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Elucidating the climate and topographic controls on stable isotope composition of meteoric waters in Morocco, using station-based and spatially-interpolated data

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ABSTRACT

Understanding the main controls on stable isotope variations in precipitation is fundamental for the interpretation of the hydrological cycle. However, spatio-temporal variations in $\delta^{18}O_p$ are poorly known in Morocco. Herein, we explore the relative influence of meteorological variables, spatial and orographic (altitudinal) effects, atmospheric circulation and moisture sources on precipitation stable isotopes in Morocco. Precipitation events and two-years-long monthly records from 17 rain-gauge stations in Morocco are investigated and compared in this study to global gridded records of monthly and annual stable isotopes in precipitation. We highlight that the main spatial controls on precipitation stable isotopes are the topography and the distance from marine source. The most depleted mean annual isotopes are located in the High Atlas Mountains ($\delta^{18}O_p = -9.56‰$ and $\delta^2H_p = -59.3‰$), while the most enriched isotope ratios exist in southwestern Morocco ($\delta^{18}O_p = -2.35‰$ and $\delta^2H_p = -7.47‰$). The well-constrained relationship between $\delta^{18}O_p$ and altitude describes a gradient of 0.11–0.18‰ per 100 m. The seasonal variation is expressed by a general enrichment that reaches −4.8‰ during the dry season, related to the recycled vapor contained within the summer precipitation. Notwithstanding the scarcity of temperature and precipitation measurements, the amount effect is observed in multiple stations during several rain events and precipitation seems to have more influence on $\delta^{18}O_p$ than temperature. Backward moisture trajectories indicate a distinct depletion in $\delta^{18}O_p$ in extreme events originating from the Atlantic Ocean. The presence of a rain shadow effect is also revealed on the lee side of High Atlas Mountains, southeastern Morocco.

1. Introduction

Stable isotope values ($\delta^{18}O$ and δ^2H) of precipitation are important indicators of modern climate dynamics (Johnson and Ingram, 2004; Cobb et al., 2007). The oxygen-18 isotope in precipitation ($\delta^{18}O_p$) in particular is widely applied to understand modern hydrologic processes, because it preserves information about the hydrologic cycle (Vuille and Werner, 2005; Liu et al., 2010). Moreover, paleoclimate reconstruction studies usually employ $\delta^{18}O_p$ in terrestrial archives as a paleoclimate indicator, based on the well-constrained relationship between air temperature, precipitation amount and $\delta^{18}O_p$ (Dansgaard, 1964) and because several natural archives preserve $\delta^{18}O_p$ directly (e.g., ice cores) (Grootes et al., 1989; Thompson et al., 1998) or are formed in equilibrium with $\delta^{18}O_p$ (e.g., pedogenic carbonates) (Cerling and Quade, 1993; Quade et al., 2007; *in* Fiorella et al., 2015). During Rayleigh distillation, the water vapor is subject to condensation when migrating to regions with low temperature. Thus, the equilibrium fractionation between the vapor mass and the condensing phases within the cloud preferentially removes heavy isotopes (^{18}O and ^2H) into the rainwater (Dansgaard, 1964; Clark and Fritz, 1997; Baldini et al., 2010). These processes are responsible for the observed decrease in $\delta^{18}O_p$ values with increasing latitude, distance inland, and altitude (Rozanski and Araguás-Araguás, 1995; Rozanski et al., 1993; Baldini et al., 2010). Additional influences on $\delta^{18}O_p$ are related to conditions at the marine water vapor source region (such as temperature, humidity, and isotopic composition),

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evaporation/transpiration effects as the air mass travels over continents, and non-equilibrium effects (Baldini et al., 2010).

At inter-annual timescales, several studies have shown that the North Atlantic Oscillation (NAO) and the Mediterranean Oscillation (MO) are the dominant modes of inter-annual variability controlling rainfall amount in Morocco (Lopez-Moreno et al., 2011; Labudová et al., 2013). However, the influence of the NAO and MO on Moroccan $\delta^{18}O_p$ variations and on the moisture sources at seasonal to inter-annual timescale has, to our knowledge, never been studied. This is in part due to the scarce local measurements of the spatio-temporal variability of modern δ^{18}Op, which should also include information on precipitation events collected at stations that are strategically situated (Ouda et al., 2005).

In the present study, we address these issues based on a network of 17 rain-gauge stations in Morocco monitoring daily or monthly rainfall totals. Taken collectively, these observations allowed an investigation of the relative influence of meteorological variables, spatial and orographic effects, atmospheric circulation, air mass history, and moisture source region on the stable isotope composition of precipitation events in Morocco.

2. Study area, data and methodology

2.1. Study area

Morocco is a country of 710,850 km^2 located in northwest Africa, on the edge of the African continent (Fig. 1), between the arid regions of the Sahara and the Mediterranean and Atlantic regions (Born et al., 2008). It is characterized by a rugged mountainous interior and large portions of desert (McSweeney et al., 2010). The climate in Morocco is as varied as its diverse geography. Morocco has wide-ranging geological features, including a vast coastline of around 3500 km^2, interior lowlands extending into the foothills and highlands of the Rif and Atlas Mountains ranges (Walroth, 2007), which rise up to 4150 m (at the Toubkal summit in the High Atlas). The mountain slopes are much more arid to the east, as they drop into the desert towards the Sahara. Generally, the climate in Morocco is moderate and subtropical, cooled by breezes off the Atlantic and Mediterranean (Born et al., 2008; Fink et al., 2010). The climate is controlled by heat and moisture brought in by air masses from the Atlantic and Mediterranean Sea interacting with the Saharan Low (Ouda et al., 2005; McSweeney et al., 2010). On average, the annual total rainfall ranges from 800 mm in the northwestern part of Morocco and many mountainous areas of the High Atlas to less than 100 mm in the South and southeastern areas. In the interior, temperatures are more extreme, winters can be fairly cold, and summers are very hot. In fact, the further areas are from the ocean, the more extreme winter and summer temperatures become. Mean summer temperatures in the coastal cities range from 18 to 28 °C. However, in the interior they frequently exceed 35 °C. In the High Atlas Mountains, temperatures can drop below 0 °C in winter and mountain summits are snowcapped throughout most of the year (Marchane et al., 2015).

