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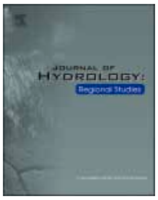

Snow hydrology in the Moroccan Atlas Mountains

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ABSTRACT

Study region: Atlas Mountains located in Morocco.
Study focus: Mountainous regions constitute an area of water production, while water is used in downstream plains. In Central Morocco, the Atlas Mountains represent the most important water supply in the country. The solid part of precipitation forms seasonal snowpack. Snowmelt is important for the water supply for different uses in neighbouring plains. Accurate knowledge of snow water equivalent is key information needed by policy-makers to help design and implement appropriate allocation strategies for water resource management. The objective of this paper is to provide a summary of our research activities on snow hydrology in the Atlas Mountains during the past twenty years. The approach combines in situ measurements, remote sensing, and modeling.
New hydrological insights for the region: Following a description of the context of the Moroccan Atlas Mountains and the experimental network, an overview of the main results obtained is presented: the characterization of the spatiotemporal dynamics of snow cover; the impact of the North Atlantic Oscillation on the snow-covered area; the snowmelt contribution to the flows of

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the Atlas rivers; the contribution of snowmelt to surface and groundwater recharge and the quantification of climate change impacts on snow and associated runoff from the Atlas Mountains. We also present challenges and future research perspectives within this topic.

1. Introduction

In semiarid and arid areas, sustainable water resource management requires precise quantification of surface and groundwater variability (Zaidi et al., 2020). In many semiarid catchments, the hydrological cycle is influenced by the presence of a mountain range, which enhances precipitation (Fayad et al., 2017; Mankin et al., 2015). The high elevation of mountainous regions constitutes an area of water production, while water is used in the downstream plains mainly for irrigation. In the upper catchment areas, the solid part of precipitation is important and forms a seasonal snowpack where water is stored during winter. Meltwater runoff feeds river stream flows, refills reservoirs and contributes to the recharge of aquifers later in the spring. The buffer effect played by snowpack is essential for the agricultural sector, particularly for crops whose water needs peak during the dry and hot period in summer. Since the pioneering work of Giorgi and Lionello (2008), several studies have pointed out the Mediterranean as a "hot spot" of climate change associated with a 2–3 °C temperature rise and a drop in precipitation of approximately 20–30%. The impact of these projected changes on water resources and the agricultural sector could lead to dramatic social instability because of the low adaptative capacity of North African countries (Schilling et al., 2020). Concerning snowfall, a warming climate could be associated with (1) a drastic drop in the water amount held in the snowpack through a change in partition between rainfall and snowfall, as already observed in Morocco (Simonneaux et al., 2008), (2) a potential increase in the water lost through sublimation (Boudhar et al., 2016) and finally (3) a shift in the timing of the water discharge that could peak earlier in the season. The latter effect could even jeopardize high-value-added crops such as citrus, apples and olives that are fostered by different agricultural policies in the region (Berbel et al., 2013). In addition, with the potential shift in terms of the snow melting, the rules of water allocation adopted by the managers for decades will probably need to be strongly modified.

In Central Morocco, which is characterized by an arid to semiarid climate, the Atlas Mountains represent the most important water supply in the country and contribute significantly to socioeconomic development (Fig. 1). Given the high elevations of the Atlas, which reaches 4167 m.a.s.l., precipitation occurs in the form of rain and snow. Due to the orographic effect, the average annual precipitation in the plains is low and varies between 150 and 250 mm, while this annual amount can exceed 800 mm in the highest regions, with a significant portion falling as snow, i.e., between 20% and 80% (Boudhar et al., 2009). Therefore, these mountain ranges can be considered as the "water tower" of Morocco

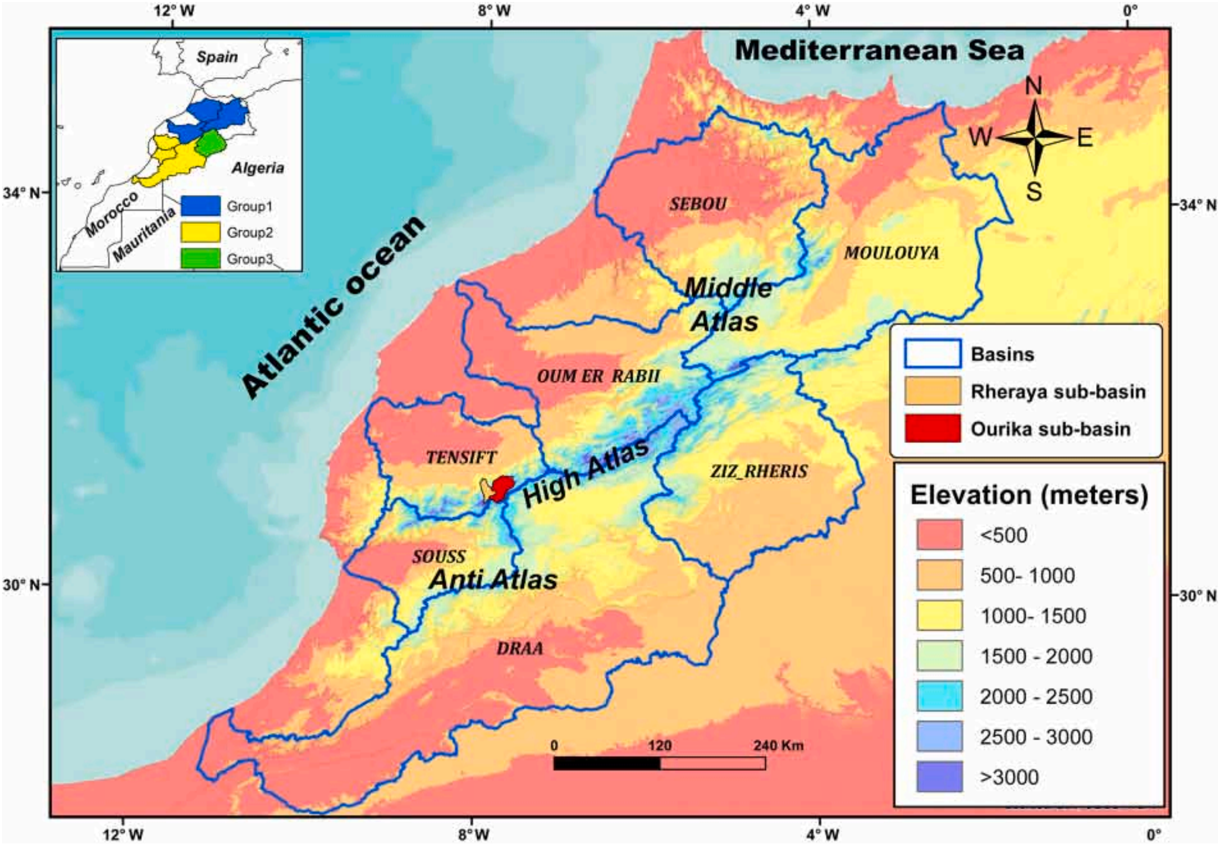

Fig. 1. Study area with the seven main catchments with a rainfall–snowmelt functioning in Morocco.

that provides freshwater for the large downstream arid plains. Snowmelt is extremely important for the water supply for different uses, especially irrigation, which is responsible for more than 85% of available water uptake (FAO, 2016; Jarlan et al., 2015; Khabba et al., 2013). As such, accurate knowledge of snow water equivalent (SWE) is key information needed by policy-makers to help design and implement appropriate allocation strategies for water resource management. This information helps to better plan the distribution of water for downstream irrigators by hydraulic basin agency managers and agriculture departments, who are in charge of monitoring Atlasic river discharge and managing water in the low-land watersheds surrounding the Moroccan Atlas Mountains. On the other hand, snow cover is highly vulnerable to climate change, especially given the evidence that atmospheric warming increases with elevation in the Mediterranean mountains (Kotlarski et al., 2015; Moucha et al., 2021; Pepin et al., 2015). It is expected that climate change will reduce the available SWE in the future (Giorgi and Lionello, 2008; López-Moreno et al., 2017; Marchane et al., 2017; Schilling et al., 2012; Tramblay et al., 2020). In addition, rising temperatures may shift the annual peak flow due to snowmelt occurring earlier in the hydrologic year, potentially compromising the supply of irrigation water to downstream areas in late spring. Therefore, studying climate change impacts on water resources for the Atlas Mountains is necessary to develop adaptation strategies for managing water (Hssaisoune et al., 2020, Marchane et al., 2017, 2015).

Ground measurements provide reliable information on snowpack properties, but their spatial representativity is difficult to characterize in remote mountain areas given that hydroclimatic and snow conditions in the mountainous environments are extremely heterogeneous in both space and time (Boudhar et al., 2011; Ouatiki et al., 2017; Vieira et al., 2017). With regards to the sparsity of the in situ network limited to snow research stations, snow studies in Morocco have often relied upon remote sensing usually used jointly with modeling tools. Taking advantage of the specific optical properties of snow (high visible and low mid-infrared reflectance properties), many studies have used optical remote sensing in particular to estimate the distribution of snow covered areas (SCAs) from different satellite sensors with various spatial and temporal resolutions (Bouamri et al., 2021; Boudhar et al., 2007, 2009, 2010, 2011, 2014; Chaponnière et al., 2005; Marchane et al., 2013, 2015; Boudhar, 2009; Hanich et al., 2003). Additionally, different modeling approaches have been developed (point-scale, semi distributed and distributed approaches) to estimate SWE and snowmelt from the point scale to the basin scale (Baba et al., 2019, 2018a, 2018b; Bouamri et al., 2018, 2021; Boudhar et al., 2009, 2016; Schulz and de Jong, 2004). Other studies have integrated snowmelt models into hydrological models to simulate streamflow (Boudhar et al., 2009; Hajhouji et al., 2018).

