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Quantification of the impact of moisture source regions on the oxygen isotope composition of precipitation over Eagle Cave, central Spain

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Abstract

The 5-day reconstruction of air mass history for the days with precipitation at Eagle Cave (central Spain), together with the determination of moisture uptake locations along back trajectories, is used to identify the moisture sources of precipitation for this site from 2009 to 2011. During this 3-year period, around 30% of precipitation at Eagle Cave originated from the moisture recycled within the Iberian Peninsula (IP), with the Proximal Atlantic being also a main source region of moisture, whereas the Mediterranean Sea and the Distal Atlantic have large variability during the studied period and other source regions are minor precipitation contributors. The comparison of monthly oxygen isotope composition of precipitation at Eagle Cave with the monthly percentage of precipitation originated in source regions shows a significant negative correlation for the IP region. Thus, the moisture recycling process in the IP region explains 12% of the variability of the monthly oxygen isotope composition of precipitation (p-value < 0.1). However, when temperature, amount of precipitation and all source regions are considered, 74% of the variability of the monthly oxygen isotope composition of precipitation is explained (p-value < 0.05). Therefore, although for Eagle Cave amount of precipitation and temperature are main contributors of the precipitation oxygen isotope variability ($r^2 = 0.54$; p-value < 0.001), the moisture uptake distribution among source regions is a substantial control and should be considered when interpreting oxygen isotope speleothem records from this cave. This research highlights the importance of moisture sources in controlling the oxygen isotope composition of precipitation in mid-latitudes, and the need of quantification of this effect in order to improve the interpretation of oxygen isotope paleo-records that depend on isotope composition of precipitation.

1. INTRODUCTION

The study of paleoclimate at different timescales is essential in order to understand the expected variability of the future climate system (IPCC, 2007). The oxygen isotope ratio is among the most used proxies in reputed archives of past climate such as ice and ocean sediment cores (e.g., Martinson et al., 1987; Dansgaard et al., 1993) or speleothems (e.g., Lachniet, 2009). This proxy is also of common use in other archives such as lake sediment cores (e.g., Leng et al., 2006) or tufas (e.g., Andrews, 2006), and its application is increasing in other records such as tree rings (e.g., McCarroll and Loader, 2006) or peat bog cores (e.g., Daley et al., 2009). The variability of oxygen isotope ratios in continental records largely depends on the variability of the isotope composition of precipitation. Therefore, the quantification of the factors governing the

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oxygen isotope ratios of precipitation is of interest for most of the land-paleoclimate disciplines. The oxygen isotopes contained in the solid, liquid or gaseous form of water depend on the hydrological cycle, and therefore involve the ocean, glaciers, atmosphere and other continental water reservoirs such as lakes, rivers, soils or aquifers (Gat, 2010). Thus, to properly comprehend the relationship of the climate and an oxygen isotope record at a particular location, apart from understanding the kinetic processes governing its variability and establishing a climate-record calibration (e.g., Mattey et al., 2008), it is of interest to evaluate the role that the hydrological cycle could play for that particular location.

The variables affecting the oxygen isotope ratios in precipitation are relatively well known (Dansgaard, 1964; Rozanski et al., 1993; Gat, 1996), and include several controls or effects. Some of these controls are stable for a particular location when considering short geological timescales (i.e., altitude, latitude or continental effects). Other effects depend on variables that change with time for a specific location and determine the variability of the isotope composition of precipitation at the site. Some of these controls have a direct empirical link to climate, such as temperature or the amount of precipitation. Although the mechanisms that link the climate and isotope ratios in precipitation are complex, involving processes such as Rayleigh distillation, diffusive exchange of isotopes between raindrops and vapour, re-evaporation of falling precipitation or plants transpiration (Fricke and O'Neil, 1999; Risi et al., 2008; Field et al., 2010), the empirical correlation of these controls is frequently used for interpreting the stable isotope variability in terms of paleoclimate (e.g., Darling et al., 2006). However, there are other factors also affecting the stable isotope variability as the changes in seasonality (Denton et al., 2005), the ice volume effect (Duplessy et al., 1992) or the modification of moisture sources (Charles et al., 1994). These controls are often difficult to compute or there is an insufficient duration of the oxygen isotope precipitation time series to evaluate their impact. Thus, despite lacking a proper analysis, these effects are ignored or considered negligible in comparison with other controls for interpreting most of the paleoclimate records. However, several studies have demonstrated that these controls are significant contributors to the oxygen isotope variability of some records (Schrag et al., 2002; Denton et al., 2005; Masson-Delmotte et al., 2005; Dayem et al., 2010).

The seasonality in the isotope values of precipitation depends mostly on the seasonal variability of other controls like temperature, amount of precipitation and moisture source (Araguás-Araguás et al., 2000). Therefore, studies considering the seasonal signature of stable isotopes of precipitation should take into account the seasonal variability of all these controls. The ice volume effect significantly impacts the isotope composition in the hydrological cycle. However, substantial modification of the continental glaciers volume (equivalent to 15–20 m of sea level rise) is required for this effect to imprint a signature larger than the analytical uncertainty reported by most laboratories (Schrag et al., 2002). Thus, this effect becomes important when studying long periods (i.e., 10^2–10^3 yrs) during the onset and demise of glaciations, although becomes negligible for shorter timescales or periods without major changes in global continental ice mass. On the other hand, the moisture source is a factor that has been suggested to impact significantly different records (e.g., Cruz et al., 2005; Fischer and Treble, 2008). Regarding this effect, the isotope signal of precipitation can be affected by changes in the isotope composition of the source region (Domínguez-Villar et al., 2009; Breitenbach et al., 2010; Badertscher et al., 2011), or/and most commonly can be affected by the modification of percentages of moisture uptake regions and their trajectory atmospheric controls (Charles et al., 1994; Masson-Delmotte et al., 2005). Despite the importance of constraining the source of moisture variability to improve the interpretation of oxygen stable isotope paleo-records, these studies are scarce due to the complexity of the traditionally used general circulation models that enable the computation of oxygen isotopes (e.g., Hoffmann et al., 2000; Werner et al., 2011). Although these models integrate the complete series of processes affecting the isotopes in precipitation, the results have inherent limitations related to the complexity of the general circulation models such as spatial and/or temporal resolution and accuracy of the results for some regions (Sodemann et al., 2008a).

However, the number of studies determining the source regions of precipitation is increasing in the last years thanks to the development of back trajectories analyses from Lagrangian models (e.g., Draxler and Hess, 1998; Stohl et al., 1998) in conjunction with the evaporation–precipitation flux calculations (Delaygue et al., 2000; Sodemann et al., 2008b; Gimeno et al., 2010). The uncertainties related to the back trajectories for periods <10 days are expected not to affect the results at the spatial scale of interest for the characterisation of moisture uptake regions (Stohl and Seibert, 1998; Sodemann et al., 2008a), and uncertainties of longer periods can be reduced when considering large number of air parcels (Sodemann and Zubler, 2010). Therefore, the possibility of identifying back trajectories and the moisture uptake locations along them provides a tool to quantify the impact of moisture regions in the isotope signal of precipitation for single sites or regions. Although the combination of Lagrangian and moisture flux models are versatile and have high spatial and temporal resolution, data acquisition and model calculations are time consuming. Therefore, some simplifications of the model (i.e., limiting the calculations to a series of atmospheric levels and considering representative for a day the run of a particular hour) allows to perform calculations for long time periods in reasonable computational time. These simplifications prevent the calculation of accurate climate simulations for the complete system, although enable to provide practical hydrometeorological information with some particular applications (e.g., Baldini et al., 2010). Nevertheless, there are still a limited number of studies considering source regions of precipitation to evaluate the isotope signal of precipitation and their analysis has different levels of complexity. Thus, some studies consider moisture uptake regions (Sodemann et al., 2008a; Baldini et al., 2010; Gao

et al., 2011; Bershaw et al., 2012), whereas others simply track the source of winds providing moisture to specific locations (Aggarwal et al., 2004, 2012; Sjostrom and Welker, 2009; Breitenbach et al., 2010; Abouelmagd et al., 2012).