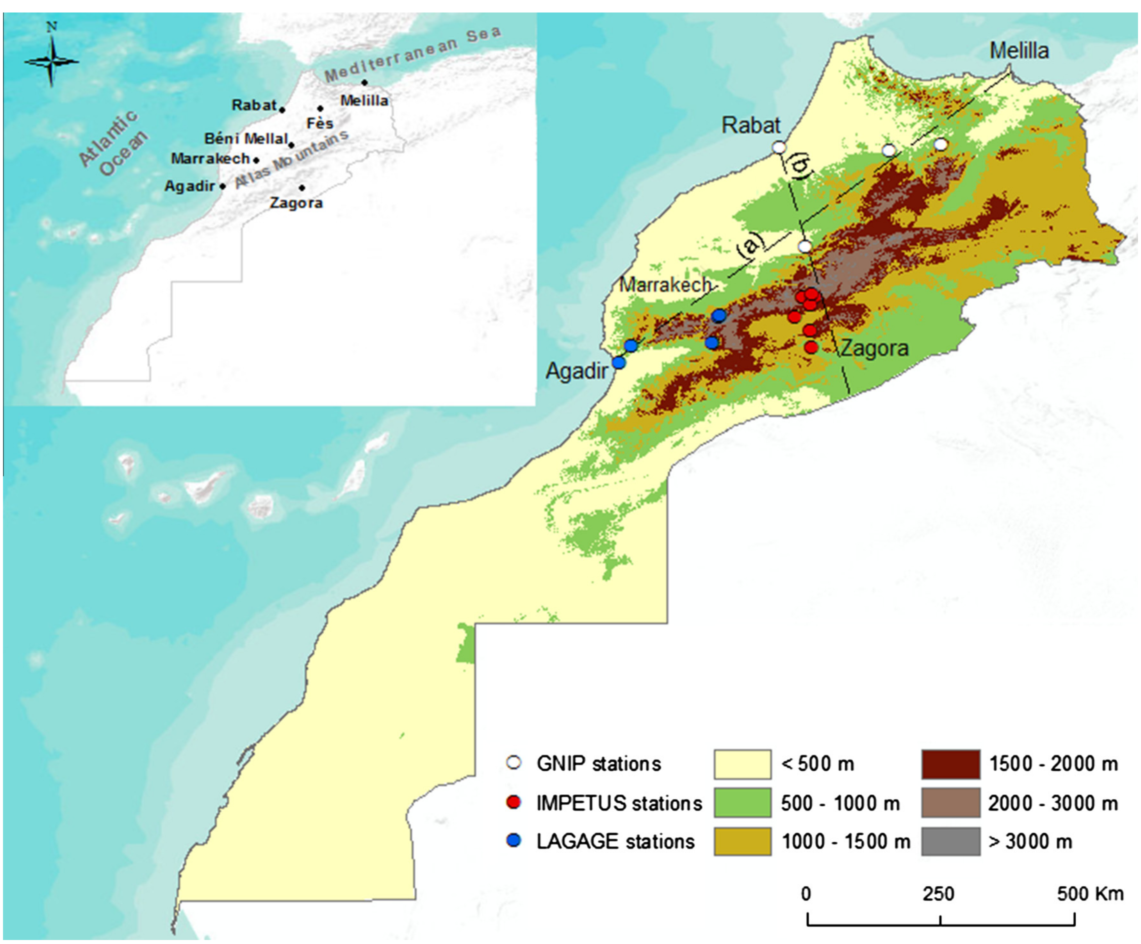

Fig. 1. Map of Morocco, showing the estimation of altitudes from a Digital Elevation Model (DEM) and the location of the stations where rainwater is collected from different monitoring networks: GNIP (Bab Bou Idir, Rabat, Béni Mellal and Fès), LAGAGE (Ifni, Oukaimden, Agadir and Wintimdouine) and IMPETUS (Mgoun, Bouskour, Tichki, Imeskar, Trab Labied, Agdz, Taoujgalt and Tizi Tounza). The dashed lines (a) and (b) are transects shown on Fig. 3. Altitudes higher than 1000 m.a.s.l. correspond to the Atlas Mountains.

2.2. Monitoring station data

In this study we use the isotopic composition of precipitation samples from 17 stations from three different monitoring networks (Fig. 1): (1) the IMPETUS project that monitored precipitation events between 2002 and 2006 (Cappy, 2007); (2) the Moroccan stations of the Global Network of Isotopes in Precipitation (GNIP) of the International Atomic Energy Agency (IAEA/WMO, 1998), which monitored monthly rainfall total and precipitation events during various periods between 1994 and 2004, depending on the station; and (3) the monitoring stations of the Laboratory of Applied Geology and Geo-Environment (LAGAGE) at Ibn Zohr University in Agadir (Morocco), recording precipitation events for several years between 2004 and 2015.

As shown in Table 1, the data consist of daily precipitation samples or monthly totals over different sampling periods for each station. Monthly sampling data are only available at the GNIP stations (Bab Bou Idir, Béni Mellal, Fès and Rabat), with the Fès station having a decade long record (1994–2004). Monthly rainfall samples were collected in a hermetic container following IAEA sampling procedures. These observations are the main source of regional information available to investigate the spatio-temporal controls of stable isotopes in meteoric waters in Morocco.

2.3. Global grids of stable isotopes in precipitation

Our current understanding of the spatial distribution of $\delta^{18}O_p$ in Morocco is hampered by the lack of a sufficiently dense precipitation sampling network. This problem is particularly acute in mountainous regions where $\delta^{18}O_p$ values of precipitation may vary dramatically over short distances due to altitude effects and microclimates, and in developing countries where financial considerations prohibit stable isotope sampling efforts (Lachniet and William, 2009). These problems may be partially overcome by relying on global grids of mean monthly and mean annual stable isotopes in precipitation, which offer a 95% confidence interval at a spatial resolution of 0.1° (Bowen and Revenaugh, 2003; Bowen et al., 2005).

To evaluate the spatial distribution of stable isotope composition of precipitation over Morocco, we used the grids of monthly and annual global hydrogen and oxygen isotope compositions of precipitation at 0.1° spatial resolution. The mean annual isotopic composition of precipitation used in the present study is an updated version of the Bowen and Revenaugh (2003) dataset, while the monthly product corresponds to the Bowen et al. (2005) dataset. We also computed the mean annual deuterium excess (d-excess, or d) directly from the $\delta^{18}O$ and δ^2H grids ($d = \delta^2H - 8\delta^{18}O$; Dansgaard, 1964; Froehlich et al., 2002).

3. Results and discussion

3.1. Spatial distribution of annual mean stable isotopes in precipitation

The gridded maps (Fig. 2) show an important spatial distribution of the mean annual stable isotopes in precipitation over Morocco with an overall tendency of both stable isotopes to decrease from south to north. The most depleted stable isotope values are recorded in the Atlas Mountains ($\delta^{18}O = -9.56$‰ and $\delta^2H = -59.3$‰), while the highest values exist in southwestern Morocco ($\delta^{18}O = -2.35$‰ and $\delta^2H = -7.47$‰). This distribution can be explained by the altitude effect and local climate conditions, since the highest areas show the lowest isotopic values in precipitation, while meteoric waters in the most arid regions (southern Morocco) are the most enriched in heavy isotopes. It is also noted that the most significant variability is observed in the Atlas Mountains region, where stable isotope values of precipitation vary dramatically over short distances due to the altitude effect and microclimates (Lachniet and William, 2009; Windhorst et al., 2013).

Moreover, the gridded map of d-excess shows the same distribution as $\delta^{18}O$ and δ^2H gridded maps, but with less spatial variation. Due to the altitude effect, the highest d-excess values exist in the Atlas Mountains. Such high d-excess values are often associated with snow or hail (Jouzel and Merlivat, 1984) with particularly depleted isotopic values. High d-excess values are also observed on the lee side of the Atlas Mountains, suggesting the presence of enhanced moisture recycling in this arid area. This effect of d-excess increase results from the partial re-evaporation of rain droplets beneath the cloud base as they fall to the ground surface, as described by Dansgaard (1964). In fact, the topographic barrier blocks the passage of humid air masses coming from the Atlantic Ocean, resulting in higher d-excess values in the dry areas of the lee side of the mountains.

Table 1
Stations where isotopic compositions of rainwater are available. Sampling scale and period, latitude, longitude, and available data ($\delta^{18}O$, δ^2H, Temperature "T" and Precipitation "P") at each station.