This paper aims to provide a summary of our research activities on snow hydrology in the Atlas Mountains in the recent years. These different activities have been carried out, within the frame of the research program SudMed project (2002–2011) (Chehbouni et al., 2008), the Young Team Associated with IRD JEAI/CREMAS (2006–2009) and the Joint International Laboratory LMI-TREMA (2011–2020) (Jarlan et al., 2015). To understand snowpack processes and their influences on the basin hydrological response, our scientific approach was focused on the joint use of in situ measurements, remote sensing of snow, and modeling by taking into consideration the sparsity of ground-based networks. This approach has evolved with the development of space technology leading to freely available and increasingly precise data in terms of spatial and temporal resolution. In terms of modeling, this increased amount of data together with the improvement of the resolution and accuracy of the meteorological forcing enabled a switch toward more physically based approaches, in contrast with the conceptual modeling tools that were implemented in early studies. This synthesis of the research results is useful; science advancement is intimately related to the availability of new data. In hydrological science as well as in other environmental sciences, the availability of new data is a driver of change of paradigm both with regard to science and to management and ultimately to policy development. In this regard, our research objectives fall under several of the unsolved problems in hydrology identified in the “23 unsolved problems in hydrology” initiative of the IAHS (International Association of Hydrological Sciences) (Blöschl et al., 2019), such as: “How will cold region runoff and groundwater change in a warmer climate?; What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions?; Why, how and when do rain-on-snow events produce exceptional runoff?; How can we use innovative technologies to measure surface and subsurface properties, states and fluxes at a range of spatial and temporal scales?; How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?” (Blöschl et al., 2019).

Following a description of the context of the Moroccan Atlas Mountains and the in situ measurements of different hydrologic and climatic variables, this paper presents an overview of the results obtained concerning (1) the spatiotemporal dynamics of snow cover by remote sensing; (2) the impact of the North Atlantic Oscillation (NAO) on the snow-covered area of the main watersheds; (3) the snowmelt contribution to the flows of the Atlas rivers using different modeling approaches; (4) the contribution of snowmelt to surface and groundwater recharge using snow isotopes and (5) the quantification of climate change impacts on snow and associated runoff from the Atlas Mountains. We also present future challenges and some future research perspectives on this topic.

2. Moroccan Atlas mountain context

The Atlas mountain range stretches over 700 kilometers along a west southwest to east-northeast axis, with a width of 70 kilometers (Fig. 1). It forms in the center of Morocco a barrier between the Mediterranean Sea in northern Morocco and the Sahara. It is made up of seven watersheds with a mixed influence of rainfall and snowmelt and it is subdivided into three physiographic units: the Anti Atlas, the High Atlas, and the Middle Atlas. The seven watersheds are the Draa and Souss, located in the Anti Atlas, with altitudes varying between 1500 and 2000 m.a.s.l. The Tensift, Oum’Er Bia and Ziz Rheris, located within the High Atlas chain, are the highest unit with altitudes exceeding 4000 m.a.s.l. and the Sebou and Moulouya located in the Middle Atlas.

3. Experimental and in situ measurements

Within the frame of the Tensift climate and water observatory, measurements of hydrological parameters and processes in the High Atlas, were focused on the Rheraya watershed located south of Marrakech, with altitudes ranging from 1000 to 4167 m.a.s.l. (Toubkal summit, the highest peak in North Africa). The basin covers an area of 228 km2 with snow present at least three months per year at an elevation above 3000 m. Starting in 2002, a network of five automatic weather stations recording temperature, air humidity, wind speed, solar radiation, and rainfall at a 30 mn time step was progressively installed. Four additional sites record only rainfall (Fig. 1, Fig. 2 and Table 1). These meteorological data are used either directly to force hydrological models or to check the quality of reanalysis, satellite precipitation datasets, or weather forecasts which are increasingly used in modeling.

To monitor snow cover, two of five stations include a Geonor “total precipitation gauge” since 2013, namely the Toubkal refuge site at 3200 m.a.s.l. and the Oukaimeden summit at 3250 m.a.s.l. The latter site has also included a snow height measurement sensor since 2003. The snow density was measured periodically between 2007 and 2016 around the Oukaimeden station located on a plateau with altitudes between 3150 and 3250 m.a.s.l. During each campaign, a transect of 10–15 points was sampled, measuring for each point the snow height and the snow weight sampled with a tube from which the density was calculated. Finally, daily minimum and maximum temperature, rainfall and fresh snowfall depth were continuously observed from 1989 to 2009 by the keeper of the Oukaimeden CAF refuge (2650 m.a.s.l.) which is highly valuable thanks to its record length and consistency with, to our knowledge, no equivalent in the region.

Finally, soil moisture has also been observed at the Aremd site (1950 m.a.s.l.) since 2013. Six sensors (ML2 Theta probes from Delta-T) continuously recorded the soil moisture at 5 and 40 cm depths for three points located at 10 m from each other on a slope of approximately 30% covered with degraded rangeland typical from this area. Additionally, moisture and temperature sensors were installed in 2019 at the Oukaimeden site at 10, 30 and 60 cm depths (3 Campbell CS215 probes) (Fig. 2).

River flow measurements at the outlet of the main subbasins of the high Atlas Mountains have been collected since the 1960′s or 1970′s by the Tensift Hydraulic Basin Agency (ABHT). These runoff estimates are obtained from water heights observed manually three times a day (8 h, 12 h and 18 h) by station keepers, with more frequent observations during flood events (frequency is left to the station keeper to capture the quick variations in runoff typical of wadis). These heights are converted into daily runoff using gauging curves determined by manual gauging achieved every month using a current meter through the riverbed section. The gauging curves are updated each time a strong flow event modifies the river cross-section. These runoff measurements are used to calibrate or validate the snowmelt and runoff models.

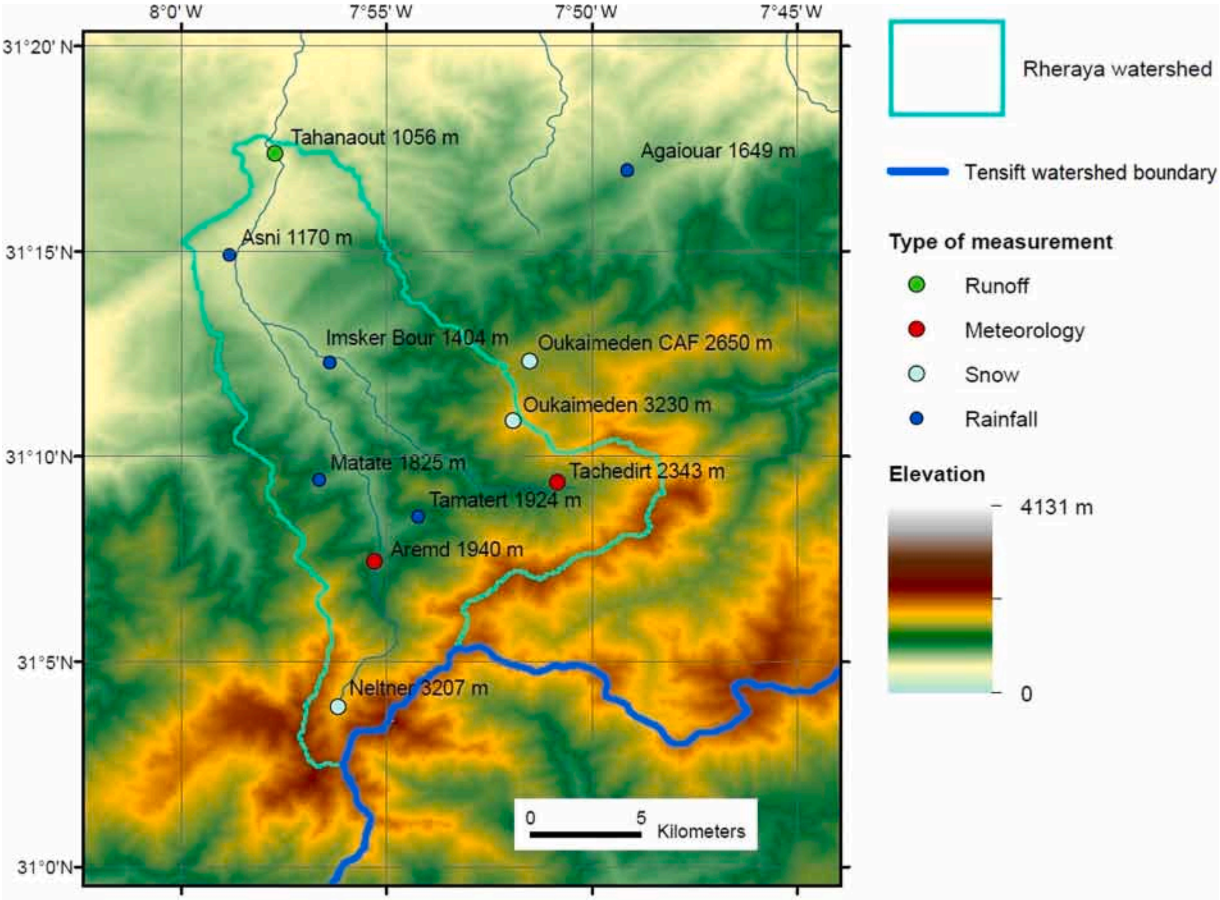

Fig. 2. Geographical location of the measurement sites in the Rheraya watershed.

Table 1
List of the main in situ variables measured within the Rheraya watershed.