In this study we use back trajectory analysis together with a moisture uptake model to determine the sources of the precipitation in central Spain. The methodology is applied to the location of Eagle Cave, where several climate parameters and monthly oxygen isotope ratios in precipitation are measured since 2009. These climate and precipitation isotope data complements the ongoing monitoring program carried out inside Eagle Cave in order to better understand the isotope signature of their speleothems. The aim of this study is to quantify the impact of the moisture sources in the available record of oxygen isotope ratios of precipitation for this site. This will enhance future understanding of the oxygen isotope variability in speleothem records. The methodology presented allows to quantify the impact of moisture sources on the oxygen isotope ratios of precipitation compared to temperature and amount effects, and can be applied to other sites with minor adjustments of local parameters.

2. REGIONAL SETTING

This study is conducted in the Tietar Valley at the coordinates 40°9′15″N, 5°4′20″W, south of Ávila province (central Spain). The site was selected because Eagle Cave is located underneath this place. In this cave, oxygen isotope speleothem records are under construction, and monitoring of cave and surface parameters commenced in 2009. Thus, in the surface above the cave a meteorological station equipped with a system to collect the precipitation at monthly intervals was installed in order to analyse their stable isotopes values, providing the meteorological and oxygen isotope datasets that we use in this study (Domínguez-Villar et al., 2013). The cave is situated under a small hill of 427 m asl (above sea level) north of the Tietar River in an open landscape. The valley is oriented WSW-ENE and the southern watershed of the valley (distant 20 km from the cave site) has a limited altitude (i.e., <600 m asl), whereas at the northern limit of the basin (distant 15 km), the Gredos Range represent a significant geographical barrier (mean altitude ~1900 m asl). Thus, the basin and local topography plays a certain role in the winds regime at the surface over the cave site that records predominant S and SW winds. The topographic control of Gredos Range becomes less relevant or negligible at the considered elevations over the cave (see supplementary material) where the air parcel trajectories are studied. However, it is worth noting that during the period 2009–2011, less than 4% of precipitation at this site originated from air masses crossing the Gredos Range from the North.

The climate at this site is temperate with mean January temperature of 5.9 °C and mean July temperature of 24.9 °C during the period 2009–2011. The precipitation distribution has a dry season during summer typical for the Mediterranean climates (Font Tullot, 2000). During these years there was a considerable total amount of annual precipitation variability. Thus, the total amount of precipitation was 572, 1160 and 698 mm during the years 2009, 2010 and 2011, respectively. During the studied period, the mean annual temperature had a limited variability with values of 15.1, 14.3 and 15.1 °C, respectively. The magnitude of these annual precipitation and temperature oscillations is within the inter-annual variability range of comparable meteorological stations that has longer records along Tietar Valley. During the studied period, the annually weighed oxygen isotope composition of the precipitation had significant variability, with values of −6.16‰, −7.90‰ and −6.66‰ VSMOW, respectively. The variability of annual weighed oxygen isotope recorded at Eagle Cave is in the same range that in other inland stations of the Iberian Peninsula (IAEA/WMO, 2006).

3. METHODS

The collection of precipitation waters followed the IAEA sampling recommendations (www-naweb.iaea.org/napc/ih/documents/userupdate/sampling.pdf). At the meteorological station a simple system connects a funnel to a two litres PVC bottle through a rubber pipe. The diameter of the funnel was selected to avoid the bottle capacity to be exceeded. The bottle is inside a manhole located just under the ground level to minimise thermal extremes, with the rubber pipe tightly connected to the bottle. The bottles are replaced the first day of each month, and to avoid evaporation, they contain a ~5 mm thick layer of paraffin oil. After separating the rain water from the paraffin, the water samples are transferred to analytical vials and stored in a fridge until their analysis. Oxygen stable isotope analyses were conducted in the University of Birmingham in an Isoprime continuous flow IRMS. The waters were analysed by the equilibration technique according to the standard protocol (de Groot, 2009) and analytical uncertainty was 0.1‰.

To estimate the probable moisture sources we used back trajectory analysis of the days with precipitation at the selected site and identified the moisture uptake locations along each trajectory. The back trajectories were calculated using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectories) trajectory model of the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (Draxler and Rolph, 2013), based on the data generated by the Global Data Assimilation System (GDAS). The model was run for the days of significant precipitation (i.e., >0.5 mm; thereafter days with precipitation) during the period 2009–2011. The selected threshold accounts for the meteorological station uncertainty. A total of 231 days with precipitation were recorded during the three years of this study. For each calculated trajectory, hourly atmospheric pressure, potential and environmental temperature, precipitation and relative humidity were acquired. Trajectories were computed 120 h (5 days) back in time at three altitudes: 1000, 2000 and 2500 m agl (above ground level). The two lower elevations used in this research were chosen since they represent altitudes slightly above the main topographic barriers such as major mountain passes and the summit elevations in Gredos Range, 15 km north of the studied site (Gredos highest peak is 2592 m asl).

The higher elevation was chosen since it is well above any topographical influence. As most of the moisture in the atmosphere is thought to be in the first 2000 m agl (Wallance and Hobbs, 2006; Bershaw et al., 2012), we did not take into account levels of the atmosphere higher than 2500 m agl. Altitudes at elevations lower than 1000 m agl were not considered in order to minimise the influence of surface topography on wind direction. The period of 120 h was chosen since most of the moisture uptake for the Iberian Peninsula occurs within this time interval (Gimeno et al., 2010). Specific humidity was calculated at hourly intervals along each trajectory using HYSPLIT output data and standard equations for saturation humidity mixing ratio, saturation vapour pressure and specific humidity, consistent with Baldini et al. (2010). The specific humidity was considered within the calculations for moisture uptake, according to Sodemann et al. (2008b), using a threshold of positive gradient in specific humidity (0.5 g/kg within 6 h) for atmospheric pressure above 900 hPa in agreement with Baldini et al. (2010). This selected threshold in specific humidity yields a conservative estimation of the moisture sources in comparison to Sodemann et al. (2008b). However, for Eagle Cave conditions, the atmospheric pressure estimated for the tracked air parcels is the most determining factor for the identification of moisture source locations. The atmospheric pressure threshold was selected as a reasonable approximation to the average level of the boundary layer in the region (Baldini et al., 2010). The moisture uptake sources were determined for all back trajectories at the three elevations. Further analyses were conducted only in the elevation dataset with the highest percentage of number of days with precipitation in which moisture uptake locations are identified. At this particular elevation dataset, the moisture balance was calculated to evaluate its impact on the isotope fractionation processes within the atmosphere (e.g., Field et al., 2010). The moisture balance (evaporation minus precipitation) of each trajectory was estimated according to Gimeno et al. (2010) for the period after the first identification of moisture uptake within the 120 h previous to the precipitation over Eagle Cave. The monthly moisture balance was weighed according to the amount of precipitation of the days with identified moisture source.

Distance of the moisture source has been also suggested to impact the isotope composition (Aggarwal et al., 2004; Breitenbach et al., 2010). Therefore, the distance between every single moisture uptake location and Eagle Cave was measured and used for the calculation of monthly weighted average distances from Eagle Cave to the moisture uptake locations. The moisture source spatial variability was analysed at monthly, seasonal (three-monthly) and annual intervals. The seasons are defined within a calendar year: winter (January, February, March), spring (April, May, June), summer (July, August, September) and autumn (October, November, December). For spatial computation of moisture uptake locations a grid of 0.5×0.5 degrees was used. Each cell integrates the percentage of moisture uptake during different events within that area for the time interval under consideration (i.e., month, season or year). In order to quantify the spatial distribution of moisture uptake, seven regions were considered (Fig. 1). These regions are the Iberian Peninsula (IP), Proximal Atlantic (PA), Distal Atlantic (DA), Mediterranean (ME), Africa (AF), Europe (EU) and Northern Seas (NS). The borders of these regions are based on geographical limits or clear distribution patterns of the moisture uptake locations obtained during these three years. Finally, the moisture uptake percentage for a particular region results from the sum of the percentages of all the cells within that region. The comparison of monthly variables uses parametrical statistical analyses since all datasets past the normality tests.

