Tellus (1992), *44B*, 226–236

Sources of precipitation over South-Eastern Spain and groundwater recharge. An isotopic study

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(Manuscript received 18 September 1991; in final form 3 February 1992)

ABSTRACT

The deuterium and oxygen-18 compositions were monitored in several single rain events in south-eastern Spain from November 1989 till April 1990. Large variations in both δD and δ^{18}O, as well as in the value of deuterium excess (d-value) of up to $+27^{o}/_{oo}$, were recorded during this time period. The observed variations are clearly related to different source regions of the vapour (Atlantic Ocean or Mediterranean Sea) as well as to different trajectories of precipitating air masses. Whereas the rains of Atlantic origin were characterized by d-values close to $+10^{o}/_{oo}$, the Mediterranean-derived precipitation showed much higher values, of up to $+27^{o}/_{oo}$. The apparent correlation between altitude of the sampling site and the d-value of the corresponding rain can be attributed to two mechanisms: the evaporative isotopic enrichment of rain drops below the clouds, especially at initial stages of the given precipitation event, and/or precipitation from air masses with different isotopic signature (d-value) of the water vapour. The range of the d-values observed in samples from local springs and wells (between $+10$ and $+13^{o}/_{oo}$) suggests that groundwater in the studied areas is recharged predominantly by the Atlantic-derived precipitation.

1. Introduction

Spatial and temporal variations in the deuterium and ^{18}O composition of precipitation are caused by isotope fractionation effects accompanying evaporation from the ocean and condensation during atmospheric transport of water vapour (Dansgaard, 1964). It has been demonstrated in numerous studies that the isotopic composition of local precipitation is primarily controlled by regional-scale processes, i.e., by water vapour transport patterns into the continents, and by the average "rainout history" of the air masses precipitating at a given place (e.g., Merlivat and Jouzel, 1979; Rozanski et al., 1982; Johnsen et al., 1989; Fisher, 1990).

The magnitude of the deuterium excess "d", defined as $d = \delta D - 8 \cdot \delta^{18}O$, is controlled by the source region of the evaporation process, primarily by the relative humidity over the evaporating surface and the wind speed (Merlivat and Jouzel, 1979). As the condensation processes in clouds appear to proceed close to isotopic equilibrium, the d-value of newly formed rain droplets is close to that of the source water vapour. Therefore, the d-value observed in precipitation should reflect specific conditions in the vapour source regions. The d-values close to $+10^{o}/_{oo}$ are observed in most continental meteoric waters at present (Craig, 1961; Yurtsever and Gat, 1981). The deuterium excess of snow may vary in response to changes of the supersaturation of vapour with respect to temperature of snow formation (Jouzel and Merlivat, 1984; Fisher, 1991; Petit et al., 1991). It is thought that this process is important only in low-temperature environments (polar regions).

Vapour generated over closed basins with or without restricted communication with the open ocean is usually characterized by a higher d-value,

due to a lower relative humidity and more pronounced kinetic isotope effects during evaporation. A well-known example of this type of evaporation process is the East Mediterranean area, where rains characterized by d-values of up to $+32‰$ have been observed (Gat and Carmi, 1970; Gat and Dansgaard, 1972; Gat and Carmi, 1987; Rindsberger et al., 1983).

High d-values in precipitation, well documented in the eastern Mediterranean region, have not been so far reported for the western Mediterranean. Two stations of the region belonging to the IAEA/WMO global network (Gibraltar and Tunis) reveal a d-value close to $+10‰$ (IAEA, 1981), suggesting predominance of Atlantic-derived precipitation. However, in these two stations as well as in the Genoa station (located on the northern coast of the Mediterranean), some measurements corresponding to months with relatively high amounts of precipitation show d-values close to $+15‰$.

The present study was undertaken with the main aim to search for Mediterranean-derived precipitation (high d-value) in the western Mediterranean, in particular in SE Spain, and to compare it with the isotope signature of the local groundwater.