Data type	Variable	Instrument	Sampling time step	Neltner (3207 m)	Aremd (1940 m)	Tamatert (1924 m)	Tachedirt (2343 m)	Matate (1825 m)	Oukaimeden (CAF Hut) (2650 m)	Oukaimeden (3230 m)	Imsker Bour (1404 m)	Agaiouar (1649 m)	Asni (1170 m)
Meteorology	Rain	Rain gauge	30 mn	2007-	2003-	2012-	2007-	2012-	1989–2009 (daily, manual)	2003-	2007-	2016-	2007-
	Temperature / Humidity	CS215 Sensor	30 mn	2007-	2003-		2007-		1989–2009 (T only, daily, manual)	2003-	2007-		
	Wind speed	Anemometer	30 mn	2013-	2003-					2003-			
	Solar radiation	Pyranometer	30 mn		2003-					2003-			
	Net Radiation	CNR1, NR0 Radiometer	30 mn							2003-			
Snow	Snow depth	Ultrasonic probe Manual samples	3–5 campaigns of 6–10 points/year						1989–2009 (daily, manual)	2003-			
	Rain + Snow	GEONOR (Weighting pluviometer)	30 mn	2013-						2013-			
	Snow density	Core tube / manual	3–5 campaigns of 6–10 points/year							2007–2016			
Soil	Soil moisture	Theta probes / CS655	30 mn		2013-					2019-			
Hydrology	Streamflow	Gauging	Monthly	From the 1970s at the outlets of the main watersheds (cf.Fig. 1)									
	Height	Scale reading	3 per day										
		Hydro station	10 min										
Hydrochemistry and isotopy (water and snow)	^{18}O and ^{2}H	Laboratory analysis	Monthly	From 2011–2014 and from 2018 on the Ourika Watershed (cf.Fig. 1)									

Photo 1. Snow cover near Oukaimeden in December 2016 (photograph: Wassim Baba).

4. Remote sensing of snow cover area

Regarding the climate aridity of the Moroccan Atlas zone, processes governing the state of snowpack and its evolution are extremely variable both in space (e.g., exposition control: photo 1) and in time, and snow can fall and melt within one week (Boudhar et al., 2009, 2007; Chaponnière et al., 2005; Hanich et al., 2003). To take into consideration the parameters controlling these changes, it is recommended to acquire snow and climate information ideally at a high temporal and spatial resolution. The lack of in situ measurements led us to use remote sensing, especially optical remote sensing, to study the spatiotemporal dynamics of snow cover over the Atlas Mountains. We focused on optical remote sensing since the specific optical properties of snow (high visible and low medium infrared reflectance properties) provide an accurate means to derive the snow cover area (e.g. using the NDSI: the normalized difference snow index) (Dozier, 1989; Hall et al., 2001; Salomonson and Appel, 2004).

4.1. *Snow cover area of five subwatersheds of the Tensift catchment using the SPOT VEGETATION product*

In early works, we developed an approach that combines data derived from two types of instruments: low spatial and high temporal resolution (SPOT VEGETATION, daily revisit time and pixel size of 1 km^2) and high spatial and low temporal resolution (Landsat-TM, 16 days revisit time and 30 m pixel size). The approach consisted of calibrating a pixel-based relationship between a low-resolution multispectral index and a high-resolution snow cover area to derive the subpixel snow cover fraction at low resolution. This relationship was then applied to a series of SPOT-VEGETATION images covering the 1998–2005 period, over five subwatersheds of the Tensift catchment within the High Atlas to map the snow cover area. (Boudhar et al., 2010, 2009, 2007; Chaponnière et al., 2005; Hanich et al., 2003).

A long time series of SCA covering the 1998–2005 period was generated for the five subbasin of the Tensift catchment (Boudhar et al., 2010, 2009, 2007). These studies highlighted the strong heterogeneity of seasonal and interannual SCA from one basin to another related to the altitudinal and exposition effects. Indeed, the snowfall period (calculated from the date of appearance of snow surfaces until its disappearance) is very variable: the onset of the snow season fluctuates between the end of September and the end of December, while the last snowfall events were recorded between the end of January and the beginning of April. The minimum snow cover altitudes are approximately 1400 m for wet seasons compared to 1800 m for dry seasons.

Based on a similar methodology, a modified normalized difference snow index (MNDSI) (Boudhar et al., 2009) was proposed to derive the SCA. The scatter plots in Fig. 3 shows the correlation between SPOT-VEGETATION and MODIS SCA fractions over the mountain part of the Tensift River basin during the 2003/2004 snow season. This date-by-date intercomparison reveals the high correlation between the two products with an average R^2 coefficient of 0.84 and RMSE of 1.29%.

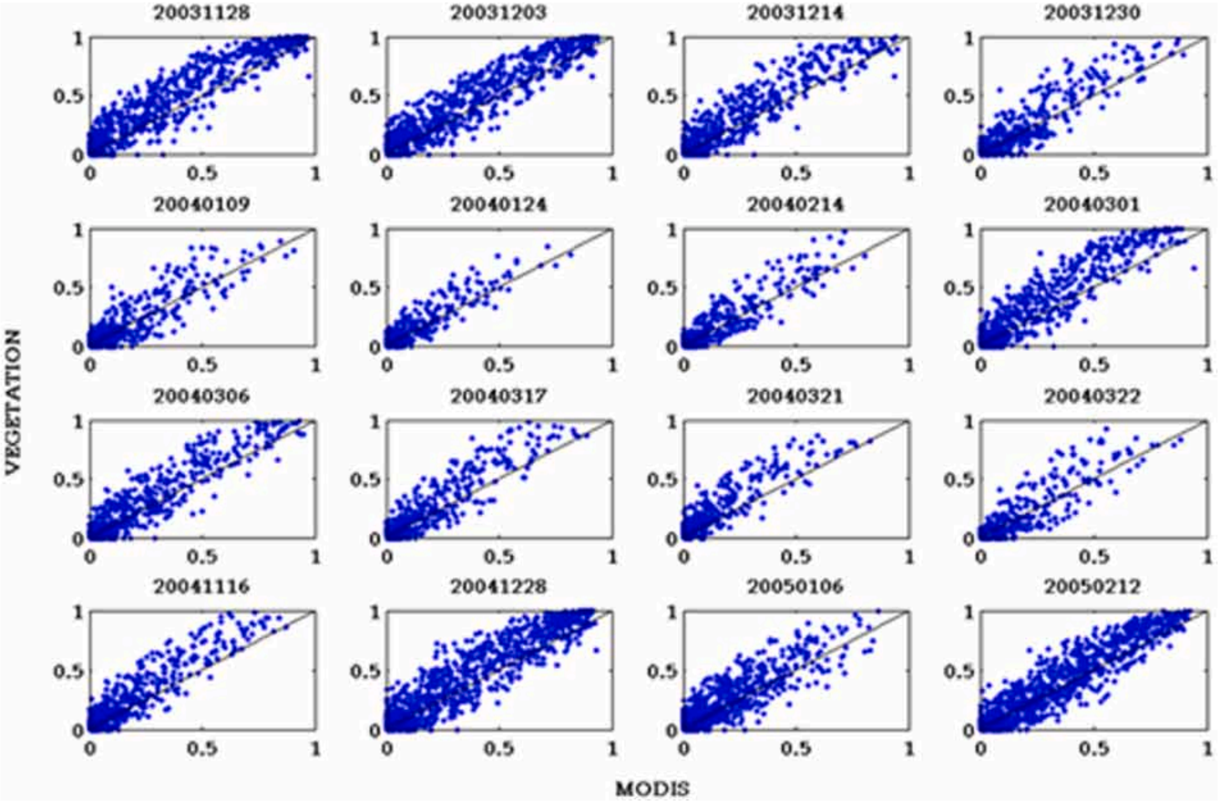

Fig. 3. Pixel-by-pixel comparison of the snow cover area (SCA) fraction from SPOT-VEGETATION and MODIS during the 2003/2004 snow season (from Boudhar et al., 2009).

4.2. *Snow cover area over the Atlas Mountains using the MODIS product*

4.2.1. *Snow cover variability*

The freely distributed snow product collection provided by the National Snow and Ice Data Center derived from Moderate Resolution Imaging Spectroradiometer (MODIS) observations (Hall et al., 2001) was assessed in the rapidly changing snow cover of the Atlas. With an overall accuracy of 89%, this product was found to be appropriate to characterize the high dynamics of snowpack in the arid to semiarid context of the Moroccan Atlas Mountains thanks to its spatial resolution (500 m) and its short revisit time (1 day) (Jarlan et al., 2015; Marchane et al., 2015, 2013). Nevertheless, it is revealed that this low spatial resolution product is not efficient in capturing the local variability of the snow extent, related to the terrain aspect effect induced by solar radiation (Bouamri et al., 2021).

The high accuracy of this product (above 80% snow detection for cloud-free images) was highlighted by several studies (Gascoin et al., 2015; Hall and Riggs, 2007; Klein and Barnett, 2003; Parajka and Blöschl, 2006), but they also pointed out two main weaknesses: (1) the monitoring of snow may be very sporadic in areas with high cloudiness; (2) due to a close spectral signature in the visible domain, a misclassification between snow and clouds may lead to up to 12% false-positives (snow detected but not present) and up to 15% SCA overestimation. Within this context, a spatiotemporal filter aiming to increase the number of usable images and to improve the snow/cloud classification adapted from Gafurov and Bárdossy (2009) and Gafurov Parajka and Blöschl (2006) for semiarid snow cover was developed by (Marchane et al., 2015). The filter reduces the number of pixels identified as a cloud (correctly or not) by 96% over the Atlas mountain range. The corrected products were also assessed against five in situ automatic snow depth stations and a series of 19 snow-cover maps derived from Formosat-2 images acquired during winter 2009 over the high Atlas in the Tensift catchment. Regarding the good accuracy of the corrected products, they have been used (1) to characterize the snow cover variability in seven catchments covering the Moroccan Atlas mountain range and (2) to assess the spatiotemporal trends (using a Mann–Kendall test; (Hirsch et al., 1982)) of snow-cover areas at the scale of all Moroccan catchments with snow–rain functioning.

To assess the spatial variability of the snow cover dynamics in Morocco, the time series of snow cover areas at the catchment level were grouped using cluster analysis. The analysis identified three groups (Fig. 1):

The first group (Moulouya, Oum'Erbia and Sebou) gathers the northern catchments whereas the second group (Tensift, Souss, Draa) is located in the southern part. Finally, Group 3 isolates the last catchment, Ziz Rheris, located in the southeastern part of the At-las chain (Fig. 4). The dynamics of SCA in the three groups are characterized by high interannual variability with a variation coefficient of the maximum SCA equal to 41%, 25% and 77% for Groups 1, 2 and 3, respectively. Group 2 is dominated by high altitudes, which explains the value of the coefficient of variation (CV), while the CV of Group 3 can be explained by solar radiation, which is the highest compared to the other groups.