The model we used here has some limitations that should be considered. We calculated the back trajectories at 00:00 h of the day with precipitation. This implies that simulations only consider one event of precipitation per day, whereas reality could be more complex. Additionally, the simulated event could have a mismatch of up to 24 h with the real precipitation event/s. To evaluate the importance of this possible time lag, we run a test during one of the days of precipitation at Eagle Cave. The day was randomly selected within those recording a large number of identified grids with moisture uptake, which should provide a large uncertainty in relation to other runs. The change in moisture uptake locations during the 24 h period was $13.0 \pm 15.4\%$ (see supplementary material). This limited modification of moisture source locations shows that the uncertainty related to the timing of the simulation within a day is not a critical factor. The analysis of the moisture source regions uses only trajectories that where at a particular elevation at the time passing over the studied location. So, although the chosen elevation provides the better fit of simulations to instrumental data, a single level does not incorporate the total amount of precipitation received at the study site. This simplification of the model prevents to perform reliable quantitative simulations of amount of precipitation. However, regardless the inaccuracy in this hydrometeorological variable, the maps of moisture uptake considering different elevations show similar moisture locations (see supplementary material). This indicates that for a particular rain event in our study, the moisture uptake locations are similar despite the considered starting elevation of the simulation. Therefore, despite the simplifications considered to the model, its application provides reliable data for the identification of moisture source regions. Finally, the model is unable to reproduce moisture uptake regions for some days with precipitation recorded at the study site. Some possible causes for the days without simulated moisture sources could be the different timing between real and simulated precipitation events, the possibility of precipitation originated at an unexpected elevation, or precipitation resulting from local convective processes not captured by GDAS database.

4. RESULTS

4.1. Back trajectories

Considering the three selected elevations, we computed 693 back trajectories for the period 2009–2011 (195 for 2009, 258 for 2010, and 240 for 2011). The back trajectories from different elevations show similar paths, with higher

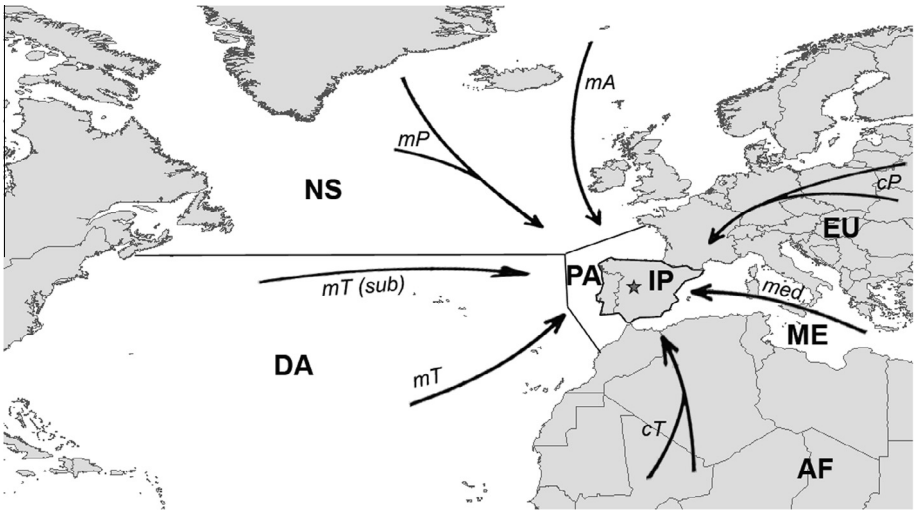

Fig. 1. Moisture regions defined for this study. Northern Seas (NS), Distal Atlantic (DA), Proximal Atlantic (PA), Europe (EU), Mediterranean Sea (ME), Iberian Peninsula (IP) and Africa (AF). The arrows and lowercase labels stands for the regional whether types according to Font Tullot (2000), whereas "m" and "c" allude to maritime and continental source regions and "A", "P", "T", "T sub" and "med" refer to Arctic, polar, tropical, subtropical and Mediterranean air masses. Eagle Cave location is identified with a star.

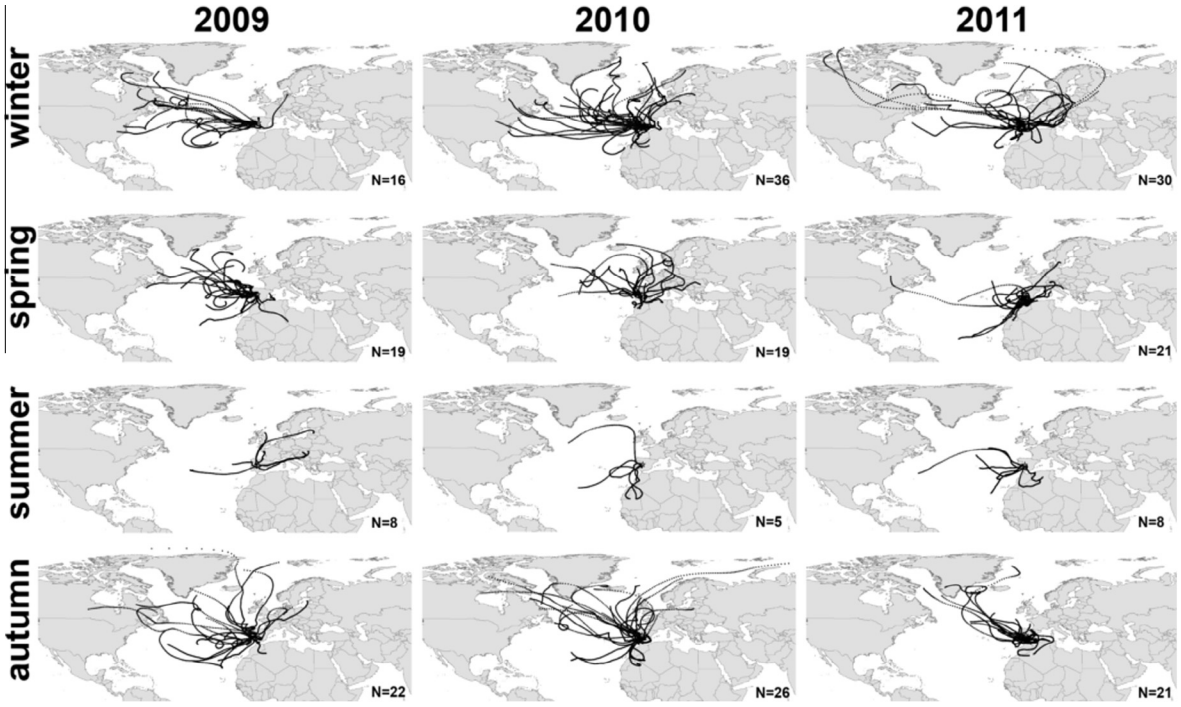

Fig. 2. Air mass history for days with precipitation at Eagle Cave calculated at 1000 m agl during the previous 120 h. Each dot represents the location of the air parcel at 6 h intervals. The back trajectories are presented seasonally for the three years of record. The total number of trajectories calculated per season is inset to each plot.

elevations having slightly longer paths for some trajectories (Fig. 2 for 1000 m agl; other elevations in supplementary material). The predominant air masses approach Eagle Cave from the NW, in agreement with the westerly circulation of the region (Martín Vide and Olcina Cantos, 2001). However, all the weather patterns described for the IP (Font Tullot, 2000) were recorded during these three years, including maritime and continental air masses from polar, Arctic, tropical and Mediterranean regions (Figs. 1 and 2).

There is a clear seasonality in the back trajectories. During the autumn and winter many trajectories are longer reflecting a faster air flow, and most of them are tracked back to different regions of the Atlantic. In contrast, during the spring and summer the trajectory paths are usually

shorter and present a wider pattern of distribution. During the year 2009 the NE and S advection weather situations were less frequent compared to the years 2010 and 2011. It is worth noting that not only were weather patterns different for this year, but also the number of days with precipitation. Thus, in 2009 there were 65 days with precipitation, whereas precipitation was more frequent in 2010 (86 days) and 2011 (80 days).