Data sources	Stations	Type of sampling	Sampling period	Longitude and latitude		Altitude (m)	Available data			
				X (°)	Y (°)		$\delta^{18}O$	δ^2H	T	P
GNIP stations	Bab Bou Idir	Monthly	2001–2002	−4.12	34.07	1500	×	×		×
	Rabat	Monthly and daily	2002–2003	−6.84	34.02	75	×	×	×	×
	Béni Mellal	Monthly and daily	2002–2003	−6.40	32.37	468	×	×	×	×
	Fès	Monthly	1994–2004	−4.98	33.97	571	×	×	×	×
IMPETUS stations	Mgoun	Daily	2002–2006	−6.45	31.50	3850	×	×		×
	Bouskour	Daily	2002–2004	−6.34	30.95	1420	×	×		×
	Tichki	Daily	2002–2006	−6.30	31.58	3260	×	×		×
	Imeskar	Daily	2002–2006	−6.25	31.50	2245	×	×		×
	Trab Labied	Daily	2002–2006	−6.58	31.17	1383	×	×		×
	Agdz	Daily	2002–2006	−6.32	30.65	1020	×	×		×
	Taoujgalt	Daily	2002–2005	−6.32	31.39	1900	×	×		×
	Tizi Tounza	Daily	2002–2004	−6.30	31.57	2960	×	×		×
LAGAGE stations	Ifni	Daily	2004–2008	−7.99	30.74	871	×	×		
	Oukaimden upstream	Daily	2011–2015	−7.87	31.18	3234	×	×		
	Oukaimden downstream	Daily	2012–2015	−7.86	31.20	2658	×	×		
	Agadir	Daily	2014–2015	−9.54	30.41	74	×	×		
	Wintimdouine	Daily	2014–2015	−9.34	30.68	1250	×	×		

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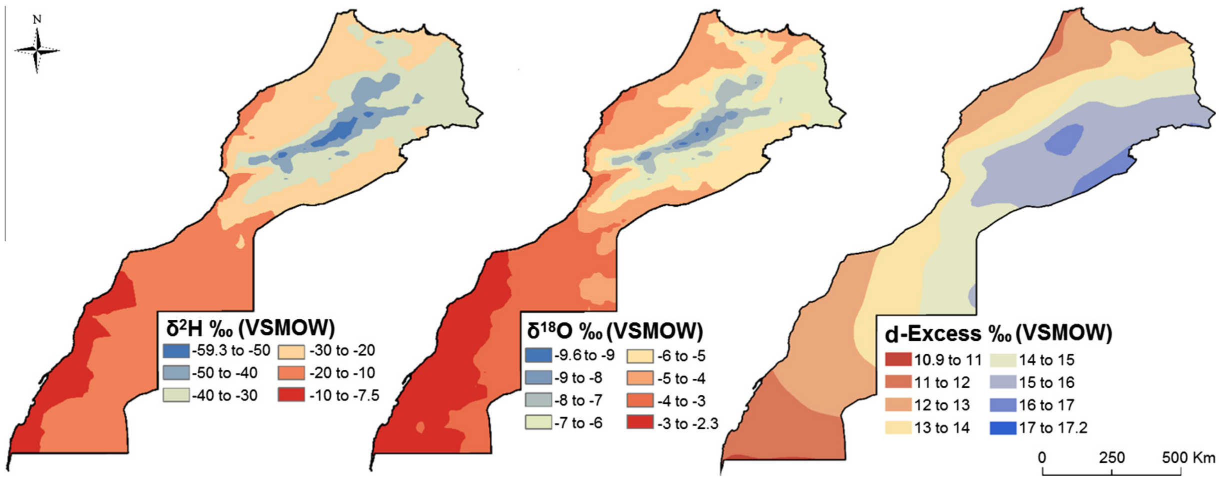

Fig. 2. Mean annual gridded values of the stable isotopes composition of meteoric waters in Morocco.

