the North Atlantic Oscillation as a potential control. Long-term observation of snow-covered areas by means of remote sensing can thus (1) provide new information for the evaluation of the impact of climatic changes on the seasonal and inter-annual variations of precipitations and (2) provide a better understanding on the dynamic of SCA over this region and, in particular, its potential control by climatic pseudo-oscillations (NAO).

This research also opens perspectives for the comprehension of the hydrological cycle of the High-Atlas catchments. One might here expect testing methods for data assimilation in hydrological models to assist in the forecasting of base flows or flood risks. SCA products can be used to evaluate the contribution of snowmelt rate to the streamflow through hydrological modelling (see our study based on the SRM model over the five atlasic sub-catchment, Boudhar et al., in press). Obviously, such information derived from remote sensing observations with a high repeatitivity can be of great interest for operational planning of water use (reinforcement of the monitoring of precipitations, identification of the dry and wet years, relation between snowfall and flow rates, etc.).

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