4.2. Moisture sources

The locations of moisture uptake were determined along back trajectories for the three elevations (Fig. 3 for 1000 m agl; other elevations in supplementary material). The dataset at the elevation of 1000 m agl has the highest percentage of days with identified moisture uptake (78.8%). The percentage of days with significant precipitation with an identified moisture source is in the same order as in similar studies (e.g., Baldini et al., 2010). For the dataset at the elevation of 2000 m agl this percentage is reduced to 45.5%, whereas the percentage of the dataset at the elevation of 2500 m agl is only 31.6%. When no moisture source was identified within the first 120 h along the back trajectory, the air mass was tracked back for additional 120 or 240 h at the three elevations. Even when we combine datasets from different elevations or extend the time of computed back trajectories, there are some days with high amount of precipitation in which no moisture source is identified. Additionally, by extending the calculation period back in time, the percentage of days with precipitation having unidentified moisture source locations is not reduced significantly and unlikely moisture sources result from the analyses. Therefore, further calculations consider only the dataset at the elevation of 1000 m agl computed for the last 120 h before the day of precipitation. This solution provides the highest percentage of identified moisture sources according to precipitation data and avoids unlikely moisture source locations.

For Eagle Cave location, the moisture uptake along back trajectories takes place in most cases nearby or within the IP (Fig. 3). Therefore, a large fraction of the trajectories does not contribute to moisture uptake even if the air masses pass over the seas. Although in most cases the moisture uptake occurs along short distances of the trajectories (e.g., <1000 km), some simulations show moisture uptake along sections of the trajectories far away from Eagle Cave (e.g., >1000 km), especially during autumn and winter seasons. There is a seasonal difference in the percentage of rainy days with identified moisture sources (Table 1). During winter and autumn the proportion of days with identified moisture source locations is large, whereas spring has slightly reduced values and during summer the proportion largely varies. The identified locations of moisture uptake for the days with precipitation at Eagle Cave have

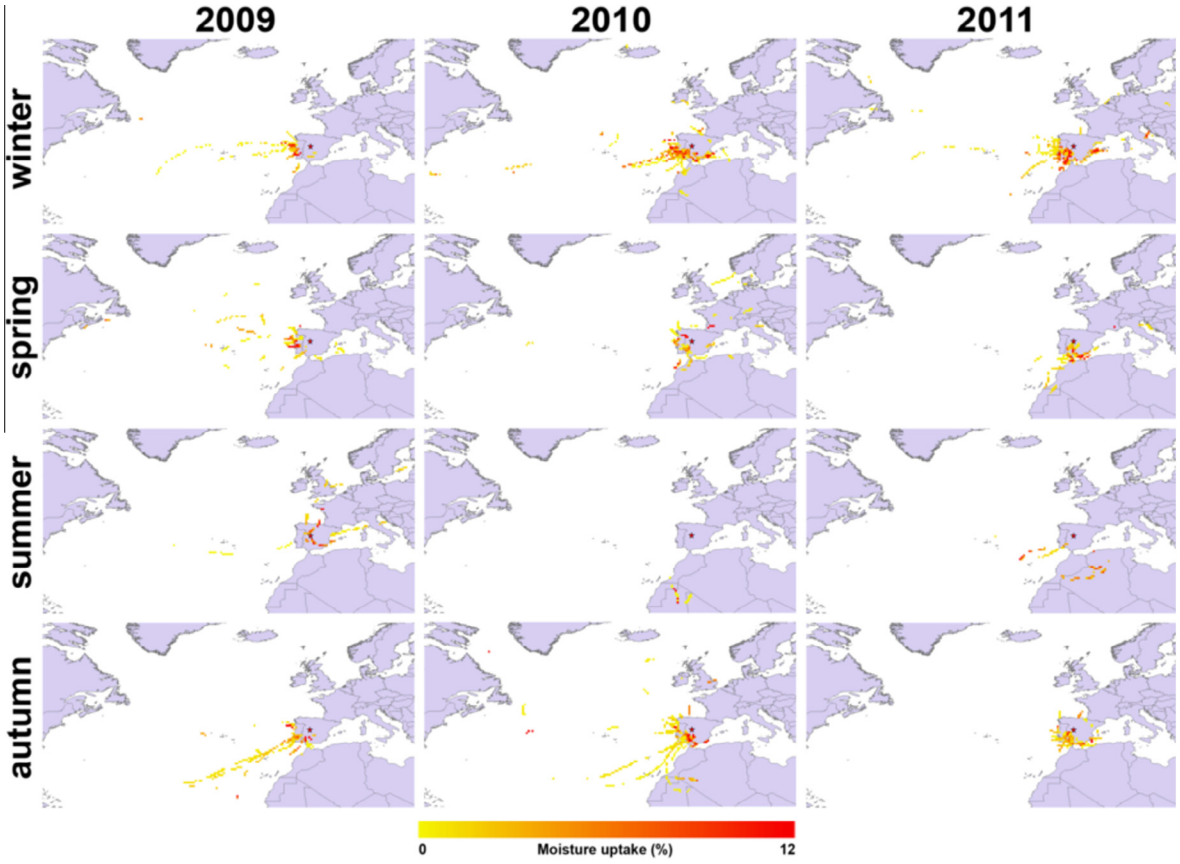

Fig. 3. Maps of seasonal percentage of moisture uptake during the three years of record for the 1000 m agl dataset.

Table 1
Distribution of the amount of precipitation percentage by its source region at seasonal and annual timescales for Eagle Cave.

		IP	ME	PA	DA	NS	EU	AF	TPIMS*
2009	Winter	29.1	0.0	58.6	6.1	3.1	0.0	0.0	96.9
	Spring	23.4	1.9	31.5	13.3	10.1	0.0	0.0	80.2
	Summer	55.3	13.3	15.2	1.8	6.2	6.6	0.0	98.3
	Autumn	30.2	0.2	29.8	28.5	0.0	0.0	0.0	88.6
	Annual	**29.5**	**1.0**	**35.8**	**19.7**	**2.9**	**0.3**	**0.0**	**89.2**
2010	Winter	33.6	9.1	33.4	17.3	0.7	0.6	0.7	95.6
	Spring	29.1	4.8	17.4	0.6	1.7	15.9	4.1	73.6
	Summer	0.0	0.0	0.0	0.1	0.0	0.0	1.6	1.7
	Autumn	33.0	11.8	16.0	12.9	5.7	1.6	5.7	86.7
	Annual	**31.8**	**8.8**	**24.0**	**12.8**	**2.4**	**2.9**	**2.9**	**85.6**
2011	Winter	25.7	17.2	28.0	6.6	1.4	3.4	0.0	82.3
	Spring	18.3	29.5	7.9	4.1	0.0	3.2	11.4	74.5
	Summer	1.3	0.0	0.8	10.0	0.0	0.0	14.8	26.9
	Autumn	36.7	32.4	23.9	0.0	0.0	0.0	0.0	93.1
	Annual	**27.3**	**23.8**	**22.3**	**3.9**	**0.6**	**2.0**	**2.7**	**82.6**

The bold value indicate annual values.
* TPIMS: Total percentage of identified moisture sources.

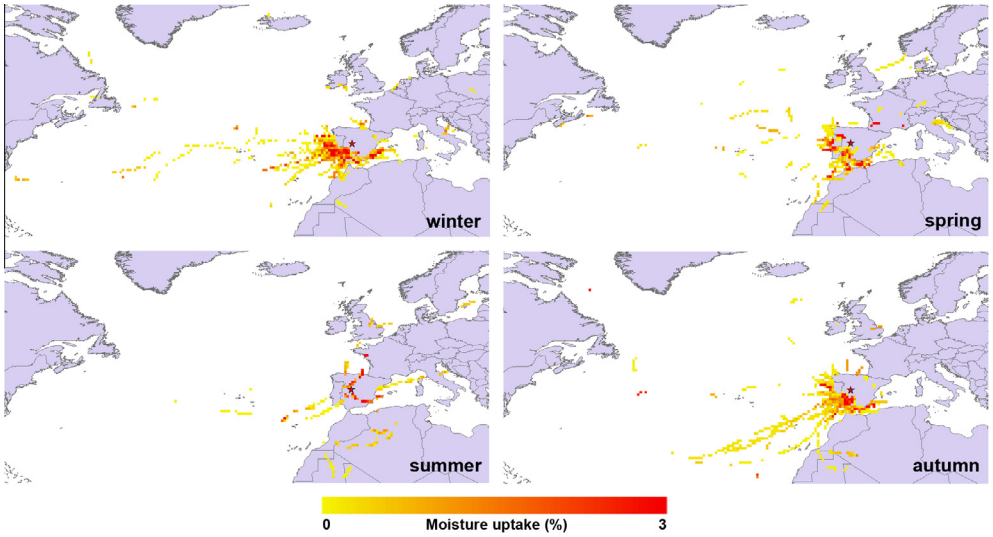

Fig. 4. Maps of integrated seasonal percentage of moisture uptake during the period 2009–2011.

a seasonal distribution (Table 1, Fig. 4). The most distinct seasonal feature is the length of several moisture uptake paths, which is commonly longer in winter and autumn.