2. The study area

Samples of precipitation representing several single events (rain and snow) were collected at different altitudes between 30 and 2000 m between coastal and continental mountains in south-eastern Spain, mainly between November 1989 and April 1990, which corresponds to the rainy season in this area (Fig. 1). Only a few samples were collected before and after this period. Several zones were selected in the region influenced by the Mediterranean climate. The coastal zone includes the Gádor and Lújar Ranges (0–2000 m.a.s.l.). The Cazorla and Segura Ranges are situated between 100 and 200 km inland; both aligned NE-SW with altitudes ranging from 600 to 2000 m.a.s.l. The

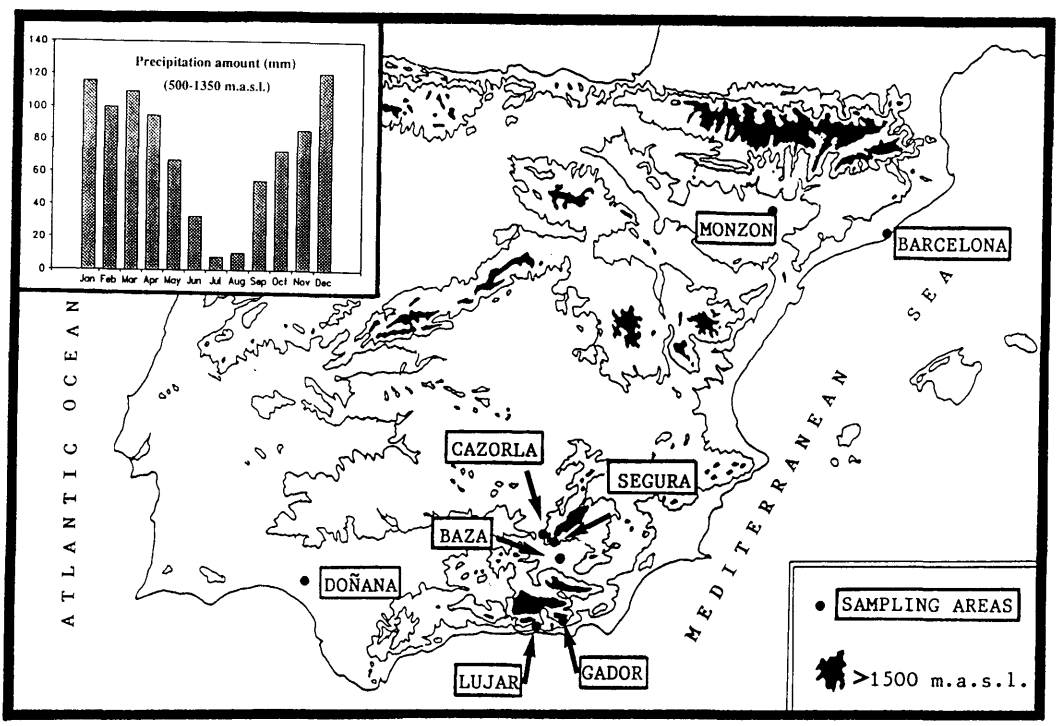


Fig. 1. Schematic map of the study area. The inserted histogram shows long-term annual distribution of precipitation in the region for selected stations in the altitude range between 500 and 1350 m.a.s.l.

Table 1. *Isotopic composition of shallow groundwaters and springs sampled in six study areas (Fig. 1) during 1990 and 1991*

Area	Altitude of the sampling site [m]	No. analyses	Range of $\delta^{18}O$ (‰)	Deuterium excess (‰)
Segura	800–1500	38	−8.0 to −8.9	12.0 ± 1.3
Cazorla	700–1450	65	−7.6 to −9.0	12.8 ± 1.5
Baza	800–1300	21	−8.4 to −9.3	11.4 ± 1.1
Gádor	150–900	23	−7.1 to −9.3	11.3 ± 1.5
Lújar	180–360	17	−6.4 to −8.1	11.1 ± 2.4
Doñana	10–100	25	−4.0 to −6.2	10.9 ± 3.1

Segura Range is closer to the Mediterranean coast. The Baza Depression is located between the coastal zone and these two ranges (Fig. 1). A few samples were obtained on the Atlantic side, in the Doñana area. The inserted histogram in Fig. 1 illustrates the annual distribution of precipitation over the studied areas (long-term means from several meteorological stations located between 500 and 1350 m.a.s.l.). It should be noted that only a small fraction, between 10 and 20 percent, of the annual precipitation was sampled for isotopic analyses.