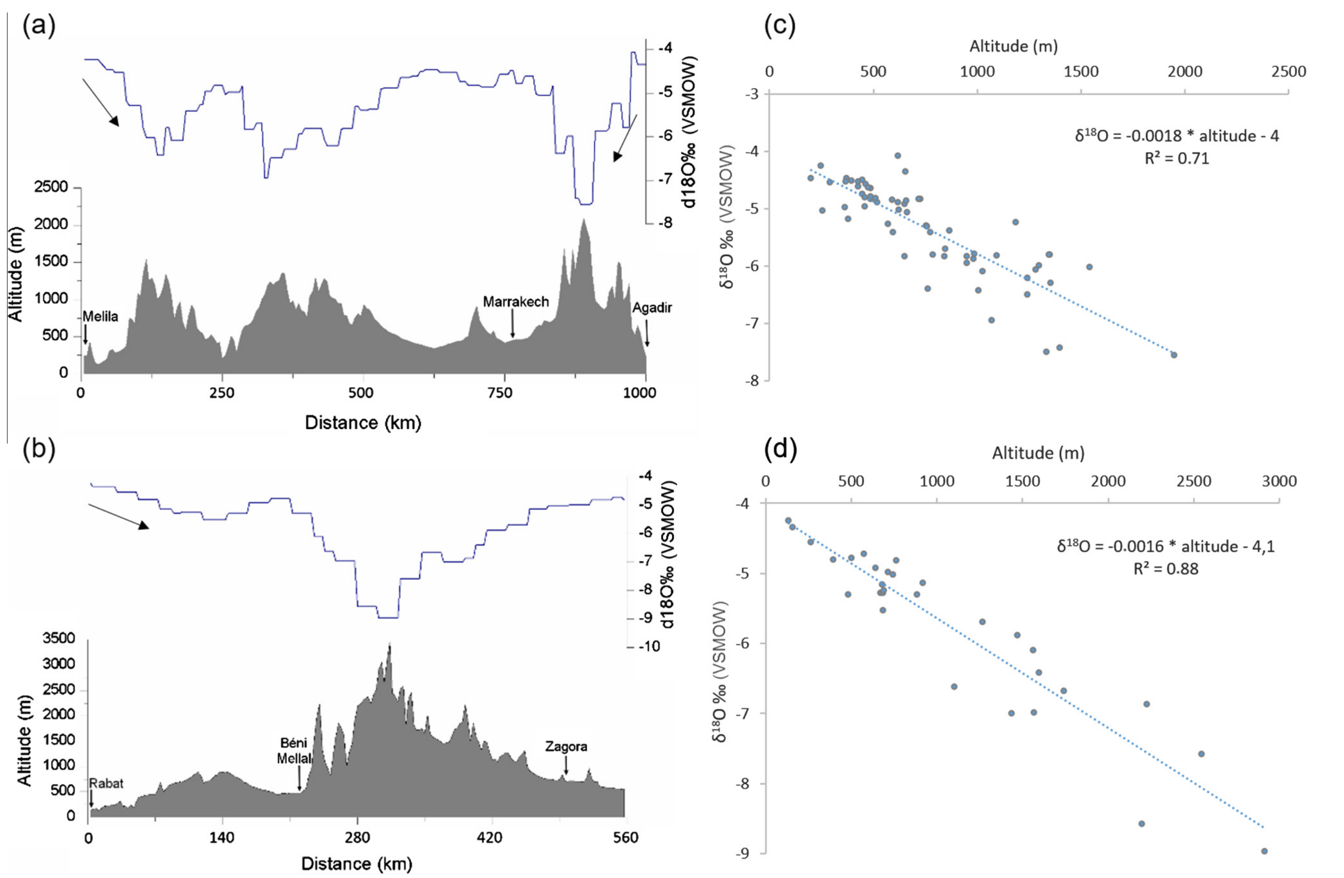

Fig. 3. Precipitation $\delta^{18}O_p$ (blue line) and topography (grey shaded profiles) along NE-SW (a) and NW-SE (b) transects across Morocco (see Fig. 1 for the locations of (a) and (b) transects). Relationship between altitude and $\delta^{18}O_p$ on the NE-SW (c) and NW-SE (d) transects, defining local altitude gradients for the transect lines of (a) and (b) respectively. The black arrows indicate the evolution of $\delta^{18}O_p$ with respect to the distance from the ocean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Besides the clear geographical variation in stable isotope values that appears dominated by the altitude effect and local climate conditions, spatial variations in $\delta^{18}O$ and $\delta^{2}H$ seem to also be controlled by distance from the sea. This continental effect, also referred to as the distance-from-coast effect (i.e. a progressive $\delta^{18}O$ depletion in precipitation with increasing distance from the ocean), varies considerably from area to area and from season to season, even over a low-relief profile. It is also strongly correlated with the temperature gradient and depends both on topography and climate regimes (Gat et al., 2001). In this case, the higher annual $\delta^{18}O$ values in the coastal area are likely related to its location near the main moisture source (Atlantic Ocean and Mediterranean Sea). These variations are apparent in stable isotope variations with distance from the Atlantic Ocean and Mediterranean Sea over for two transect lines oriented NE-SW and NW-SE (Fig. 3a and b, respectively). They are used here to compare

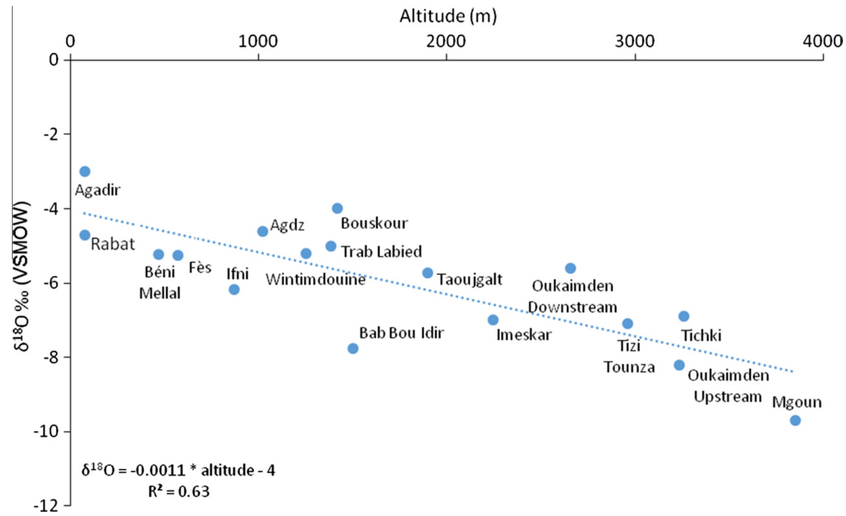

Fig. 4. Relationship between the altitude and the mean $\delta^{18}O_p$ values from the rainwater monitoring stations listed in Table 1.

the precipitation $\delta^{18}O$ variations from the Atlantic Ocean to the continent and from the Mediterranean Sea to the Atlantic Ocean.

$\delta^{18}O$ values decrease from −4‰ on the Atlantic coast at Rabat to −9‰ over the High Atlas Mountains, and subsequently increase to −5‰ on the lee side of the mountains, demonstrating a clear moisture recycling effect in Zagora. Similarly, $\delta^{18}O$ decreases from −4.2‰ on the Atlantic Coast at Agadir to −7.6‰ over the High Atlas Mountains and then increases to −4.3‰ in Marrakech. The decreasing $\delta^{18}O$ values with distance away from the Atlantic Ocean may be best interpreted as air mass rainout along the trajectory of Atlantic-sourced moisture, which is a manifestation of Rayleigh distillation as the fraction of moisture changes in an air mass (Brown, 2004). The same result is observed for the Mediterranean Sea, where $\delta^{18}O$ values decrease from −4.1‰ on Melilla's coast to −6.1‰ over the Rif Mountains, and subsequently increase to −4.5‰. There is a significant continental effect that reflects rainout of Atlantic-Mediterranean sourced air masses as they traverse the Rif Mountains.

Furthermore, the $\delta^{18}O_p$ minimum values over the High Atlas Mountains show a clear altitude effect, with values reaching −7.6‰ for transect (a) (altitude ~ 2000 m) and −9‰ for transect (b) (altitude ~ 3500 m). In fact, both transects show a good correlation between elevation and oxygen-18 with quite similar altitude gradients (0.16–0.18‰ per 100 m). However, the comparison of weighted mean $\delta^{18}O_p$ values of precipitation to the altitude from each monitoring station of GNIP, LAGAGE and IMPETUS (cf. Table 1 and Fig. 4) shows more spread around the regression line (R^2 = 0.63) when compared to the gridded values. The altitude gradient defined by these stations is 0.11‰ per 100 m. The altitude gradients from the gridded data seem to be more reliable since they show less variability (R^2 > 0.7) and they are closer to the results that were found by other authors in Morocco. According to Ouda et al. (2005) and Cappy (2007) the altitude gradient is 0.2‰ per 100 m, while El Ouali et al. (2011) defined an altitude gradient of 0.27‰ per 100 m.

3.2. Climate controls on the isotopic composition of precipitation

The $\delta^{18}O_p$ vs. δ^2H_p plot indicates a high variability of the isotopic composition in rainfall events. The $\delta^{18}O_p$ values range from −21.4‰ to −0.07‰ and δ^2H_p values range from −161.2‰ to 13.1‰ (Fig. 5). Based on 494 samples from rain events, a local meteoric water line is defined (LMWL: $\delta^2H = 7.73\ \delta^{18}O + 9.18$; R^2 = 0.93). The slope of 7.73 reflects that these samples have been enriched in ^{18}O, probably due to raindrop evaporation beneath the cloud base. This evaporation effect occurs during rainfalls due to

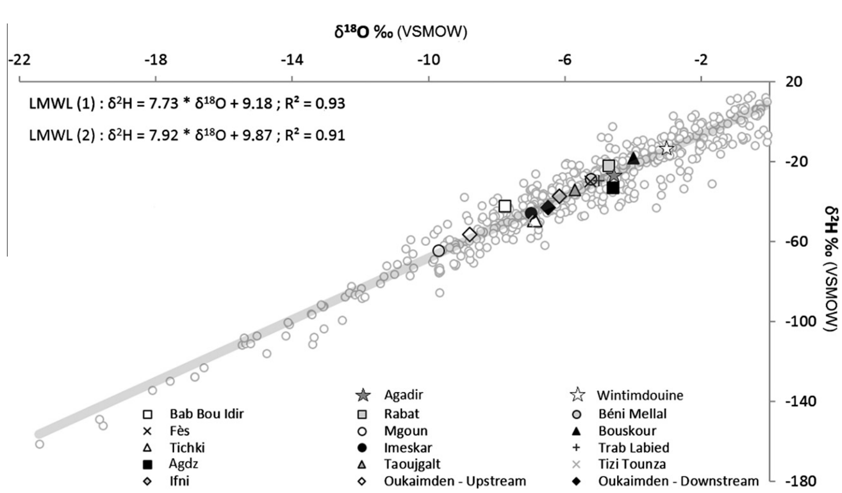

Fig. 5. Stable isotopic composition of 494 precipitation samples collected at the GNIP, IMPETUS and LAGAGE stations, defining the local meteoric water lines: LMWL-1 for all the data points (presented by grey open circles) and LMWL-2 for the weighted mean values (indicated by labeled markers).

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the arid conditions prevailing around the stations of southeastern Morocco (Bouchaou et al., 2008; Warner et al., 2013; Lgourna et al., 2015).