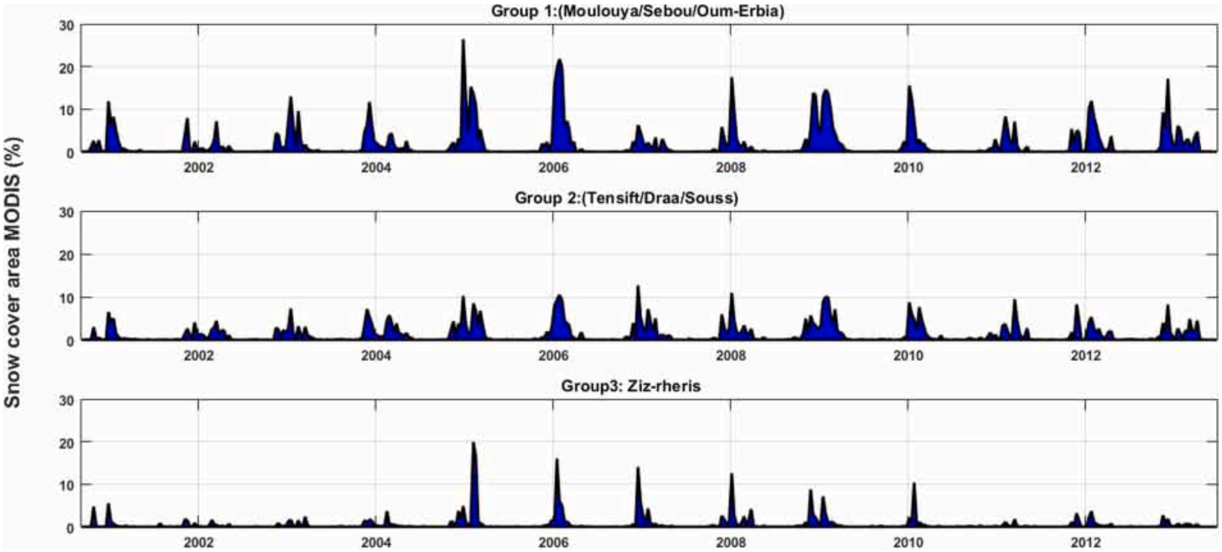

Fig. 4. Variation in the normalized snow-covered area for the three catchment groups (see text).

The inter and intra-annual variability is extremely high both in terms of maximum and total snow cover as well as in terms of event distribution and season length. Fig. 5 shows, in particular, the strong seasonal dynamics of snow cover at the scale of the whole Moroccan Atlas. Additionally, the number of snow events is limited and there are periods of almost complete ablation even at the scale of the whole massif and in the middle of winter (2002–2003 season in particular).

In terms of interannual variability, the maximum snow cover area varies from 13,433 km^2 for the 2013–2014 season to 42,000 km^2 for the 2004–2005 season, which induces significant consequences on water availability in spring. Similarly, the date of seasonal maximum snow cover also shows high variability from one year to another with an occurrence in mid-December for the 2006–2007 season and up to mid-March for the 2001–2002 and 2010–2011 seasons.

Finally, to assess the trend of the snowy days, a 2-month period was chosen here following Brown and Mote (2009), who showed that the duration of snow cover was the most climate-sensitive variable. The analysis of the trend maps (Fig. 6) led to the following remarks:

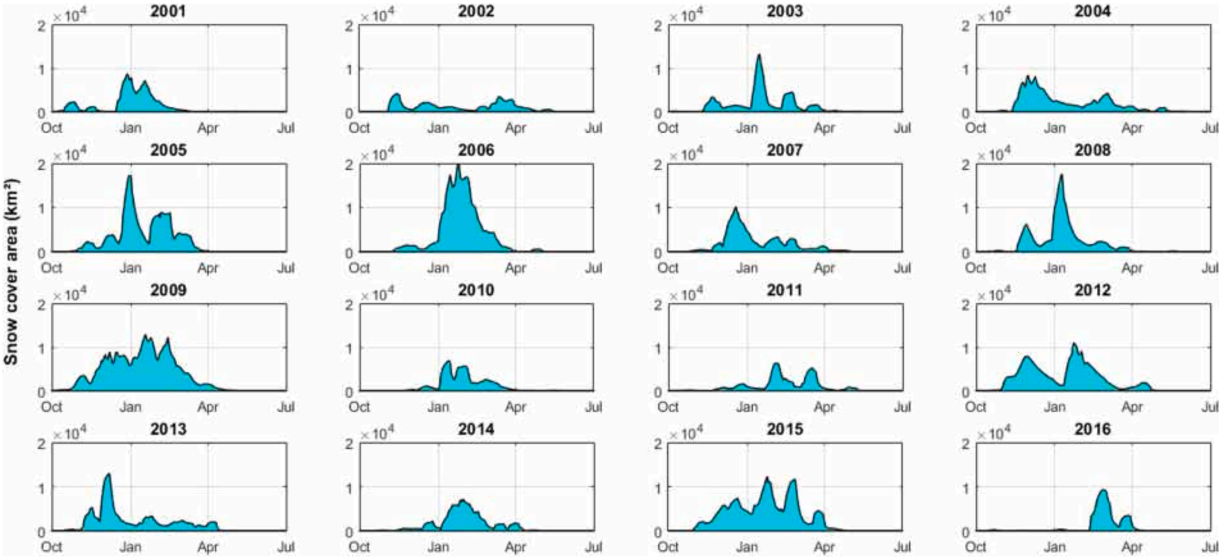

Fig. 5. A 10-day moving average of daily SCA on the Moroccan Atlas from October 2000 to May 2016 by the MOD10A1 product.

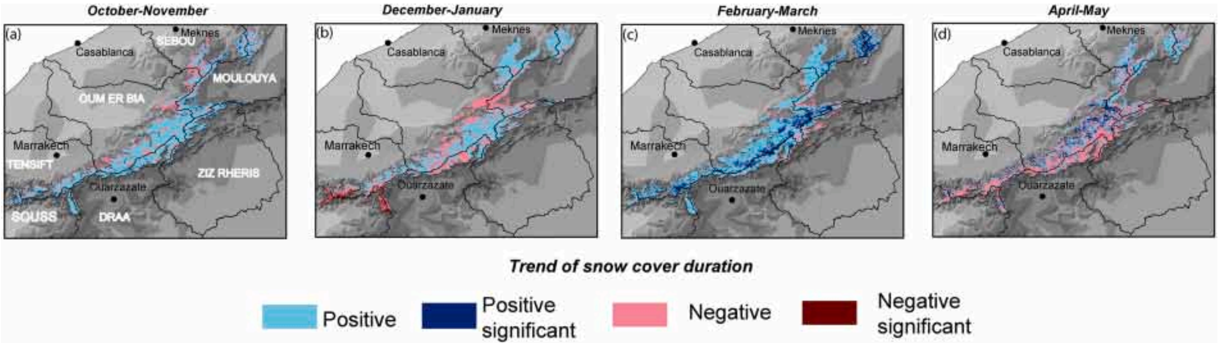

Fig. 6. Sign and significance of trends of snow cover duration for 2-month periods during the period 2000–2013: (a) October–November; (b) December–January; (c) February–March; (d) April–May (From Marchane et al., 2015).

- At the start of the season, in October-November, a general increasing trend was observed for most of the region (77% of the pixels) with a few scattered spatial patterns mainly located on the north side of the Atlas, where a decrease was detected. Nevertheless, these observations should be analyzed with caution, as only 7.9% of the pixels passed the Mann-Kendall test.
- In December-January, there is no evidence of strong long-term trends that would impact the entire region. Nonetheless, there is a clear trend toward a decrease in the duration of snowfall that passes the Mann Kendall test in the southern part of the study area, in the Souss and Tensift basins.
- In February-March, the increasing trend is significant over the region (96.4% of the pixels among which 36.8% showed a positive and significant trend). Most of these pixels are located at high altitudes: 53.1% of the area above 2500 m above sea level shows a significant increase in snow duration. For pixels where the trend is significant, the median slope is 5.8 days/10 years, and it is even above 9.7 days/10 years for 10% of the pixels.
- Finally, April-May is the only period where the downward trend dominates the region with 68.8% of the area, but only 11.5% passes the Mann-Kendall test. Most of this observed drop was detected below 2500 m altitude, with 76.1% of the pixels below this altitude showing a downward trend (15.1% is significant). The slopes of 11.5% of the pixels with a significant trend are much weaker with a median value of 2.1 days / 10 years.

Even if the observed trends are not, for most pixels, statistically significant in the long term, the spatial consistency of the results suggests an increasing trend in the duration of snow cover in February and March, mainly impacting areas of high altitude (above 2500 m) and, to a lesser extent, a slight decrease in the duration of snow cover in April and May. Although not significant, the decrease affects 76.1% of areas below 2500 m. The observed increase of SCA during February-March (Marchane et al., 2015) is corroborated by the negative trend of December-February NAO (not shown) observed during the period of study (2000–2013). This means that an extension to the recent years (after 2015) characterized by mainly positive NAO during winter could turn this positive SCA trend into a decrease of SCA. The advent of Sentinel-2 opens new avenues in the monitoring of snow cover area in the Atlas. Sentinel-2 provides 20-meter resolution multispectral images with only five days of revisit time, in contrast to 16 days for Landsat-8. Similar to MODIS and VEGETATION, the snow cover area can easily be distinguished from snow-free areas and clouds using the NDSI. The Theia Land Data Centre provides operational snow products for a large region of the Atlas Mountains (Gascoin et al., 2019).