Shallow groundwaters and springs were sampled in all the above mentioned areas during a time interval covering more than one year (Cruz-San Julián et al., 1990; Benavente et al., 1990). The ranges of the isotopic composition and the altitude of the sampling sites of groundwater collected in each area are presented in Table 1.

Deuterium and oxygen-18 composition in samples of precipitation and groundwater was determined in the IAEA Isotope Hydrology Laboratory in Vienna using the standard techniques (Epstein and Mayeda, 1953; Coleman et al., 1982). The results are expressed as per mille deviations from the internationally accepted standard V-SMOW (Gonfiantini, 1978). The analytical error is ±0.1‰ for $\delta^{18}O$ and ±1‰ for δD.

3. Results

The results of isotopic analyses of precipitation samples collected mainly between November 1989 and April 1990 are summarized in Table 2. The table also contains isotope analyses of precipitation samples collected in Barcelona and Monzón, approximately 600–700 km NE of the study area (Fig. 1). The observed range of $\delta^{18}O$ values is between −1.2 and −14.6‰, whereas the

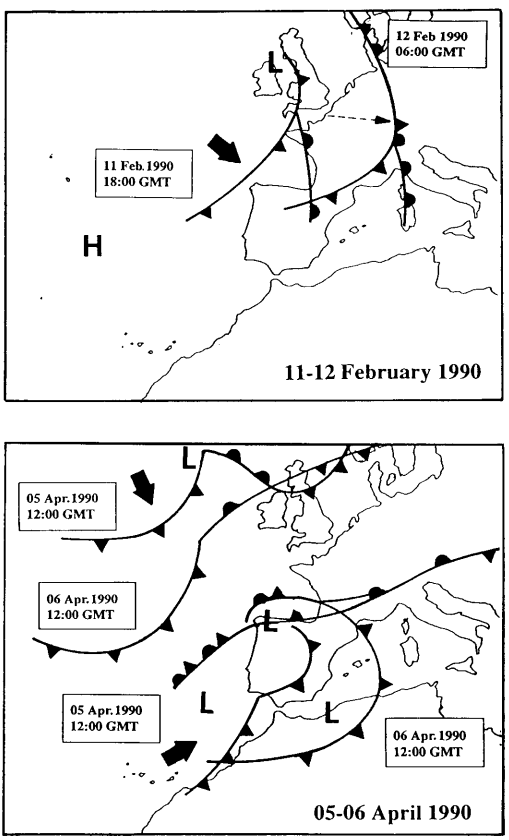


Fig. 2. Schematic presentation of two characteristic meteorological situations resulting in the Atlantic- and Mediterranean-derived precipitation in south-eastern Spain. (See text for details).