Table 2
Percentage of integrated seasonal moisture uptake by seasons during the period 2009–2011.

Source region	Winter	Spring	Summer	Autumn
IP	30.7	23.6	14.1	32.9
ME	10.4	12.0	3.3	12.8
PA	35.0	18.4	4.0	23.3
DA	12.8	5.4	3.2	14.7
NS	1.1	3.6	1.5	2.3
EU	1.4	7.2	1.6	0.6
AF	0.4	5.3	4.8	2.4
TPIMS*	91.7	75.5	32.5	89.0

* TPIMS: Total percentage of identified moisture sources.

Additionally, some regions provide more moisture than others depending on the season (Table 2), although due to the large percentage of unidentified moisture uptake locations for days with precipitation during some seasons, this variability should be taken with caution. Thus, winter and autumn have IP and PA as principal sources, with DA and ME as substantial contributors, whereas the rest of the regions have little impact in the total budget (i.e., <6%). During spring and summer IP is the region that contributes the most of the moisture to the precipitation at Eagle Cave. In this period, PA and ME regions are also important sources, DA region diminish its relevance and secondary regions increase their significance. Thus, in summer AF is the second most common source region, and in spring EU becomes relevant.

The budget of moisture uptake at annual timescale shows that the IP and PA are the most significant regions (i.e., roughly >50%) in all years (Table 1 and Fig. 5).

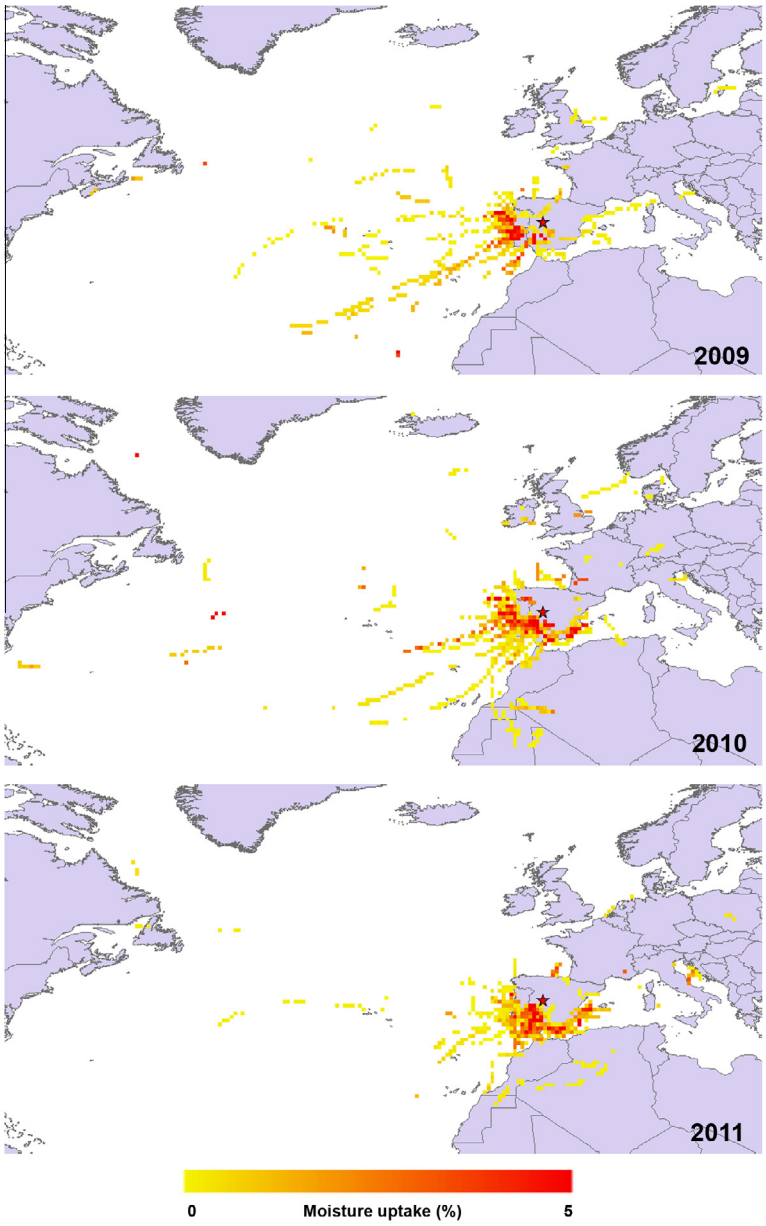

Fig. 5. Annual maps of percentage of moisture uptake during the three years of record.

However, there are substantial differences in secondary source regions. Thus, during 2009 the ME region has a minor contribution to the annual budget, which progressively increases during the subsequent years. In contrast, the DA region has a progressive decreasing impact on the annual budget during the studied period. This variability in moisture source regions is in response to changes in the atmospheric circulation. Fig. 6 shows that there is a significant correlation between the pressure field at surface level and the percentage of moisture source in the ME (positive relationship) and the DA (negative relationship) regions. Higher geopotential heights (e.g., 500 hPa) provide similar results although have slightly less significant correlations (not shown). The regions of significant correlation correspond with usual locations for the Icelandic Low and the Central European High pressure areas when affecting the Iberian Peninsula. In consequence, the major annual changes of moisture source regions during the studied period are related to the variability of the atmospheric circulation.

5. CONTROL OF AMOUNT OF PRECIPITATION, TEMPERATURE AND MOISTURE SOURCES ON OXYGEN ISOTOPE VARIABILITY

From all the effects that can impact the oxygen isotope composition of precipitation (e.g., Rozanski et al., 1993; Lachniet, 2009), some of them can be considered constant at a particular location for the short time period considered in this study (i.e., latitude, altitude, continentality, ice