4.2.2. Impact of the North Atlantic Oscillation (NAO) on the snow-covered area

The North Atlantic Oscillation (NAO) has long been known to be the main climatic pseudooscillation impacting winter precipitation in the euro-Mediterranean region. Over Morocco, Lamb and Peppler (1987) showed for the first time a strong negative correlation between winter precipitation (December-April) and NAO from December-February. The daily series of the corrected snow-covered area products were synthesized using seasonal indicators (the maximum snow-covered area (SCAmax), the sum of total snow-covered areas (SCAsum), the average of the snow-covered areas (SCAmean) and the dates of maximum snow cover) that were related to the North Atlantic Oscillation through simple lagged correlations (Marchane et al., 2016), highlighting for the first time the linkages between snow cover and NAO in western North Africa.

As a preliminary step, the relationships between, precipitation and air temperature and NAO were revisited. Precipitation and air temperature were obtained from 17 meteorological stations from the synoptic network between 1993 and 2011 and from the NCEP reanalysis (National Center for Environmental Prediction reanalysis). In line with previous studies, winter precipitation in Morocco appeared to be inversely related to the NAO, excluding the inland stations located southwestern (Midelt, Er-Rachidia and Ouarzazate) and in the Mediterranean area (Al Hoceima and Nouasseur) stations. As expected, the correlation decreased significantly after February. A negative correlation is demonstrated with temperature, which means that the negative (positive) phase of the NAO preferentially leads to a temperature higher than normal (lower than normal). This could be attributed to the increased advection of air from the warm ocean during the negative phase. By contrast with the NAO-precipitation correlation, two significant differences can be highlighted for the NAO-temperature linkage: (1) the correlation is significant inland even on the southern slope of the Atlas: the stations of Er-Rachidia and Midelt in February show a negative correlation of − 0.67 and − 0.56, respectively; (2) the negative correlation remains later in the season. In April, all the

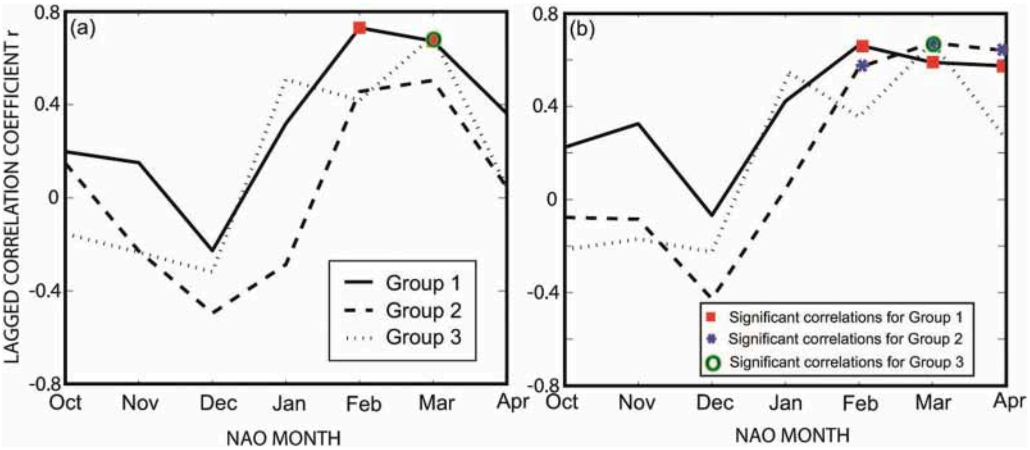

Fig. 7. Lagged correlation between monthly NAO and indicators of the snow season (2001 −2013): (a) duration; (b) ablation date. The symbols correspond to significant correlation values at the 95% level (from (Marchane et al., 2016).

southern stations show very high negative values and a spatial pattern of negative correlation over the same area is also very marked for the NCEP reanalysis.

Concerning snow indicators, no significant correlation was found between NAO and the start date of the snow season. The main striking results are a positive correlation significant at the 95% level for the duration of the snow season and the date of complete ablation, which means that a positive (negative) NAO is favorable for a longer (shorter) season (Fig. 7). This is consistent with the correlation between the NAO in March and the air temperature in April at the end of the season. Stated differently, milder temperatures during the negative phases of the NAO promote earlier snow clearing. Additionally, this emphasizes the dominant influence of temperature anomalies on the snowpack induced by the NAO rather than an effect of precipitation, which turned out to be weak beyond the winter months (and which, moreover, would imply a negative correlation). A positive correlation is also found with the average SCA in April-May and, to a lesser extent, in December-January. These correlations also support a dominant effect of temperature: (1) the sign of the correlation is positive; if the effect of the rains were dominant, a negative sign would have been expected; (2) a significant correlation is demonstrated for the whole Atlas, including the area located south of the Atlas Mountains, in agreement with the spatial pattern of the correlation between NAO and temperature, which covers the whole country; and (3) the correlation is significant even at the end of the season when the correlation between precipitation and NAO has disappeared.

5. Snowmelt hydrology modeling

To estimate the snowpack state (e.g., snow height (HS), snow water equivalent (SWE), melt and sublimation), different modeling approaches have been evaluated as follows:

- Point-scale, which consists of modeling the snowpack evolution at a particular point. Generally, this point is the location of the weather station that provides meteorological data. We used an energy balance model to monitor the different processes of energy and mass balance of the snowpack at the Oukaimeden (3200 m.a.s.l) automatic weather station from 2003 to 2004–2009–2010 (Bouamri et al., 2018; Boudhar et al., 2016). The objective of this approach is to test the efficiency of various melting models and examine the physical processes affecting the evolution of snowpack, notably the inversion of turbulent fluxes and the sublimation rate.
- Semidistributed modeling consists of dividing the basin into different units that are supposed to have the same characteristics (e.g., altitudes). Many studies have highlighted the importance of semidistributed models in mountain hydrology (Douglas-Mankin et al., 2010; Fontaine et al., 2002; Grusson et al., 2015; Rahman et al., 2013). For that, we evaluated the performance of integrated snowmelt models, on some subwatersheds of the Tensift catchment through the High Atlas range, to simulate streamflow (Boudhar et al., 2009; Hajhouji et al., 2018). The objective of this approach consists of a simple spatialization that makes it possible to consider the first-order factors governing the dynamic of the snowpack, in particular, altitude.
- Distributed modeling: The study area is divided into a regular grid, where each grid cell has its own characteristics (e.g. altitude, slope, orientation). This approach was used for the simulation of the snow water equivalent evolution in the High Atlas (Baba et al., 2019, 2018a, 2018b; Bouamri et al., 2021). This approach allows the use of 3D methods that consider fine-scale variations in radiative and turbulent heat fluxes in the landscape.

5.1. Modeling at the point-scale

Snowpack modeling in dry mountainous environments is an issue since many processes can interact, while little is known about each process taken separately. The separation between melt and sublimation or evaporation is particularly important in those environments.

A comparative study of snowmelt modeling approaches, varying from simple to physically based models, was carried out by Boudhar et al. (2009) using automatic data recorded at the Oukaimden AWS (3200 m.a.s.l) and ground measurements sampled in the vicinity of the same site. First, the simplified degree day approach has been evaluated with a focus on how the DDF (degree-day factor) methodology influences simulations of SWE. In this regard, three formulations, i.e., those from Kuusisto (1980) and Martinec (1960) and the radiative approach of Brubaker et al. (1996), were considered to simulate DDF for snowmelt quantification. The calibration procedure was carried out using field observations acquired during the snow season 2007/2008. However, the other seasons (2003/2004, 2004/2005 and 2005/2006) were used for the validation phase. For physically based modeling, the ISBA-ES model (Boone, 2000) was applied to analyze different snowpack processes from the 2003–2004–2009–2010 snow seasons. The results show interannual variation in snow water equivalent (SWE) observed and simulated using ISBA-ES and the three degree-day models. All models efficiently simulate the variation in SWE over the calibration season. During the validation period, the Martinec model cannot simulate SWE efficiently during the season, while the Brubaker and Kuustisto models provide a better simulation in all seasons with a correlation coefficient more than 0.8 and Bias between − 13 mm to - 2.32 mm.

The use of the ISBA-ES model at the Oukaimden site during four seasons shows that most of the snow ablation is due to the melting process. However, a significant proportion of water losses are caused by sublimation. The melting process is generally characterized by the sudden release of water in short periods, concomitant with the increase in air temperature. However, the sublimation process occurs regularly throughout the season and can reach 38% of the total ablation depending on the year. A simple approach, based on a simple energy balance equation forced by all available measurements (radiative budget, surface temperature, etc.) was implemented by Boudhar et al. (2016) to monitor the different processes of energy and mass balance of the snowpack. This confirmed the importance of sublimation (between 7% and 20% of the cumulative snowfall) over 5 years of data. It also showed the superiority of energy balance tools in snowmelt retrieval performances compared to traditional temperature or radiation index-based methods. The ISBA-CROCUS, characterized with a better representation of physical processes involved in the snowpack and in the superficial soil with regards to ISBA-ES, implemented by Chaponnière (2005) showed that albedo, specifically the maximum albedo, is the most important driving factor.