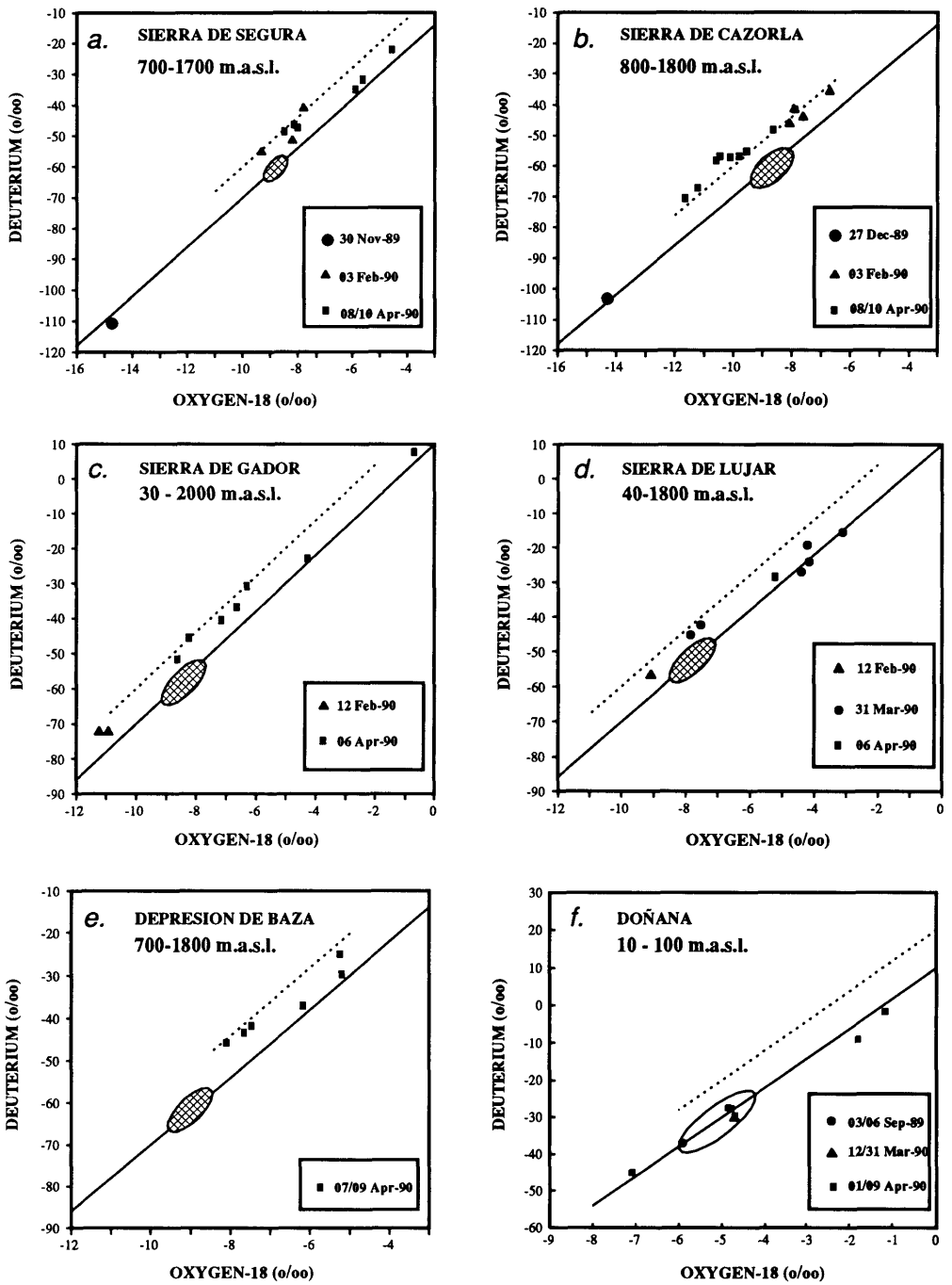


Fig. 3. $\delta D/\delta^{18}O$ relationship for precipitation samples collected during selected rain events at six study areas. The heavy line indicates the position of the Global Meteoric Water Line, $\delta D = 8 \cdot \delta^{18}O + 10$. The broken lines represent the Western Mediterranean Meteoric Water Line, $\delta D = 8 \cdot \delta^{18}O + 22$. The isotopic composition of local shallow groundwater and springs is marked by ellipses.