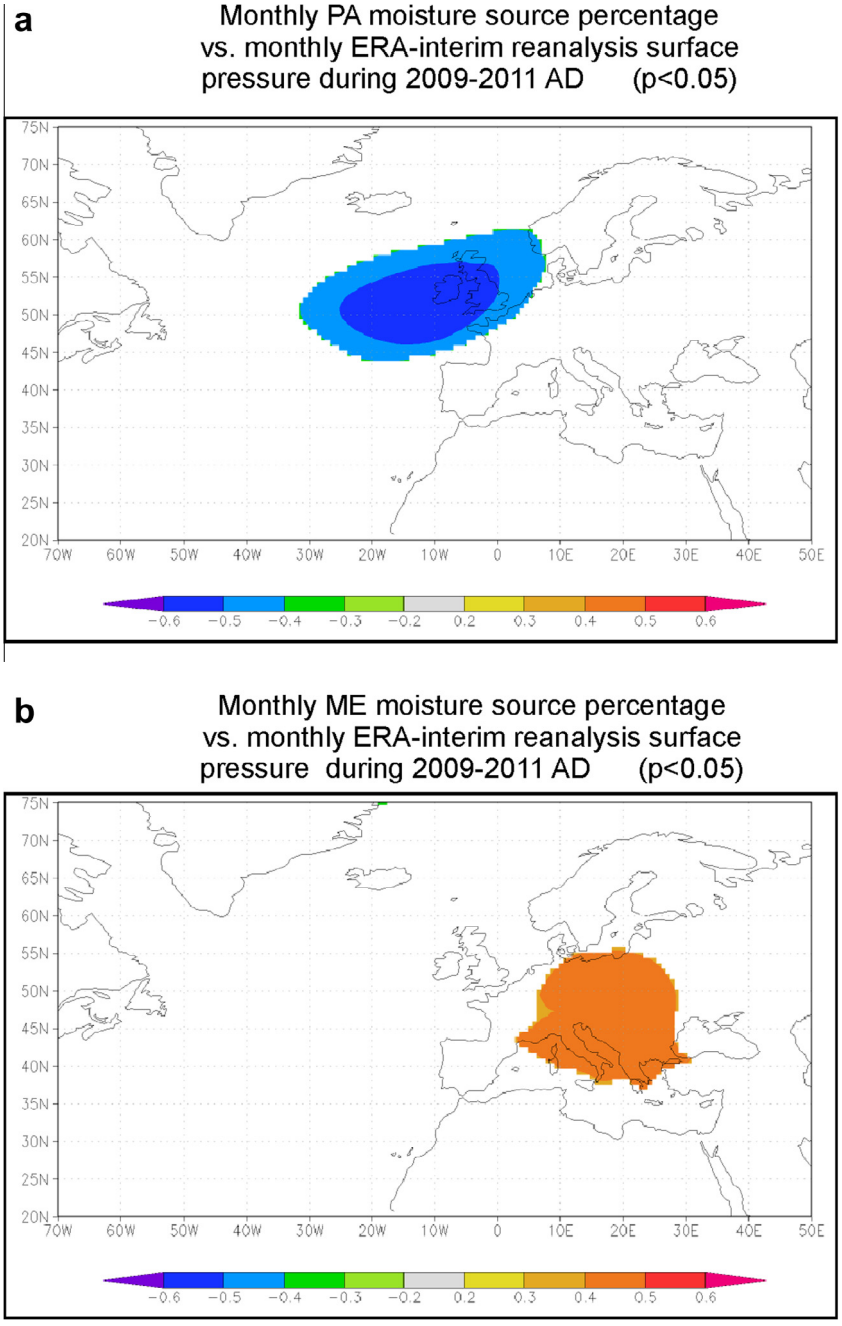

Fig. 6. Correlation maps between monthly moisture uptake percentages of precipitation at Eagle Cave from different regions and reanalysis sea level pressure field from ERA-interim database for the period 2009–2011. (a) For the PA region (b) for ME region. Sea level pressure data was accessed and maps produced using KNMI Climate Explorer (van Oldenborgh et al., 2009).

volume effect or long-term changes in ocean surface isotope composition due to other mechanisms). Thus, the temperature, amount of precipitation and moisture sources are the effects that control most of the isotope composition of precipitation at the timescale here studied. Also, the distance from the moisture uptake location and the post-condensational processes within the atmosphere are potential contributors to this variability and were investigated. In this section we focus on the empirical correlations with these general controls.

5.1. Amount of precipitation and temperature effects

At a monthly timescale, the precipitation oxygen isotope composition from Eagle Cave co-varies with the amount of precipitation (negative relationship) and temperature (positive relationship) at this site (Fig. 7). The mean monthly temperature has a higher correlation with the precipitation oxygen isotope ratios ($r^2 = 0.42$; p-value < 0.001), showing a 0.23‰/°C gradient. The total amount of monthly precipitation has significant correlation with the precipitation

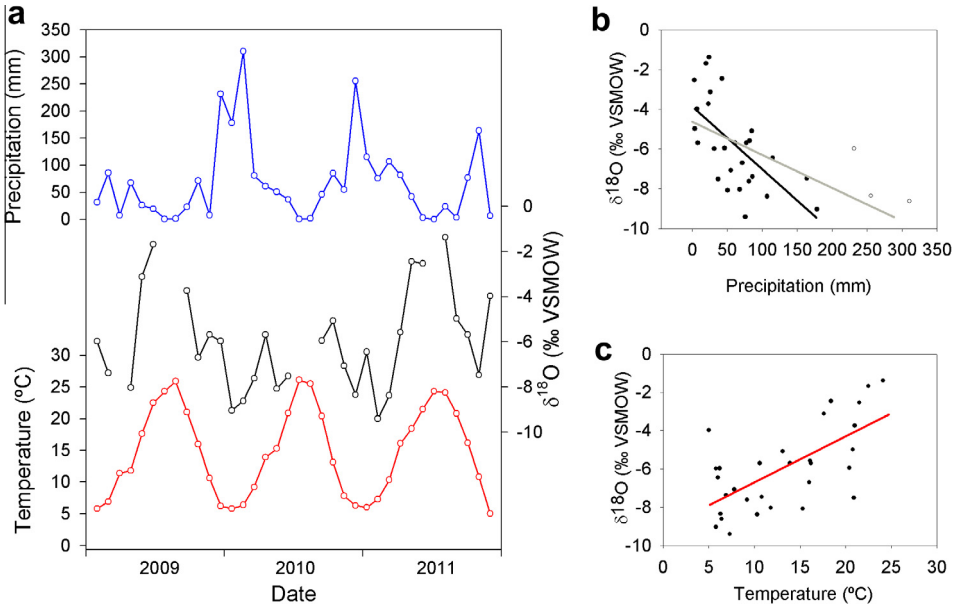

Fig. 7. Data recorded at Eagle Cave meteorological station. (a) Mean monthly temperature, monthly amount of precipitation and monthly oxygen isotope composition of precipitation. Note that no isotope values are available when amount of precipitation was insufficient for its analysis. (b) Relationship of monthly oxygen isotope composition of precipitation and amount of precipitation. The two regression lines corresponds to the dataset including all the months (full circles), and the dataset that excludes months with >200 mm (open circles). (c) Relationship of monthly oxygen isotope composition of precipitation and mean monthly temperature.

oxygen isotope composition ($r^2 = 0.32$; p-value < 0.005). However, it seems that the months with very large amounts of precipitation (i.e., >200 mm) do not have a linear relationship with the rest of the dataset. If these months are discarded ($n = 3$), the correlation between amount of precipitation and its oxygen isotope composition improves ($r^2 = 0.41$; p-value < 0.001), providing a gradient of −4.15‰/100 mm. By discarding the months with large amount of precipitation, the regression line has a better fit of the isotope composition for most of the months, especially for those with moderate to low amount of precipitation that constitute the majority of the record. Although above the cave there is no surficial runoff, during intense precipitation events, the excess of water is expected to be drained by the large conduits within the epikarst. Therefore, months with large amount of precipitation do not necessarily have more impact on the oxygen isotope composition of the water feeding cave drips than those months with less precipitation. The exhaustion of the moisture storage in the atmosphere during intense precipitation events could explain the different isotope pattern of these months with high amount of precipitation (e.g., Gat, 2010). According to the GNIP database (IAEA/WMO, 2006), the thermal gradients do not differ significantly from other sites located south of the Spanish Central System and less than 200 km apart from Eagle Cave, such as Ciudad Real (0.24‰/°C, $r^2 = 0.25$, p-value < 0.005) or Cáceres (0.21‰/°C, $r^2 = 0.21$, p-value < 0.01), although the importance of amount of precipitation is more variable (Ciudad Real: −5.53‰/100 mm, $r^2 = 0.27$, p-value < 0.005; Cáceres: −2.10‰/100 mm, $r^2 = 0.15$, p-value < 0.01).

Due to the Mediterranean climate at Eagle Cave, temperature (precipitation) has a clear seasonality with maximum (minimum) values in summer. Thus, as the isotope signal in precipitation also shows an annual cycle, the seasonality has a strong influence on the monthly correlations. Any parameter with a strong seasonal component in phase with the temperature/precipitation would show a certain correlation with precipitation isotope composition. This would occur even without a link existing between both variables, since they share an in phase cycle pattern with the same wave-length that controls their variability. Therefore, correlating variables at different timescales is important in order to evaluate their real dependence. Unfortunately, the oxygen isotope composition of single events of precipitation is not available at Eagle Cave, and the annual series is too short to consider variability statistically significant. However, it is worth noting that the positive (negative) gradient observed in the monthly database is also observed in the annual temperature (amount of precipitation) timescale. This is in agreement with studies of oxygen isotope composition of precipitation in the IP that counts with precipitation events and longer (>10 yr) inter-annual records (Araguás-Araguás and Díaz Teijeiro, 2005; Carreira et al., 2005). Although a longer time series in Eagle Cave would be needed in order to confirm the link of amount of rainfall and temperature with the oxygen isotope composition of precipitation, the available data and the regional context support that these variables are direct controls of the isotope signal of precipitation.