Additionally, empirical snowmelt models have been examined by Bouamri et al. (2018), using five years of meteorological and SWE

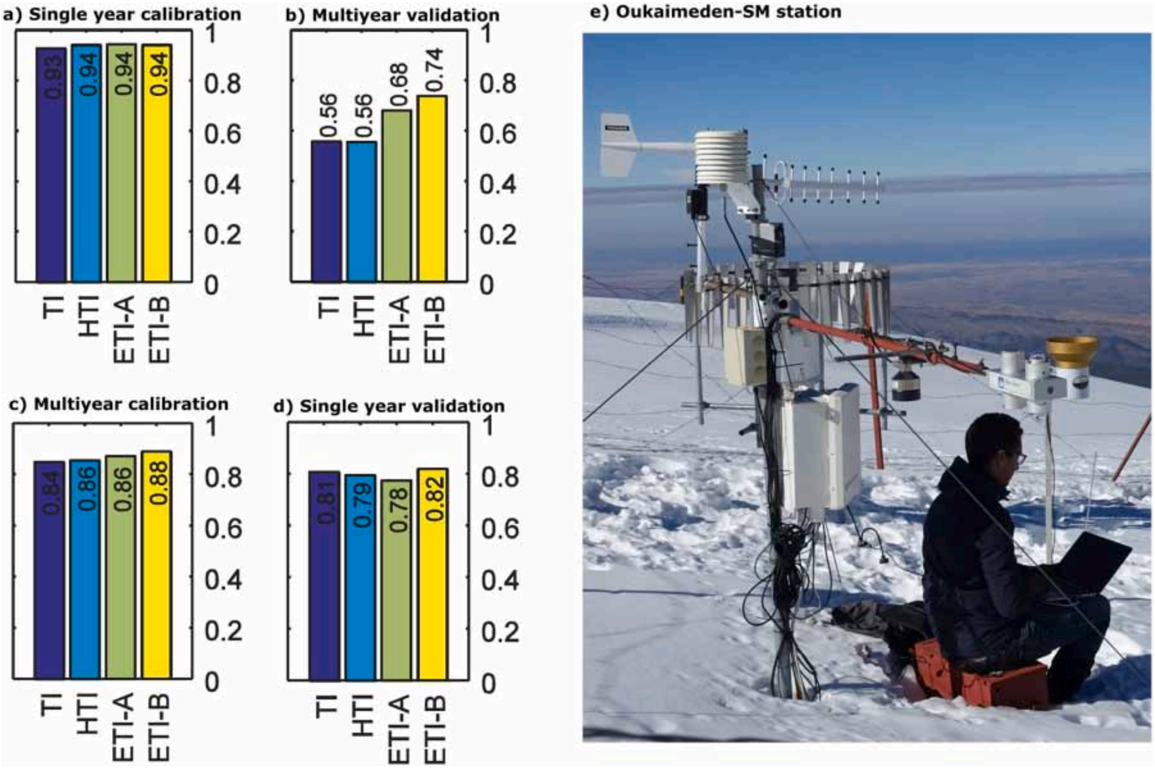

Fig. 8. Performance (Nash-Sutcliffe efficiency score: NSE) of empirical models in simulating SWE at the point scale. (a) Mean single year calibration NSE with (b) corresponding multiyear validation; (c) mean multiyear calibration NSE with (d) corresponding mean single year validation NSE. TI: temperature index model; HTI: Hock's temperature model (Hock, 1999); ETI: enhanced temperature model (Pellicciotti et al., 2005) with global radiation (ETIA) and net solar radiation (ETIB). (e) Photo of the automatic weather station Oukaimeden-SM (3200 m.a.s.l.). Figure credit: LMI TREMA.
Redrawn from Bouamri et al. (2018).

observations at the Oukaimeden weather station. They compared a traditional temperature-index (TI) melt model with various ‘enhanced’ versions that include different treatments of solar radiation (potential, global and net solar radiation). They performed extensive calibration and validation on different sub-periods and found that all models performed equally well in calibration when calibrated on a single year of observations, whereas the enhanced models with an additive radiation term were most transferable between years. The model including snow albedo (ETIB model) was found to perform best (Fig. 8, a, b). Conversely, when calibrating on multiyear periods all models performed equally well, with the simple TI model performing only slightly worse than the ETIB model that includes the net solar radiation (Fig. 8, c d). Hence, temporal variations in snowmelt could be adequately reproduced when sufficiently long periods are available for calibration of the TI model, as suggested previously by Réveillet et al. (2017) in the case of glacier melt modeling (Bouamri et al., 2018). This study also found large interannual variations in model parameters. While previous studies proposed that this parameter variability is related to climate conditions (Carenzo et al., 2009; Gabbi et al., 2014), Bouamri et al. (2018) showed no correlation between parameters and climate, but rather found equifinality in model coefficients (i.e., several combinations of the temperature and radiation parameters leading to similar performance, were the main reason for parameter variability). Equifinality was attributed to the partial collinearity of air temperature and solar radiation, which hampers parameter identifiability and increases their uncertainty. Despite equifinality, enhanced models were still found to better transfer to other years when calibrated over a short period, compared to the simple TI model. These results highlight the flexible nature of enhanced empirical melt models for the scarce data context of the Atlas, and the need to obtain long observational records to better constrain simpler models such as TI.

5.2. Semidistributed modeling

We have used two semidistributed snowmelt models: the Snowmelt Runoff Model (SRM) range (Boudhar et al., 2009) and the CemaNeige model (Hajhouji et al., 2018).

The Snowmelt Runoff Model (SRM) was used to simulate the streamflow at the outlet of the five subwatersheds of the Tensift River Basin throughout the High Atlas range, in which high melting rates contribute to baseflow from late winter to early summer. In this study, the added value of using remotely sensed snow cover area maps (SCAs) to simulate streamflow over ungauged basins, in this case, issued from the SPOT-VEGETATION instrument, was demonstrated. Indeed, accurate streamflow predictions are obtained when the remotely sensed data are used to force SRM instead of data from an in situ forcing station that missed a significant snow event in the early season (Fig. 9).

Following the interannual and interwatershed variability of the observed snow-covered area, the fractions of snowmelt contributing to streamflow are also variable from one year to another and from one watershed to another. It was revealed that the contribution of snowmelt to streamflow at the outlets of the watersheds varies from 15% to 51%.

The CemaNeige model (Valéry et al., 2014) was used as a module upstream of the conceptual model GR4J (Perrin et al., 2003) to simulate the rain-snow partition, the evolution of snow cover and snow melting. CemaNeige uses a discretization of the watershed in five altitudinal bands, which makes it possible to represent the altitudinal effect on temperature and precipitation. The melt is simulated using a temperature index approach accounting for the snowpack cold content evolution. This model was applied over the Rheraya watershed.

The daily snow cover simulated by CemaNeige is in good agreement with that extracted from the MODIS snow product during the period 2000 2009 ($R^2 = 0.63$). Additionally, the simulated daily snow water equivalent is consistent with that measured at a weather station. Finally, the streamflow simulation at the outlet of the Rheraya watershed reproduces the strong seasonal and interannual variability (Hajhouji et al., 2018).

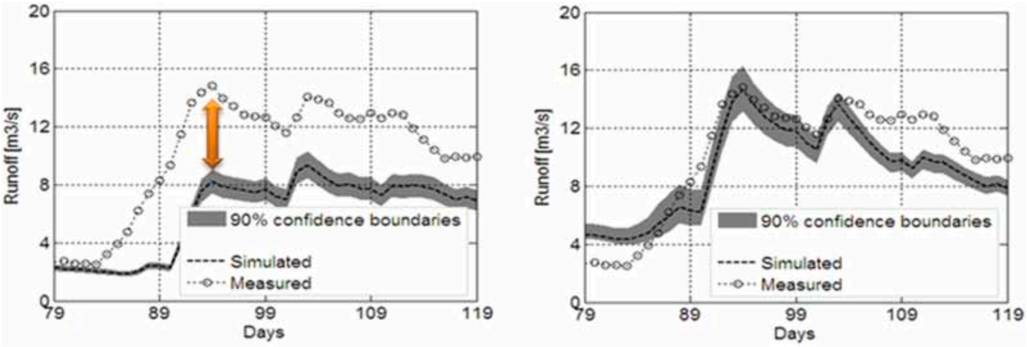

Fig. 9. Example of streamflow simulation; without using remotely sensed snow cover area maps (SCA) (figure on the left) and by using SCA (figure on the right) (from Boudhar et al., 2009).

5.3. Distributed modelling

Bouamri et al. (2021) used the same empirical melt models developed at the point scale by Bouamri et al. (2018) (Fig. 8) to model snow accumulation and melting in the Rheraya catchment. Bouamri et al. (2021) developed grid-based (100 m) temperature-index (TI) models enhanced with either potential clear-sky radiation (HTI model), global radiation (ETIA model) or net solar radiation (ETIB) and compared their respective performance in simulating snow cover area (SCA) over 14 years (2003–2016). SCA maps were derived from blended and cloud-filtered MODIS snow products from the Terra and Aqua satellites. The authors hypothesized that including solar radiation would explain more of the snow cover spatial heterogeneity, allowing us to later improve hydrological forecasts. They also found that while models enhanced with solar radiation did improve the simulation of snow cover area, inter-model differences in model performance were overall small, and the simple TI model appeared sufficient for basin-scale snowmelt modeling. This was attributed to two reasons: (1) topographic-induced variations in solar radiation tend to average out due to a near-uniform distribution of slope aspects in the basin (Fig. 10c), so that mean simulated melt rates, SWE and SCA do not differ greatly from using temperature alone to predict snowmelt; (2) the necessary aggregation of finer-scale model outputs to a resolution larger than key processes scales, such as that where interactions between topography and solar radiation are greatest, suppresses valid model information (Fig. 10a, b). The authors called for caution when using medium resolution satellite products such as MODIS to validate spatially distributed snow models, a widely used practice in snow hydrological modeling (e.g. Parajka and Blöschl, 2006).

Lumped or semidistributed models do not enable us to represent the high spatial heterogeneity of the snow cover in the Atlas Mountains. In semiarid mountain regions, the SWE distribution is influenced by many accumulation and ablation processes that are primarily controlled by weather patterns and complex topography (Gascoin et al., 2013; Winstral and Marks, 2002). Key factors are the dependence of precipitation and temperature on elevation, the effect of slope and aspect on incoming solar radiation, and the deflection of the wind field by the terrain. Distributed snowpack models aim to resolve the main effects of topography and the related variability in meteorological forcing on snowpack properties. They are typically based on a gridded representation of the terrain which is derived from a digital elevation model (DEM).