Table 2. *Results of isotope analyses of precipitation samples collected during selected rain events between September 1989 and April 1990, at six locations in south-eastern Spain; for comparison, the results for samples collected at Barcelona and Monzón, about 600 km NE from the study area, are also reported*

No.	Sampling date	Site	Area	Altitude (m)	Amount of precipitation (mm)	Oxygen-18 (‰)	Deuterium (‰)	Deuterium excess (‰)
1	03/06 Sep-89	P. Doñana	Doñana	10	n.a.	−5.95	−36.1	11.5
2	30 Nov-89	Natividad	Segura	1110	20	−14.58	−109.6	7.0
3	27 Dec-89	Mornico	Cazorla	1020	10	−14.25	−103.3	10.7
4	07 Jan-90	Monzón	Monzón	277	15	−7.58	−55.6	5.0
5	31 Jan-90	Monzón	Monzón	277	18	−3.81	−15.3	19.8
6	01/03 Feb-90	El Charco	Segura	1450 (*)		−7.75	−40.7	21.3
7		Cañada Hermosa	Segura	1600 (*)		−8.19	−51.9	13.6
8		Cuerda Mirabete	Segura	1750 (*)	between	−9.36	−55.1	19.8
9		Arroyo Frío	Cazorla	1180 (*)	11	−8.10	−45.7	19.1
10		Las Palomas	Cazorla	1380 (*)	and	−6.78	−35.8	18.4
11		La Canal	Cazorla	1520 (*)	23	−7.90	−41.6	21.6
12		Puertollano	Cazorla	1800 (*)		−7.58	−43.9	16.7
13	12 Feb-90	Barranco Sabinar	Gádor	1845	n.a.	−11.30	−72.7	17.7
14		Barranco Cordero	Gádor	1950	n.a.	−10.90	−72.4	14.8
15		Pico Los Pelaos	Lújar	1830 (*)	n.a.	−9.07	−57.0	11.9
16	12/31 Mar-90	P. Doñana	Doñana	10	15	−4.81	−29.5	9.0
17	31 Mar-90	Motril	Lújar	40	7	−4.07	−23.3	9.3
18		Orgiva	Lújar	180	7	−4.39	−25.9	9.2
19		Albuñol	Lújar	240	5	−3.00	−16.2	7.8
20		Velez	Lújar	470	8	−4.21	−19.8	13.9
21		Sierra Lújar	Lújar	1170	n.a.	−7.54	−42.8	17.5
22		Sierra Lújar	Lújar	1840	n.a.	−7.76	−45.6	16.5
23	03 Apr-90	P. Doñana	Doñana	10	n.a.	−1.21	−1.6	8.1
24		El Caoso	Doñana	60	n.a.	−1.83	−9.0	5.6
25		Rociana	Doñana	100	n.a.	−4.90	−27.4	11.8
26	02/09 Apr-90	P. Doñana	Doñana	10	n.a.	−4.97	−27.2	12.6
27	06 Apr-90	F. Adra	Gádor	30		−4.25	−22.7	11.3
28		Canjayar	Gádor	550		−0.68	7.9	13.3
29		Laujar	Gádor	910	between	−8.23	−45.4	20.4
30		Barranco Lena	Gádor	1260	7	−6.64	−36.6	16.5
31		P. Boliche	Gádor	1540	and	−7.15	−40.4	16.8
32		C. Animas	Gádor	1790	15	−9.34	−57.0	17.7
33		L. Barjali	Gádor	2030		−8.61	−51.6	17.3
34		Torvizcon	Lújar	689		−5.19	−28.1	13.4
35	07/09 Apr-90	C. Legua	Baza	713		−5.20	−29.5	12.1
36		Venta Angulo	Baza	905	between	−5.24	−24.8	17.1
37		Atalaya	Baza	1040	9	−6.18	−36.9	12.5
38		B. Madroño	Baza	1228	and	−7.48	−41.5	18.3
39		Narvaez	Baza	1380	31	−7.66	−43.2	18.1
40		C. Clarin	Baza	1780		−8.10	−45.6	19.2

Table continued

Table 2 (*cont'd*)