The variability of oxygen isotopes in precipitation explained by amount of precipitation (discarding months with

>200 mm of precipitation) and temperature is 41% and 42%, respectively. However, the total variability explained by both effects is not the sum of them, since some overlapping of the explained variability is expected. Thus, in order to explore the variability explained by the combination of these two controls we conducted a multivariate regression analysis. The combined amount of precipitation and temperature effects explains 54% of the variability of the oxygen precipitation composition (p-value < 0.001).

5.2. Moisture source effect

The distance between the moisture source and the site of precipitation has been suggested to impact the oxygen isotope composition of precipitation (Aggarwal et al., 2004; Breitenbach et al., 2010). According to the Rayleigh distillation process governing this relationship (Field, 2010), the depletion of moisture vapour due to precipitation along the air mass trajectory results in a progressive 18-O depletion of the remaining moisture fraction in the atmosphere and the subsequent precipitation events. As the possibility of water vapour depletion in the air mass increases with the distance due to longer residence time of moisture in the atmosphere, precipitation from proximal sources could show higher oxygen isotope ratios in comparison with precipitation originated at distant sources. At Eagle Cave, the correlation of monthly weighted average distances of moisture uptake locations with monthly isotope composition is not significant (p-value $= 0.2111$). The results presented in Fig. 4 show more distant moisture uptake locations in winter and autumn for some trajectories. However, the longer paths of some trajectories are compensated by the shorter paths of other trajectories and the weighted monthly average during these seasons in not longer than during other months of the year. Thus, although we do not discard that this effect could be significant for single precipitation events, its impact is not recorded in the isotope signal of precipitation at the monthly timescale. Additionally, partial evaporation of droplets and their equilibration with the surrounding vapour in the atmosphere along the trajectory of the air parcel could impact the isotope composition of precipitation (Field et al., 2010). We estimate the moisture balance (evaporation minus precipitation) since the first moisture uptake identification within the last 120 h along the trajectories with precipitation over Eagle Cave. At this site there is no significant correlation between atmosphere moisture balance and oxygen isotope composition of precipitation (p-value $= 0.1607$). Therefore, although we cannot discard that these processes could be significant for single precipitation events, its impact on the oxygen isotope composition of precipitation is not recorded at the monthly timescale.

We also compared the relationship of the oxygen isotope composition of precipitation with the percentage of moisture uptake in the different regions defined in Fig. 1. Due to the significant lack of known moisture sources for days with precipitation during some months, we decided to split the monthly record into two databases: A and B. The former integrates all the months with isotope values, whereas the database B considers only the months with isotope values in which >80% of the days with precipitation had identified moisture source locations. By using this threshold we discard the months with poor fit between model and instrumental data and still have a database large enough to perform statistics. The correlation of regional distribution of moisture sources at a monthly timescale for both datasets has been compared to the oxygen isotope composition of precipitation at Eagle Cave (Table 3). First, when considering dataset A ($n = 30$), the IP, PA and AF regions have significant correlations (p-value < 0.1), and the source of moisture uptake of each of these regions explains 10–20% of the isotope variability in the precipitation. The results show that the regions with higher supply of moisture to Eagle Cave precipitation (IP and PA) control a large fraction of its isotope variability. It is worth noting that the ME region, which is an important moisture contributor (especially during 2011), does not have a significant impact on the isotope signal of precipitation. On the other hand, the AF region, which at an annual scale represents <3% of the moisture contribution to the site, explains a substantial variability of the isotope signal of precipitation. This is due to the considerable precipitation amount in some particular months, where AF region accounts for up to 50% of the monthly moisture supply. Moreover, it is worth noting that AF region does not provide moisture just in summer, but also in other seasons (Table 2). Second, when considering the dataset B ($n = 23$), only the IP region has a significant correlation with the precipitation isotope signal (p-value < 0.1), explaining 12% of the oxygen isotope variability in precipitation.

In order to evaluate the integrated influence of the moisture source regions on the precipitation isotope record we conduct a multivariate regression on dataset B, the results of which we consider more reliable than dataset A. The better multivariate model explains 44% of the variability in the precipitation oxygen isotope composition (p-value $=$ 0.0596), and considers IP, PA, DA, ME and AF regions. This analysis shows that when considering the reduced but more reliable dataset B an important fraction of the variability of the oxygen isotope composition of precipitation depends on the moisture source regions.

Table 3
Linear correlation parameters of monthly oxygen isotope composition of precipitation with monthly percentage of moisture uptake regions. Dataset A considers all months with available isotope values ($n = 30$). Dataset B considers months with >80% of identified moisture uptake regions for months with available isotope values ($n = 23$).

Source region	Dateset A		Dateset B	
	p-Value	r^2	p-Value	r^2
IP	**0.0174**	**0.192**	**0.0993**	**0.124**
PA	**0.0612**	**0.124**	0.3642	0.039
AF	**0.0404**	**0.147**	0.5561	0.017
DA	0.9370	0.002	0.7435	0.001
ME	0.4478	0.022	0.2117	0.057
EU	0.7952	0.002	0.4929	0.023
NS	0.3652	0.031	0.1743	0.086

All correlations significant at 90% (in bold) have inverse relationship between variables.

6. DISCUSSION

The change in moisture sources is an important contributor to the precipitation isotope variability (e.g., Rindsberger et al., 1983). Thus, the paleoclimate oxygen isotope records depending on the isotope composition of precipitation are potentially impacted by moisture sources (Charles et al., 1994; Stute and Talma, 1998; Sodemann et al., 2008a). However, despite the importance of this factor being highlighted in general reviews (e.g., Lachniet, 2009), most authors do not consider the moisture source control when interpreting their paleoclimate records unless having contrasting isotope composition of their moisture sources (e.g., Cruz et al., 2005). The improvement in the paleoclimate interpretations based on oxygen isotope records by taking into account the moisture sources is ongoing for over a decade. Nevertheless, these studies are still limited to key paleoclimate locations regardless the importance that this control has shown so far (Delaygue et al., 2000; Masson-Delmotte et al., 2005; Sodemann et al., 2008a).

Traditionally different moisture sources were evaluated based on isotope relationships of precipitation (e.g., Cruz-San Julián et al., 1992; Celle-Jeanton et al., 2001), although this approach has substantial limitations related to the vague geographical definition of the moisture sources and the existence of local processes affecting the isotope ratios. Thus, recent studies evaluating the contribution of moisture uptake regions on the precipitation oxygen isotope variability use powerful models (e.g., Sodemann et al., 2008a; Baldini et al., 2010; Gao et al., 2011; Bershaw et al., 2012). The application of some of these models to Eagle Cave precipitation emphasises the importance of moisture source regions in explaining the variability of oxygen isotope signal in the precipitation at this site. However, it should be noted that the quantification of the moisture source control is based on a modelling approach and that the considered database does not explain 100% of the observed precipitation events. Therefore, although the variability analysis already shows statistically significant relationships during the studied period, the absolute impact of the moisture source control here presented depends on the limitations and uncertainties of the used models.