Physically based models compute the energy balance at the snow surface (Liston and Elder, 2006). A finer digital elevation model (DEM) resolution is expected to better capture the variability of the snow cover; however, the computing cost of distributed models increases

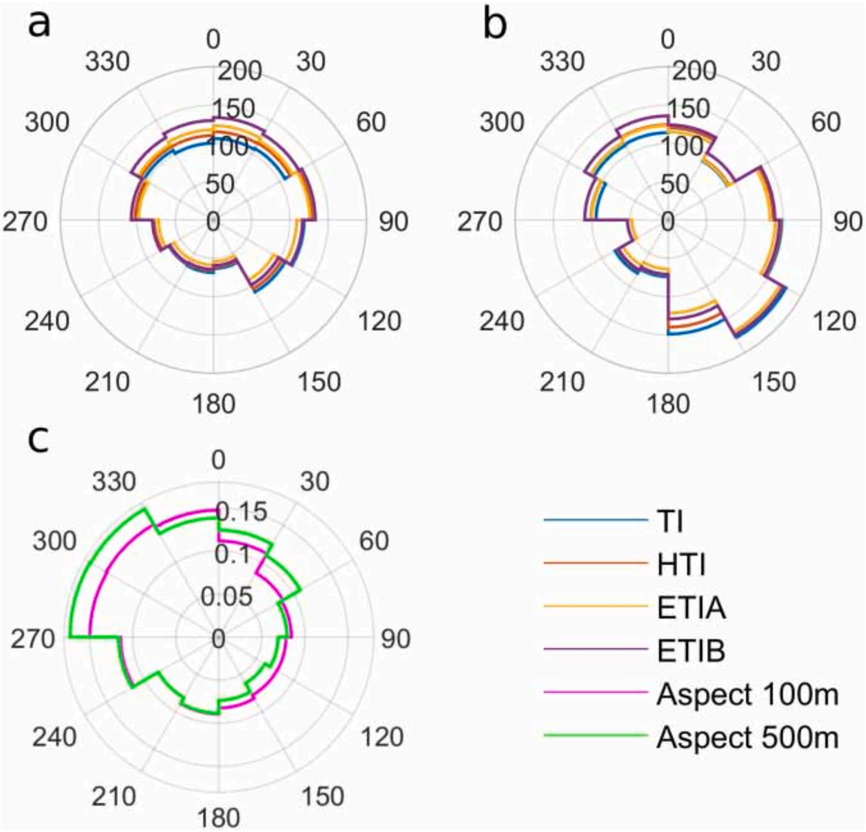

Fig. 10. Effect of aggregating modeled snow cover duration from the original resolution (100 m) to MODIS resolution (500 m) on the topographic snow cover variability in the Rheraya catchment. (a) Snow cover duration (days) by aspects simulated at 100 m resolution by four different empirical models and (b) aggregated at 500 m resolution; (c) slope aspects from the original 100 m resolution digital elevation model (green) and aggregated to 500 m (pink).

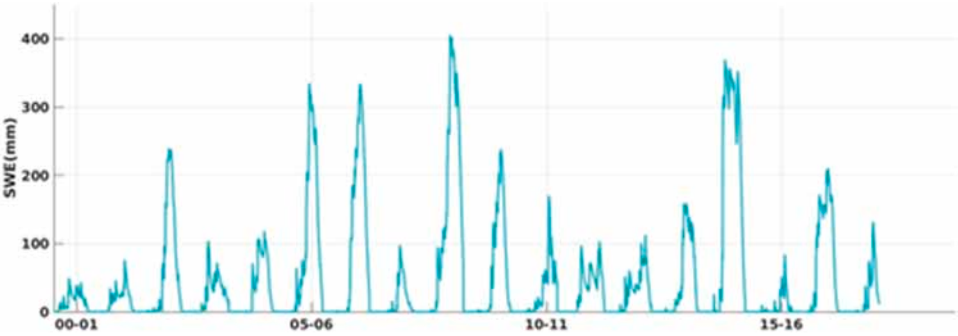

Fig. 11. Mean modeled snow water equivalent (SWE) over the Ourika catchment from 2000 to 2018.

strongly dependent on the DEM resolution (Baba et al., 2019). This is a critical issue, particularly for data assimilation, which requires large ensembles of model runs. For this reason (Baba et al., 2019) investigated the effect of the (DEM) resolution on the simulation of the snow water equivalent evolution in the High Atlas. This study was conducted using the distributed snowpack model SnowModel (Liston and Elder, 2006), which was forced by meteorological data provided by six automatic weather stations (AWS) located at the Rheraya catchment. The outcomes of this study revealed that 250 m spatial resolution reproduced efficiently the main spatial patterns of the snowpack and especially the SWE. The use of SnowModel from 2000 to 2018 at Ourika catchment showed the possibility of modeling the SWE evolution in such region even with the lack of weather station measurements (Fig. 11). In the high Atlas of Morocco, snow water equivalent varies widely spatio-temporally. It is strongly dependent on elevations (Baba et al., 2019) which control the amount of precipitation, and the gradient of air temperature. In normal seasons, the SWE in higher regions (>3000 m.a.s.l) is higher than 200 mm from December to March and could reach 800 mm or more as a peak during the wet years. Baba et al. (2021), paved the way to monitor the spatiotemporal evolution of the snowpack at Tensift subbasins on a daily scale since 1981. These studies highlighted that recent progress of meteorological reanalyses data (e.g., MERRA-2 and ERA5) could open new perspectives to overcome the data scarcity issue in the High Atlas. Although SnowModel fed by meteorological reanalyses data performed well compared to observations, significant biases remained in some years. Indeed, the R.M.S.E, between modeled air temperature with ERA5 and the observed temperature in four stations, was closer to 2 °C and with strong correlation for all of them ($R2 > 0.9$). While the comparison between modeled snow height and observed one at Oukaimeden summit (3200 m.a.s.l) showed that the R.M.S.E varies in general between 15 cm and 30 cm, except for 2010–2011 water year, where it reaches 43 cm. This suggests that data assimilation of remote sensing products could be used to reduce the biases of inputs (Liu et al., 2021). To that end, a particle filter using Sentinel-2 snow cover maps was developed to reduce precipitation and temperature bias and to better estimate SWE in a Tensift subbasin (Rheraya) (Baba et al., 2018a). This assimilation scheme has the potential to better estimate SWE in data-scarce regions when additional meteorological variables, e.g., shortwave radiations, are used as control variables of the scheme.

6. Snowmelt contribution to surface water and groundwater recharge

Evidence of the contribution of a fairly constant slow water redistribution within the fractured rock media has been provided by Chaponnière et al. (2008) using tracing silica and dissolved organic carbon concentrations in the streamflow at the outlet of the Rheraya watershed between April and December 2003. This slow component corresponds to almost 100% of the recharge flow during the driest months (summer) and might be mostly related to snowmelt. Using stable isotopes, groundwater recharge in the plains was shown to be linked to the mountain streamflow (Bouimouass et al., 2020; Boukhari et al., 2014, Howell et al., 2019).

To estimate the contribution of the end-members (rainfall and snowmelt), we used the isotopic mass balance model (N'da et al., 2016; Bouchaou et al., 2008). Based on the average oxygen-18 values of groundwater obtained in the Souss (N'da et al., 2016; Bouchaou et al., 2008; Bouragba et al., 2011; Dindane et al., 2003), Haouz aquifer (Rhoujjati et al., 2021, Boukhari et al., 2014) and Draa basin (Cappy, 2007; Warner et al., 2013), the contributions of precipitation (rain and snow) in the High Atlas and the surrounding plains were established.

The contribution of snowmelt varies between 42% and 80% in the different studied areas (N'da et al., 2016; Cappy, 2007). These results are consistent with those obtained by modeling the contribution of snowmelt to streamflow in the High Atlas, with a proportions varying between 15% and 51% (Boudhar et al., 2009; Cappy, 2007; Schulz and de Jong, 2004). These recharge rates indicate the role of the Atlas Mountains and the significant contribution of snow cover in supplying water resources in surrounding semiarid areas. In addition to this quantitative contribution, the snowmelt coming from the Atlas with lower mineralisation plays an important role in decreasing water salinity in many hydrologic systems beyond the experimental sites of the Rheraya catchment including the Souss, Tensift and Draa basins (Bouimouass et al., 2022, Bouchaou et al., 2008; Warner et al., 2013). Using isotopic tracers is a very relevant proxy but it should be extended to other catchments of the mountain range.

7. Climate change impact on snow reservoir

The climate evolution in the Mediterranean mountains suggests an earlier decline in high flows due to snowmelt in spring and a reduced influence of snow accumulation and snowmelt processes on river runoff (García-Ruiz et al., 2011). In Morocco, regional climate model

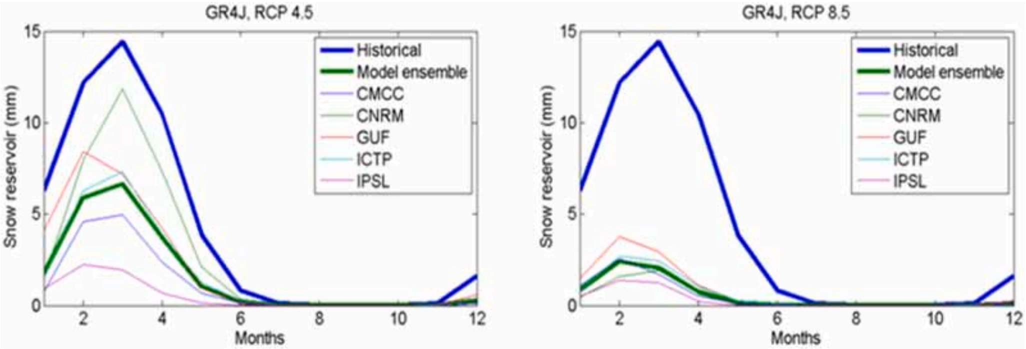

Fig. 12. Projected changes in snow stock levels from five regional climate model (RCM) simulations for the future period 2049–2065 (from Marchane et al., 2017).

simulations indicate that minimum temperatures are expected to increase more than the maximum temperature in most parts of the country, with a strong agreement between models (Filahi et al., 2017); mountainous areas showing higher increase than in the plains (Moucha et al., 2021). These projected changes in temperature are associated with a decrease in precipitation totals that could exceed − 20% following a north-south gradient (Filahi et al., 2017). Indeed, the southern regions of Morocco have been identified as the most at risk of strong climate change impacts in the region, with temperatures rising by 6 °C under the RCP8.5 scenarios leading to a sharp decrease in surface water resources due to the combined effects of declining precipitation and stronger evapotranspiration rates (Tramblay et al., 2018a). For the Rheraya basin in the High Atlas, hydrological scenarios have been provided with an ensemble of regional climate model simulations from the Med-CORDEX initiative (Marchane et al., 2017). The future projections for 2050 under two scenarios (RCP4.5 and RCP8.5) indicate a significant decrease in surface runoff (−19% to −63% depending on the scenario and hydro-logical model), associated with a strong reduction of snow accumulation, from − 57% under RCP4.5 but with a considerable spread with different models to − 82% under RCP8.5 with less model spread. (Fig. 12) (Marchane et al., 2017). Similar projections have been obtained for the Bin Ouidane catchment upstream of the Tadla region (Tramblay et al., 2018b), following the trends in observations indicating a shift from a snow-pluvial flow regime to a pluvial regime (Ahbari et al., 2017).