Another local meteoric water line is defined by the $\delta^{18}O$ weighted means with respect to precipitation: $\delta^2H = 7.92\ \delta^{18}O + 9.87$; $R^2 = 0.87$. This equation is quite close to the global meteoric water line (GMWL: $\delta^2H = 8\ \delta^{18}O + 10$; Craig, 1961). From the weighted mean values of precipitation stable isotopes, it is clear that the rain collected at Bouskour station is the most enriched in heavy isotopes ($\delta^{18}O = -4‰$ and $\delta^2H = -18.2$ ‰) due to the high aridity of this zone. Due to the altitude effect, the stations of Mgoun and Oukaimden (upstream) are the most depleted in heavy isotopes (Cappy, 2007).

To evaluate the meteorological effects on the isotopic composition of rain water, temperature and precipitation measurements are often compared to $\delta^{18}O_p$ values (Fig. 6). Temperature data are only available at three GNIP stations: (i) Béni Mellal, Rabat (daily data) and Fès (monthly data). The correlation between temperature and $\delta^{18}O_p$ at these stations shows an unreliable relationship between the two parameters ($R^2 < 0.15$; Table 2). This is probably related to the fact that the temperature effect is masked by other parameters such as relative humidity. Moreover, in arid or convective regions, most of the time, no intimate relationship can be found between temperature and precipitation and the isotope-temperature relationship breaks down. On the other hand, the relationship between $\delta^{18}O_p$ and rainfall amount informs the "amount effect" that expresses the depletion in heavy isotopes for higher rainfall amounts. In fact, the anti-correlation between rainfall amount and $\delta^{18}O_p$ is expressed for all stations by the general trend lines (Fig. 6b and c) and the negative correlation coefficients. The correlation between precipitation and $\delta^{18}O_p$ is nonetheless only significant in Bab Bou Idir, Fès, Rabat, Tizi Tounza, Imeskar, Taoujgalt and Agdz. Based on these results, it is suggested that the amount effect is a more dominant control than the temperature effect on $\delta^{18}O_p$ variations in Morocco. However, caution should be taken in such interpretations because of the lack of temperature measurements in many stations and also the scarcity of precipitation observations, particularly in the IMPETUS stations that are located in a very arid region where rainfall events are scarce.

On the other hand, after the examination of individual precipitation events in different stations, rapid variations in $\delta^{18}O$ are observed in samples collected within 24 h (Table 3). The magnitude of such small-scale temporal variations depends on the character of the precipitation process such as convective storms or weather fronts (Gat et al., 2001). The selected events shown in Table 3 indicate a significant decrease of isotopic values by the end of each event. Thus, changes in the isotopic composition due to the amount of precipitation could be clearly deduced for these events in Rabat, Béni Mellal, Agdz, Bouskour and Trab Labied.

Additionally, to evaluate how the seasonality can influence the spatial distribution of $\delta^{18}O_p$ values, we calculated the mean seasonal $\delta^{18}O$ for the two main climatological seasons (the humid period from October to January and the dry period from June to September) (Fig. 7). The calculation process was based on the mean monthly precipitation grids of $\delta^{18}O_p$. The $\delta^{18}O_p$ gridded data show an important enrichment during the dry season compared to the humid period. This enrichment of heavy isotopes in summer precipitation can be attributed to evaporative enrichment in the falling droplets beneath the cloud base, effective during warm and dry months (Peng et al., 2015) when rain amounts are small. Thus, the partially evaporated rain is characterized by relatively high $\delta^{18}O_p$. The seasonal cycle in $\delta^{18}O_p$ shows the highest variability in the High Atlas Mountains where $\delta^{18}O_p$ ranges from -5 to $-9.8‰$, with the lowest values during the October to January wet season (N'da et al., 2016). Less seasonal variation is observed in

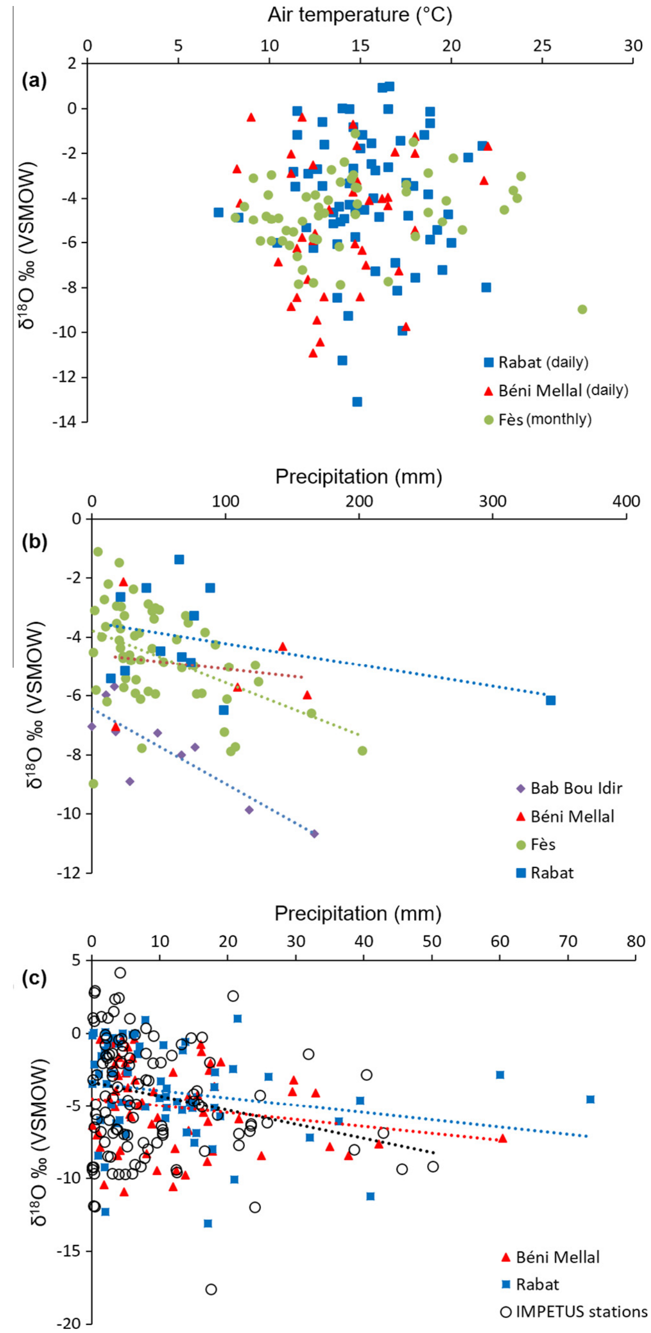

Fig. 6. Relationship between $\delta^{18}O_p$ and meteorological variables (temperature and precipitation); (a) $\delta^{18}O_p$ vs. air temperature (°C) from GNIP data (b) $\delta^{18}O_p$ vs. rainfall amount (mm) from monthly GNIP data and (c) daily data from GNIP and IMPETUS stations.

the area of Moroccan Sahara (southern Morocco) due to the scarcity of precipitation in this region, which results in an important year-long moisture recycling.

3.3. Atmospheric teleconnections and moisture trajectories

One of the most pronounced factors that determine the offset of monthly data at any station from a classical meteoric water relationship is different source characteristics of the moisture, either due to seasonal change of meteorological conditions over the ocean, or different location of the source regions (Gat et al., 2001). In Morocco, precipitation events are associated with three

Table 2
Correlation between $\delta^{18}O_p$ and meteorological parameters: rainfall amount (P, mm) and temperature (T, °C).

