Journal of Hydrology 543 (2016) 305–315

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

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

Yassine Ait Brahim [a,*], Lhoussaine Bouchaou [a], Abdelfettah Sifeddine [b], Myriam Khodri [c], Barbara Reichert [d], Francisco W. Cruz [e]

[a] Laboratory of Applied Geology and Geo-Environment, Ibn Zohr University, BP8106, 80060 Agadir, Morocco
[b] Institute of Research for Development, 32 Avenue Henri Varagnat, 93143 Bondy, France
[c] LOCEAN, UMR CNRS/IRD/MNHN, Boîte 100, 4, Place Jussieu, 75252 Paris Cedex 05, France
[d] Steinmann Institute, University of Bonn, Nussallee 8, 53115 Bonn, Germany
[e] Institute of Geoscience, University of São Paulo, R. do Lago, 562, Cidade Universitária, São Paulo, SP 05508-080, Brazil

ARTICLE INFO

Article history:
Received 21 March 2016
Received in revised form 12 August 2016
Accepted 2 October 2016
Available online 5 October 2016
This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Philippe Negrel, Associate Editor

Keywords:
Precipitation
Stable isotopes
Morocco
Amount effect
North Atlantic Oscillation

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),

* Corresponding author.
E-mail address: aitbrahim.yassine@gmail.com (Y. Ait Brahim).

http://dx.doi.org/10.1016/j.jhydrol.2016.10.001
0022-1694/

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).

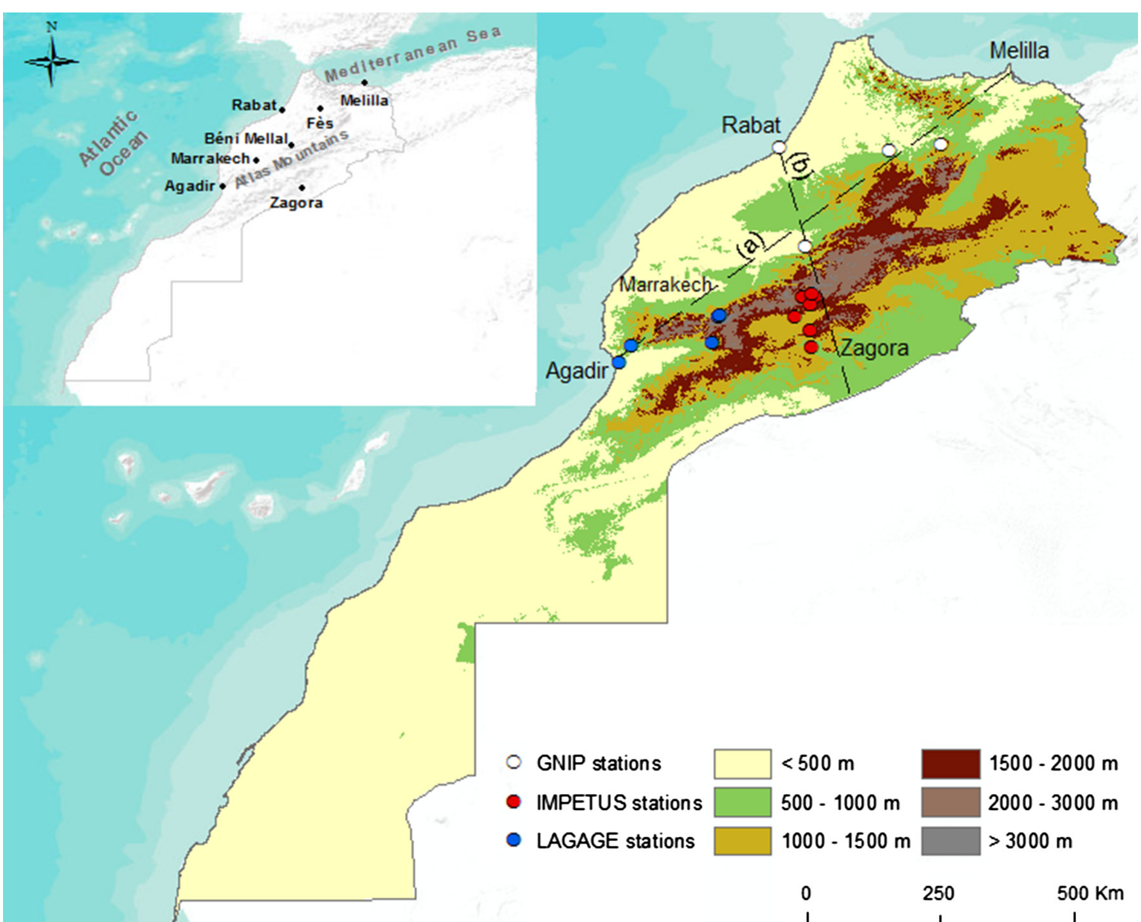

Fig. 1. Map of Morocco, showing the estimation of altitudes from a Digital Elevation Model (DEM) and the location of the stations where rainwater is collected from different monitoring networks: GNIP (Bab Bou Idir, Rabat, Béni Mellal and Fès), LAGAGE (Ifni, Oukaimden, Agadir and Wintimdouine) and IMPETUS (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.