8. Research perspectives

In our work on Moroccan Atlas snow hydrology, the spatiotemporal dynamics of snow cover, the contribution of snowmelt to surface and groundwater recharge and the quantification of climate change impacts on snow have been evaluated. For this purpose, we used a scientific approach based on the synergy between in situ measurements, remote sensing of snow, and modeling. Despite the substantial advances that have been made, there are still many challenges to be taken up to contribute to a better understanding of Atlas snow hydrology.

The results of remote sensing and modeling are encouraging, but the integration of hydrometeorological data and in situ measurements for validation and model bias correction are needed. It would therefore be important to develop a hydrometeorological network, especially for, sublimation, direct SWE, snow depths and runoff measurements over the Moroccan Atlas watersheds.

The potential to map melting snow (Karbou et al., 2021; Nagler et al., 2016) and snow depth (Lievens et al., 2019) using C-band radar data such as those acquired by the Sentinel-1 satellite, should be assessed in the near future in the specific conditions of our study area characterized by marked orography. Likewise, new opportunities for monitoring the properties of snowpack will also be given by future missions at high spatial and temporal resolutions in the thermal infrared (TIR) domain, such as TRISHNA (Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment: https://ieeexplore.ieee.org/document/8518720) and LSTM (Land Surface Temperature Monitoring). Indeed, TIR data could be used to reduce uncertainties in the snowpack energy budget and assess the thermal inertia.

GRACE data have been used to monitor seasonal dynamics and long term trends of major snow and ice regions such as the Himalayas (e.g. Chen et al., 2016), Greenland (e.g. Slobbe et al., 2009), the Arctic (e.g.Niu et al., 2007) and Canada (e.g. Forman et al., 2012), and at a global scale (Frappart et al., 2006). In the Atlas, the mass of the snowpack over the mountain may fall within the uncertainty range of the GRACE and GRACE follow-on missions (Tapley et al., 2019). In the future, scientists have shown that a constellation of pairs of GRACE satellites could significantly improve the current limits of the temporal and spatial resolution of the GRACE missions and allow us to measure smaller mass fluctuations (Elsaka et al., 2013; Wiese et al., 2011). For now, it is interesting to use GRACE data to replace and compare the dynamics of the Atlas snowpack with that of the large hydrological basins of the region. Ouatiki et al. (submitted) found that, in the Oum Er Rbia and Tensift basins, the peak of the snow cover occurs 2–3 months ahead of the Total Terrestrial Water storage in the basins. They attributed this time lag to the fact that evaporation and groundwater recharge processes are more influenced by frequency of wet days and the length of the wet spells than the average and total monthly precipitation.

Given the importance of snow in the regional water balance and on socioeconomic activities, it is essential to characterize the snow deficits over the Atlas mountain area (snow drought). Snow drought is defined as a deficit in snow water equivalent (SWE) (Huning and

AghaKouchak, 2020). Huning and AghaKouchak (2020) used a standardized snow water equivalent index (SWEI) as a metric to characterize the temporal evolution of snow drought. This index is used to assess the duration and intensity of snow drought at the spatial scale.

Concerning the climate impacts, despite a lower sensitivity to warming of snowpack in the Atlas Mountains due to shallow and cold snowpack and the influence of net radiation on the snow energy and mass balance (López-Moreno et al., 2017), climate scenarios indicate strong impacts on snowmelt runoff. However, a better understanding of the snow ablation processes under climate change is needed for this region. If snowmelt is the dominant process for altitudes below 3000 m, snow sublimation at higher altitudes can exceed 40% (Schulz and de Jong, 2004), and this direct water loss to the atmosphere does not contribute to runoff. Current climate model simulations are not able to adequately reproduce these processes to quantify the relative impacts of the different components of the water balance; notably to look at the water partitioning between runoff, evaporation and sublimation. However, recent advances in regional climate modeling at convection-permitting scales (Coppola et al., 2020) open new perspectives to evaluate climate change impacts on the mountain hydrology in these regions.

Regarding operational aspects, we are developing a DSS (Decision Support System) tool in the framework of MorSnow-1 research program within the UM6P (Mohammed VI Poly-technic University). The intended DSS tool will integrate a multi-modelling scheme with a focus on the combined use of both ground measurement and spatial observations issued from different sensors as inputs. The Specific context of the ungauged basin will be taken into consideration toward earlier spring snowmelt and peak spring streamflows prediction.

9. Conclusion

In this paper, we presented an overview of the results obtained concerning our research activities on snow hydrology in the Moroccan Atlas Mountains during the past twenty years, from 2001 to 2021. We have also targeted unsolved issues to identify any challenges to be taken up to contribute to a better understanding of Atlas snow hydrology.

To understand snowpack processes and their influence on the hydrological basin response, our scientific approach was focused on the joint use of in situ measurements, remote sensing of snow, and modeling by taking into consideration the sparsity of ground-based networks. Our research activities are supported by in situ data measurements that we designed within the Tensift Climate and Water Observatory. Our approach has evolved with the development of space technology, leading to increasingly precise data in terms of spatial and temporal resolution as well as their availability for free. In terms of modeling, we opted for more physically based approaches, in contrast with the conceptual modeling tools that were implemented in the early studies.

Substantial results were obtained during this first phase of our work and concern the following points:

(1) The spatiotemporal dynamics of snow cover by remote sensing:

The dynamics of the snow cover area are characterized by very strong inter- and intra-annual variability both in terms of maximum and total snow cover and in terms of event distribution and season length. On average, it is found that the snow season occurs between November and April for the upper regions of the Atlas Mountains.

Using cluster analysis of the time series of snow cover areas at the catchment level over the Atlas Mountains, three groups of catchments were identified that have similar intra-annual snowfall dynamics. The first group (Moulouya, Oum'Erbia and Sebou) gathers the northern catchments, whereas the second group (Tensift, Souss, Draa) is located in the southern part. Finally, Group 3 isolates the last catchment, Ziz Rheris, located in the southeastern part of the Atlas chain.

The analysis of the bimonthly trends in the number of snowy days revealed a tendency for accumulation in February-March and a tendency for early snow melting in the spring (April-May).

(2) The impact of the North Atlantic Oscillation (NAO) on the snow-covered area of the main watersheds:

The impact of NAO on the snow cover (SCA) area is shown to be the result of the NAO's influence on temperature. The primary striking result is a significant positive correlation at 95% for the duration of the snow season and the date of complete ablation, which means that a positive (negative) NAO in spring may favor later (earlier) melting and link higher (lower) SCA on average.

(3) The snowmelt contribution to the flows of the Atlas rivers using different model-ing approaches:

Following the interannual and interwatershed variability of the observed snow-covered area, the fractions of snowmelt contributing to streamflow are also variable from one year to another and from one watershed to another. It was revealed that the contribution of snowmelt to streamflow at the outlets of the watersheds varies from 15% to 51%.

The assimilation of remotely sensed snow cover areas can improve the estimation of the SWE in this region. This assimilation was performed using Sentinel-2 snow cover products. These results indicated that remote sensing products and global-scale reanalysis, such as MERRA-2 or ERA5, have reached a level of accuracy which now allows the estimation of SWE distribution with physically-based models in the Atlas Mountains even without in situ measurements.

(4) Both modeling results and observed snow height highlighted that the snowpack has a strong annual variation. In general, the peak of snow height exceeds 1 m, and in some seasons (e.g 2008–2009 water year) it reaches two meters in the upper regions (>3000 m.a.s.l).

(5) The contribution of snowmelt to the surface and groundwater recharge using snow isotopes:

Based on the isotopes of water and the mass balance model, the contributions of precipitation (rain and snow) in the High Atlas and the surrounding plains were established. This contribution of snowmelt varies between 42% and 80% in the different areas studied. These results are consistent with those obtained by modeling the contribution of snowmelt. These recharge rates indicate the role of the Atlas Mountains and their significant snow cover in supplying water resources in surrounding semiarid areas.

(6) Quantification of climate change impacts on snow and associated runoff from the Atlas Mountains:

The quantitative evaluation of the possible impact of future climate for the High-Atlas focused on the Rheraya basin, indicates a significant decrease in surface runoff for 2050, with a strong reduction of half of the snow accumulation related to reduced precipitation and increased temperature. Similar projections have been obtained for the Bin Ouidane catchment upstream of the Tadla region, following the trends in observations indicating a shift from a snow-pluvial flow regime to a pluvial regime.

Although substantial progress has been made, we present challenges and some perspectives for future research on this topic to contribute to a better understanding of Atlas snow hydrology. Among these scientific challenges to be addressed, we cite: (1) Development of the hydrometeorological network, especially for, sublimation, direct SWE, snow depths and runoff measurements over the Moroccan Atlas watersheds for model validation and bias correction, (2) Extrapolation, over the Atlas Mountains, the use of the assimilation of Sentinel-2 snow cover products with the use of the reanalysis of remote sensing data will provide better results of snow water equivalent, (3) Replace and compare the dynamics of the Atlas snowpack with that of the integral water cycle over the region as recorded in the GRACE data as terrestrial total water storage, (4) Characterization of the temporal evolution of snow drought using a standardized snow water equivalent index (SWEI), (5) Evaluation of climate change impacts on the mountain hydrology in these regions using recent advances in regional climate modeling.

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Conflict of interest

The authors declare no conflict of interest.

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