	Station	T	n	P	n
Monthly	Bab Bou Idir	–	–	−0.85*	10
	Béni Mellal	–	–	−0.17	5
	Fès	0.11	56	−0.44*	60
	Rabat			−0.23	12
Daily	Beni Mellal	0.14	40	−0.19	63
	Rabat	−0.023	65	−0.22**	65
	Tizi Tounza	–	–	−0.8*	9
	Mgoun	–	–	−0.33	7
	Tichki	–	–	0.15	14
	Imeskar	–	–	−0.73**	6
	Taoujgalt	–	–	−0.38*	24
	TrabLabied	–	–	−0.3	17
	Bouskour	–	–	0.06	18
	Agdz	–	–	−0.51*	21

* $p < 0.01$.
** $p < 0.05$.

Table 3
Small-scale temporal variations of stable isotopes in precipitation in Morocco (selected events show a significant decrease of isotopic values by the end of each event).

Station	Altitude	Date	^{18}O	^{2}H	d-Excess	P (mm)	NAO index	MO index
Rabat	75 m	11/01/2001	−4.6	−24.7	12.1	–	−1.867	−2.053
		12/01/2001	−5.72	−25.8	19.96	–	−1.298	−2.604
		13/01/2001	−7.44	−45.8	13.72	–	−0.14	−1.041
Béni Mellal	468 m	10/04/2002	−1.68	−4.8	8.64	6	−0.203	−1.603
		11/04/2002	−3.19	−7.9	17.62	29.7	0.474	−3.517
		12/04/2002	−3.73	−9.1	20.74	5.3	1.047	−2.907
Rabat	75 m	14/11/2002	−3.44	−16.8	10.72	2.2	−2.024	−3.99
		15/11/2002	−4.62	−27.5	9.46	39.5	−1.898	−4.627
		16/11/2002	−6.06	−36.8	11.68	36.3	−0.895	−3.279
Béni Mellal	468 m	23/11/2002	−4.01	−12.4	19.68	9.1	−2.931	−1.591
		24/11/2002	−4.09	−13	19.72	32.9	−3.455	−2.515
		25/11/2002	−10.44	−73.1	10.42	1.8	−2.848	−2.489
		26/11/2002	−10.92	−71.5	15.86	4.8	−2.261	−1.146
Béni Mellal	468 m	09/12/2002	−2.69	−8.2	13.32	5	−1.466	0.14
		10/12/2002	−2.89	−7.3	15.82	3.9	−0.372	−1.35
		11/12/2002	−5.75	−25.5	20.5	5.8	−0.031	−1.601
		12/12/2002	−6.34	−35.7	15.02	0.1	−0.686	−1.285
Agdz	1020 m	11/12/2002	−6	−45.15	2.85	2.6	−0.031	−1.601
		12/12/2002	−6.185	−48.85	0.63	–	−0.686	−1.285
		13/12/2002	−8.615	−58.65	10.27	7.8	−1.433	−2.063
Béni Mellal	468 m	06/01/2003	−0.39	6.1	9.22	4.5	−0.189	−1.464
		08/01/2003	−0.38	3.1	6.14	6.3	−1.389	−1.23
		09/01/2003	−2.03	−0.9	15.34	17.5	−2.245	−1.66
		10/01/2003	−4.2	−11.2	22.4	15.6	−1.485	−2.052
Rabat	75 m	08/01/2003	−1.16	3.9	13.18	13.4	−1.389	−1.23
		09/01/2003	−2.67	−0.6	20.76	18.1	−2.245	−1.66
		10/01/2003	−2.81	−4.2	18.28	1.1	−1.485	−2.052
		11/01/2003	−4.84	−18.5	20.22	5.4	−0.259	−0.349
Bouskour	1420 m	17/03/2003	2.59	30.3	9.6	20.8	−0.231	0.218
		17/03/2003	−1.67	2.6	15.9	–	−0.231	0.218
		17/03/2003	−2.19	−3.2	14.4	–	−0.231	0.218
Rabat	75 m	17/03/2003	−1.41	−0.5	10.78	6.7	−0.231	0.218
		18/03/2003	−2.44	−8.6	10.92	20.8	−0.192	1.054
		19/03/2003	−7.25	−46.5	11.5	–	0.455	1.086
Agdz	1020 m	21/10/2003	−6.655	−36.85	16.39	10.4	−1.927	−1.745
		21/10/2003	−12.16	−86.45	10.83	–	−1.927	−1.745
		22/10/2003	−15.23	−110.95	10.89	36.8	−1.439	−1.575
		23/10/2003	−17.59	−129.8	10.96	17.6	−1.41	−1.128
		23/10/2003	−18.10	−134.2	10.64	–	−1.41	−1.128
Trab Labied	1383 m	21/10/2003	−4.89	−24.3	14.9	15.8	−1.927	−1.745
		22/10/2003	−12.34	−85.6	13.1	43.4	−1.439	−1.575
		22/10/2003	−13.42	−96.5	10.9	–	−1.439	−1.575
		23/10/2003	−21.43	−161.2	10.2	11	−1.41	−1.128
Bouskour	1420 m	20/02/2004	−5.66	−32.3	13.0	18.5	−2.137	−5.279
		21/02/2004	−7.01	−42.4	13.7	5.2	−2.454	−4.327
		22/02/2004	−10.63	−69.5	15.5	–	−2.345	−1.857

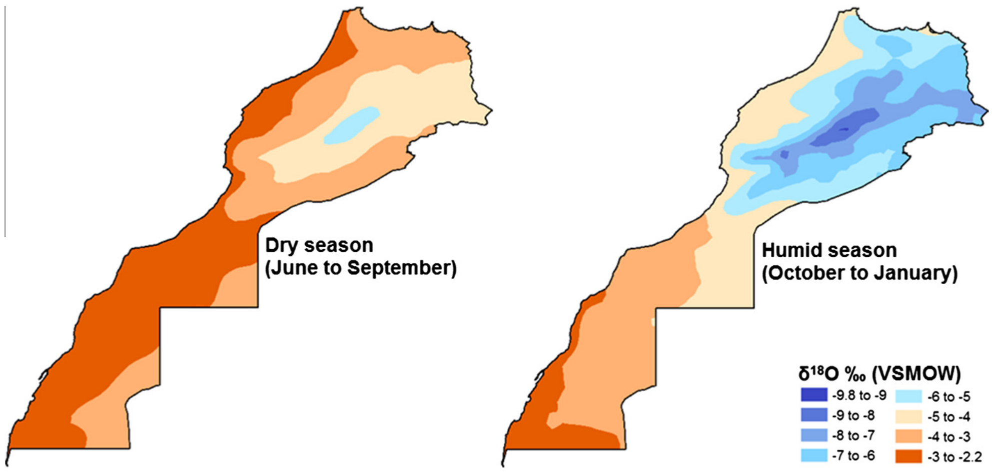

Fig. 7. Seasonal variation of $\delta^{18}O_p$ between the dry season (June to September, left map) and the humid season (October to January, right map).

distinct meteorological situations: (i) a NW circulation bringing relatively cold air masses from the central Atlantic Ocean, (ii) cold air masses coming from the North Atlantic along the western part of the Mediterranean Sea, and (iii) cold and warm air masses coming from the eastern Mediterranean Sea and partly over North Africa along the western part of the Mediterranean Sea (Knippertz et al., 2003; Ouda et al., 2005). Precipitation events are usually related to a negative phase of the NAO in Morocco (Knippertz et al., 2003; Lopez-Moreno et al., 2011). From our data, the daily NAO index is negative in 93% of rain events. The positive values of the NAO index observed in Rabat and Béni Mellal are explained by the influence on these stations of other atmospheric teleconnection systems or being dominated by Mediterranean-sourced air masses (Ouda et al., 2005) or local effects like moisture recycling. This fact is confirmed by the high d-excess values in many rainfall events. It is also important to note that some other teleconnection patterns are known to influence precipitation amount at inter-annual timescales in the Mediterranean region to a lesser extent, such as the East Atlantic or the Scandinavian patterns (Lionello, 2012; Filahi et al., 2016). We focus on the relationships between the isotopic composition of precipitation in Morocco and the large-scale atmospheric circulations over the North Atlantic-European-Mediterranean area, represented by NAO and MO indices. The daily NAO index corresponds to the NAO patterns, which vary from one month to the next. It is constructed by projecting the daily (00Z) 500 mb height anomalies over the Northern Hemisphere onto the loading pattern of the NAO. The MO index is defined by Palutikof et al. (1996) and Conte et al. (1989) as the normalized pressure difference between Algiers (36.4°N, 3.1°E) and Cairo (30.1°N, 31.4°E).