In Eagle Cave, the monthly temperature and amount of precipitation have significant correlations with the oxygen isotope composition of precipitation. The multivariate correlation indicates that these two effects account for 54% of its variability. However, when the moisture uptake regions are considered together with temperature and amount of precipitation into the modelled oxygen isotope precipitation, the multivariate regression explains 74% of the observed variability in the oxygen isotope composition of precipitation with a significance >95% (Eq. (1)). This correlation considers monthly values of temperature (in °C), monthly amount of precipitation (in mm; for months with <200 mm), and the percentage of moisture uptake in all regions for the months with >80% of precipitation with identified moisture uptake locations.

$$\begin{aligned}\delta^{18}O = {} & -0.0117 * \text{Prec} + 0.1788 * \text{Temp} + 0.0110 * \text{IP} \\ & + 0.0274 * \text{PA} + 0.0401 * \text{ME} + 0.0198 * \text{DA} \\ & + 0.0113 * \text{AF} + 0.0342 * \text{EU} + 0.1327 * \text{NS} \\ & - 10.079 \quad (r^2 = 0.74;\ p\text{-value} = 0.0428) \end{aligned} \tag{1}$$

This equation quantifies the impact of moisture sources, amount of precipitation and temperature effects on the oxygen isotope composition of precipitation at Eagle Cave for the studied period. All the moisture sources have a direct relationship with oxygen isotope composition in the precipitation. In order to evaluate the impact of moisture sources variability in the simulated oxygen isotope ratio in precipitation, it should be taken into account that they represent percentages (i.e., for a region to increase the percentage other/s have to decrease it). However, the relevance of some moisture sources is clear, as the IP region, which precipitation has lower isotope values compared to other sources. The IP region provides annually around 30% of the moisture to Eagle Cave, and its moisture uptake implies a moisture recycling process (Numaguti, 1999; Gimeno et al., 2010). The oxygen isotope variability within the ocean/sea regions of the Atlantic and Mediterranean, where the uptake of moisture for Eagle Cave precipitation takes place, is in the order of 2‰ (Schmidt, 1999). However, the isotope composition of precipitation in the IP region is in the order of 5‰ lower than in the ocean/sea (IAEA/WMO, 2006). Continental moisture originates from evaporation of soils, surface waters and plants transpiration. The latter does not produce any isotope fractionation (Gat, 2010) whereas evaporation process causes progressive 18-O enrichment of the remaining waters (Gat, 1996). However, the seasonality of isotopes in precipitation should be considered, since the uptake of moisture from the continental Europe in summer mostly originates from the previous winter precipitation (Numaguti, 1999). Thus, although recycled moisture is affected by fractionation during the evaporation process, the precipitation originated from the continents is still, in most cases, lighter than ocean-sourced precipitation (Dansgaard, 1964; Gat and Matsui, 1991; Njitchoua et al., 1999). At Eagle Cave, a significant negative relationship exists between the percentage of precipitation with uptake of moisture within the IP region and the monthly oxygen isotope composition of precipitation (Table 3). However, this component of the moisture source effect had a low variability during the three years of monitoring and its impact on the modelled oxygen isotope in precipitation is limited. On the other hand, it is worth noting that the NS region, that normally accounts for a small fraction of the amount of precipitation at Eagle Cave (i.e., <10%), has a main control compared to other moisture sources. In the best fit of the multivariable analysis that considers only the percentage of contribution from the source regions and the oxygen isotope record, the NS and EU regions are not included, and AF region is an important quantitative variability contributor. This suggests that the role of the regions with minor contribution to Eagle Cave precipitation (i.e., NS, EU and AF) in explaining the variability of oxygen isotope ratios of precipitation during some particular months is very important, but they do not control the overall isotope values. To properly capture the specific role of

these minor source regions contributors, longer time series would be required. Therefore, although Eq. (1) represents the best fit to observed data during the studied period, to evaluate the importance of moisture sources beyond the 2009–2011 period the minor contribution to precipitation to Eagle Cave (i.e., NS, EU and AF regions) should be excluded in order to avoid the relatively large control of singular events. This relationship is expressed in Eq. (2):

$$\delta^{18}O = -0.0154 * Prec + 0.1748 * Temp - 0.0199 * IP - 0.0123 * DA + 0.0034 * PA + 0.0064 * ME - 6.8778 \quad (r^2 = 0.70;\ p\text{-value} = 0.0073) \qquad (2)$$

This equation provides the relevance of the major contributors to Eagle Cave precipitation. Thus, lower oxygen isotope composition of precipitation at Eagle Cave would result from increasing the IP region contribution to precipitation. The resulting oxygen isotope composition of precipitation would be higher according to the sequence IP < DA < PA < ME, where higher percentages of precipitation from ME region contributes to higher oxygen isotope ratios of precipitation.

During the period 2009–2011, the atmospheric dynamic had a control on the percentage of moisture uptake from DA and ME regions (Fig. 6). The relative annual variation of these two regions has an inverse proportional relationship (Table 1). According to Eq. (2), the oxygen isotope composition of precipitation should have had higher values in 2011 when compared to 2009 as a response to the variations of moisture sources (i.e., more precipitation from Mediterranean in relation to Atlantic sources). However, although temperature was the same in both years, precipitation was 126 mm higher in 2011. As the amount effect is the most determining control on the oxygen isotope composition of this site, the higher precipitation in 2011 counteracted the impact of moisture sources, and the oxygen isotope composition of precipitation of 2011 had lower value than in 2009. Significant changes in the proportion of recycled moisture in the IP region could have more relevant role in the oxygen isotope composition of precipitation, although during the short period studied its variability was limited. So, the study of longer periods is required to evaluate whether or not the recorded variability of moisture sources is stationary. In any case, considering the range of variability of contributions from different moisture source regions, temperature and amount of precipitation, it is obvious that the amount of precipitation is by far the dominant variable controlling the oxygen isotope composition of precipitation. Other variables also have a significant impact controlling the oxygen isotope composition of precipitation at Eagle Cave, although they just modulate the major impact of the amount effect.

The regional impact of this research is limited by the complexity of climate in the Iberian Peninsula as the result of its irregular topography and the ocean/land distribution (e.g., Martín Vide and Olcina Cantos, 2001). However, a study of the moisture sources covering the complete Iberian Peninsula showed that the larger differences were found between NW Atlantic and the Mediterranean facades, whereas south-central and northern regions had less marked differences (Gimeno et al., 2010). Therefore, we expect relatively similar distribution of moisture sources in central Spain (unless for sites with particular microclimate), and larger differences in sites closer to the ocean/sea.

7. CONCLUSIONS

We calculated the back trajectories of air masses for the days with precipitation at Eagle Cave during the years 2009–2011 using a Lagrangian model. The analysis has shown that the period of study integrates all the source areas previously described for the IP (Font Tullot, 2000). Along these back trajectories, we computed the moisture uptake sources based on threshold parameters suitable for our site. At annual timescale, the model explained the source of precipitation for 80–90% of the days with measured precipitation at Eagle Cave. Based on the geographical context and the distribution pattern of the moisture sources during these three years, we defined seven regions of moisture uptake: Iberian Peninsula, Mediterranean, Proximal Atlantic, Distal Atlantic, Northern Seas, Europe and Africa. The sum of moisture uptake was calculated for cells of 0.5 degrees in size at different timescales.

The IP and PA regions were the principal contributors of moisture to Eagle Cave during the period 2009–2011. Contributions from ME and DA regions varied from year to year and other sources had a secondary role in the amount of moisture uptake. A large percentage of the annual precipitation was originated from moisture recycling within the IP. There was an apparent seasonality in the moisture sources, although its quantification is difficult due to unidentified moisture uptake locations in summer for most of the days with precipitation. The monthly isotope composition of precipitation at Eagle Cave during 2009–2011 was statistically correlated with the monthly percentage of moisture sources in different regions. The most significant correlation was found with the IP region. Thus, the recycling of moisture shifted the oxygen isotope composition of precipitation towards lower values. When temperature, amount of precipitation and regions of moisture uptake are considered together, a 74% of the variability of the oxygen isotope values in precipitation was explained at 95% confidence interval. Alternatively, the consideration of just temperature and amount of precipitation explained only 54% of the variability. Thus, although based on the isotope regression model here presented, the isotope composition of the precipitation over Eagle Cave during the period 2009–2011 was mostly controlled by amount of precipitation and temperature, moisture sources also contributed significantly to its variability. Therefore, this study highlights the importance that for some sites the integration of moisture sources has for the precise interpretation of oxygen isotope paleo-records depending on isotopes from precipitation. During the three years period of this study we found that the relative importance of some moisture sources such as the Mediterranean and the Distal Atlantic regions depends on the pressure fields. So, in order to understand if the variability found in this study could be considered stationary, longer periods that would track different cycles of the atmospheric dynamic should be studied.

The application of the method presented in this study would require only minor adaptations to the local/regional context in other sites. Therefore, we hope that application of this or similar methods would become of common use in order to advance in our knowledge of the oxygen isotope composition at different regions and to improve the interpretations of paleo-records depending on it.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gca.2014.03.011.

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