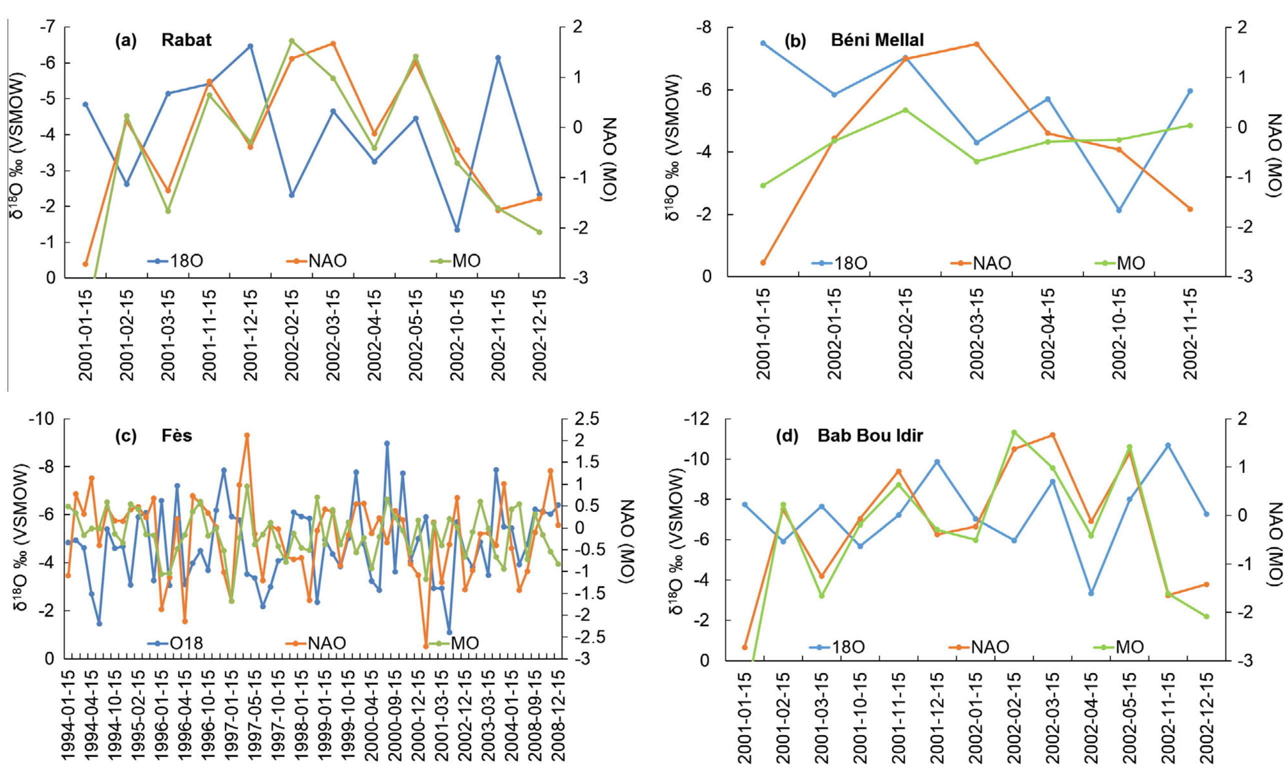

Fig. 8. Monthly $\delta^{18}O_p$ values from GNIP stations in Morocco compared to the monthly NAO and MO indices. The monthly NAO index and MO index values are calculated from the daily indices averaged over the monthly sampling periods.

Table 4
Spearman's rank correlation between monthly stable isotopes, rainfall amount and NAO and MO indices.

	Rabat (n = 12)		Fès (n = 64)		Bab Bou Idir (n = 13)		Béni Mellal (n = 7)	
	NAO	MO	NAO	MO	NAO	MO	NAO	MO
$\delta^{18}O$	0.22	0.15	−0.03	0.21	0.26	0.1	0.4	0.05
$\delta^{2}H$	0.17	0.13	−0.04	0.18	0.31	0.12	0.54	0.18
d-Excess	−0.14	0.01	0.07	−0.1	0.51**	0.34	0.18	0.08

** $p < 0.05$.

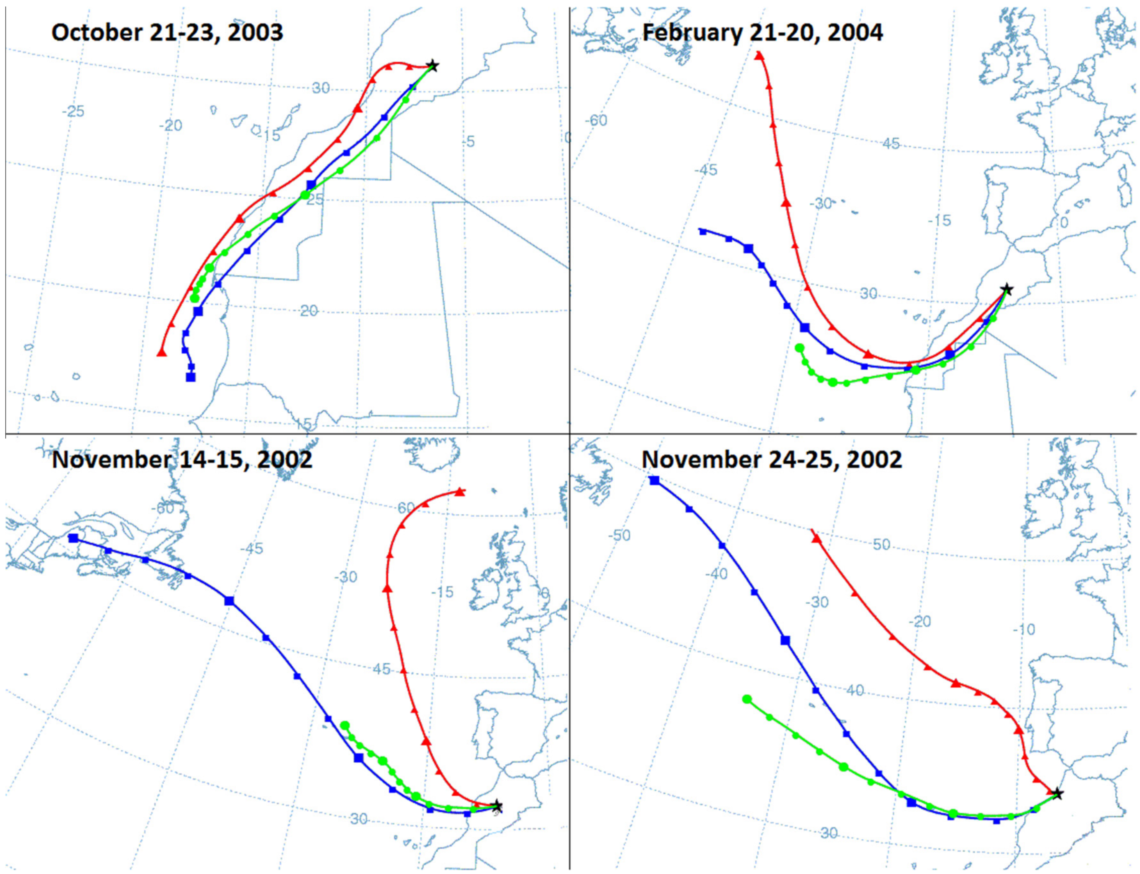

Fig. 9. 120-h back trajectories of particular extreme events in Morocco at three atmospheric levels 500 (red), 700 (blue) and 850 hPa (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Comparison of NAO and MO indices with δ^2H_p, $\delta^{18}O_p$ and d-excess values on a monthly scale for the Moroccan GNIP stations (Rabat, Béni Mellal, Bab Bou Idir and Fès) shows high variabilities in all parameters (Fig. 8). The statistical relationship of the non-parametric Spearman's (1904) rank correlation with NAO and MO indices is shown in Table 4. The results indicate a significant correlation between the NAO index and d-excess at Bab Bou Idir station. Other correlation coefficients remain unreliable in other parameters and for other stations.

This complex relationship between air-mass origin and the isotopic composition of individual precipitation events in Morocco prompted examination of particular events in detail. The air mass history of the events of interest was estimated using five-day (120-h) kinematic back trajectories originating at the concerned station. Back trajectories were computed at three atmospheric levels (500, 700 and 850 hPa, according to recommendations by the U.S. National Oceanographic and Atmospheric Administration Air Resources Laboratory (NOAA ARL)), which provides a good first approximation of the levels from which frontal and synoptic precipitation is primarily derived. We used the NOAA ARL Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model (http://www.arl.noaa.gov/HySPLIT_FAQ.php; Draxler and Rolph, 2003). HYSPLIT computes trajectories using synoptic scale, accurate wind field data generated by the global data assimilation system (GDAS) forecast/analysis model that is run operationally by the U.S. National Weather Service's National Center for Environmental Prediction (NCEP) and stored in the final run (FNL) data archive (Baldini et al., 2010).

Based on the available data of isotopic composition of precipitation, the most ^{18}O-depleted rain event occurred between October 21 and 24, 2003, in Taoujgalt (−21.43‰). In fact, this extreme event was recorded at five stations in southeastern Morocco with the most $\delta^{18}O$-depleted values and the highest daily rainfall amount (Trab Labied 43.4 mm, Tichki 39.2 mm, Agdz 36.8 mm, Imeskar 34 mm and Taoujgalt 30 mm). Another extreme event occurred in the same area on February 20, 2004, and was recorded at three stations (Imeskar 45.6 mm, Taoujgalt 38.6 mm and Bouskour 18.5 mm). The back trajectories of both events reveal tropical-extratropical interactions where the moisture is transported northward. Most of the transport occurs above the dry Saharan planetary boundary layer (Fig. 9). Consequently, the isotopic composition of this event is related to rainout, but can also

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be explained by the rain shadow effect. According to Knippertz et al. (2003), the High Atlas Mountains create an orographic lifting responsible for the rainfalls. Consequently, the windward side of the High Atlas mountain range tends to receive greater precipitation than the lee side, which results in more depleted $\delta^{18}O_p$ than normally expected for the distance from the moisture source. This rain shadow effect is only observed in extreme events that can cross the High Atlas Mountains and reach their lee side. Such kind of extreme events are uncommon in southeastern Morocco. For this reason, the rain shadow effect is not observed along the transects of Fig. 3, because it is masked by the mean annual $\delta^{18}O_p$ values (in the case of Zagora).

High d-excess values are observed in the daily GNIP data indicate enhanced moisture recycling in Rabat and Béni Mellal, which could be due to interaction with the Mediterranean Sea. However, backward trajectories for the most extreme events, which occurred on November 24–25, 2002, in Rabat (114.3 mm) and on November 14–15, 2002, in Béni Mellal (102.6 mm), reveal that both events are related to a NW circulation, bringing humid air masses from the Atlantic Ocean. It is also interesting to note that there is a distinct depletion of $\delta^{18}O_p$ values in these events (−11.23‰ in Rabat and −8.45‰ in Béni Mellal), suggestive of the amount effect. However, the increasing d-excess values at these events suggest a response to an enhanced moisture recycling effect (d-excess equals 22.5 and 25.7‰ for Rabat and Béni Mellal, respectively).

4. Conclusion

Herein, we demonstrate that the main controls on the spatial distribution of stable isotopes in precipitation over Morocco are the topographic effect and the distance from the sea. The most depleted mean annual values of stable isotopes are recorded in the High Atlas Mountains ($\delta^{18}O = -9.56‰$ and $\delta^2H = -59.3‰$) and the most enriched values are highlighted in southwestern Morocco ($\delta^{18}O = -2.35‰$ and $\delta^2H = -7.47‰$). There is a well-constrained relationship between $\delta^{18}O$ and altitude, with a gradient between 0.11 and 0.18‰ per 100 m. The High Atlas Mountains constitute a topographic barrier, limiting the passage of humid air masses coming from the Atlantic Ocean, which results in higher d-excess values in the dry areas of the lee side of these mountains.

Seasonally, there is an important enrichment during the dry season compared to the humid period due to summer precipitation containing more recycled water condensed at a warmer temperature. The highest seasonal variability is recorded in the Atlas Mountains, where $\delta^{18}O_p$ ranges from −5 to −9.8‰, with the lowest values during the humid season (October to January).

Two local meteoric water lines are defined based on rainfall events and monthly data from 17 monitoring stations: $\delta^2H = 7.73\ \delta^{18}O + 9.18$ and $\delta^2H = 7.92\ \delta^{18}O + 9.87$, respectively. These equations are quite close to the global meteoric water line with a slope slightly under 8 due to the evaporation effect. The evaluation of the meteorological controls on the isotopic composition of rain waters does not indicate any relationship between temperature and $\delta^{18}O_p$ ($R^2 < 0.15$). However, the amount effect was observed during several rainfall events in many stations (Rabat, Béni Mellal, Agdz, Bouskour and Trab Labied).

Furthermore, the higher annual $\delta^{18}O$ in the coastal area relative to the continental area is likely related to its location near the main moisture sources (Atlantic Ocean and Mediterranean Sea). The moisture backward trajectories computed with the HYSPLIT model for the most ^{18}O-depleted extreme rain events (October 21 and 24, 2003; February 20, 2004) recorded in the southeastern stations, revealed that moisture originating in the tropical Atlantic is transported northeastward and that most of the transport occurs above the dry Saharan planetary boundary layer. Consequently, the isotopic composition of this event is related to rainout and the rain shadow effect, since the High Atlas Mountains create an orographic lifting responsible for the rainfalls. As for the GNIP event data, the backward trajectories of two extreme events (November 24–25, 2002, and November 14–15, 2002) show a NW circulation, which brings relatively cold and warm air masses from the Atlantic Ocean with a distinct depletion of heavy isotopes in these events (−11.23‰ in Rabat and −8.45‰ in Béni Mellal).

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