No.	Sampling date	Site	Area	Altitude (m)	Amount of precipitation (mm)	Oxygen-18 (‰)	Deuterium (‰)	Deuterium excess (‰)
41	08/10 Apr-90	La Canal	Cazorla	800		−8.64	−48.2	20.9
42		La Losilla	Cazorla	1100		−9.79	−56.8	21.5
43		Rayal	Cazorla	1160	between	−10.45	−56.8	26.8
44		Las Chozuelas	Cazorla	1300	13	−9.54	−55.2	21.1
45		Barr. La Canal	Cazorla	1520	and	−11.64	−70.4	22.7
46		Barr. La Canal	Cazorla	1520	38	−11.21	−67.2	22.5
47		Cota 1700	Cazorla	1700		−10.57	−58.3	26.3
48		Puertollano	Cazorla	1800		−10.09	−57.1	23.6
49	08/10 Apr-90	Alcantarilla	Segura	720		−4.55	−22.0	14.4
50		Emb. La Vieja	Segura	910	between	−5.61	−31.7	13.2
51		La Natividad	Segura	1090	10	−5.87	−34.9	12.1
52		Arroyo Zumeta	Segura	1300	and	−7.99	−47.2	16.7
53		El Espino	Segura	1480	37	−8.48	−48.4	19.4
54		Barr. Conejero	Segura	1720		−8.12	−46.3	18.7
55	19 Apr-90	R. J. Campos	Gádor	1065	n.a.	−6.29	−30.6	19.7
56	25 Sep-90	Barcelona	Barcelona	65		−5.09	−26.2	14.5
57		Barcelona	Barcelona	65	35	−5.13	−22.1	18.9
58		Barcelona	Barcelona	65		−6.84	−34.1	20.6

(*) Snow samples

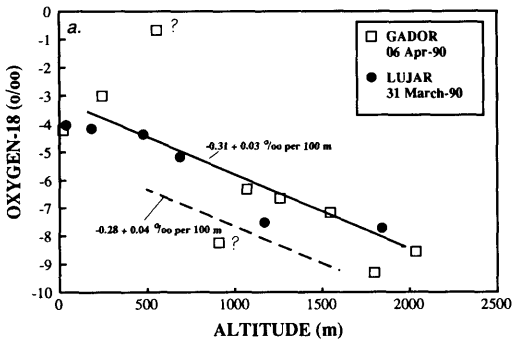
d-values for most of the samples are higher than +10‰, reaching values up to +27‰. The elevation of the collection sites ranges between 10 and 2030 m.a.s.l. The amount of precipitation corresponding to the sampled rain events was recorded only at few collection sites (Table 2).

The majority of precipitation events sampled for isotope analyses was associated with two distinct meteorological situations as presented schematically in Fig. 2. The first one is characterized by a high pressure center over the Azores and a pronounced depression over the British Islands. It results in a strong NW circulation bringing relatively cold air masses from the North Atlantic. This situation is characterized by the weather maps corresponding to 11 and 12 February 1990. The second situation is associated with a deep low initially located over the Gulf of Cádiz and moving slowly eastward. Strong anticyclonic circulation pushes moist air masses from the subtropical Atlantic towards southern Spain and North Africa. The eastern coast of Spain receives at that time moisture of western Mediterranean origin. This type of circulation prevailed during 5 and 6 April 1990.

The observed relationship between isotopic composition of local groundwater (as summarized in Table 1) and precipitation samples collected in the investigated areas is shown in Fig. 3 in the form of $\delta D/\delta^{18}O$ diagrams. Apparent correlations between $\delta^{18}O$ and *d*-value of the precipitation samples collected in March and April 1990 during single rain events, and the elevation of the sampling sites are shown in Figs. 4 and 5, respectively.

4. Discussion

The concept most often applied in modelling isotope variations observed in precipitation assumes that the marine water vapour entering the continent undergoes a Rayleigh process in which the rain is formed in isotopic equilibrium with the vapour and is immediately removed from the cloud (Dansgaard, 1964; Rozanski et al., 1982; Siegenthaler and Matter, 1983; Van der Straaten and Mook, 1983). Because heavy water molecules ($H_2{}^{18}O$, HDO) are preferred in the condensation process, the remaining cloud vapour is



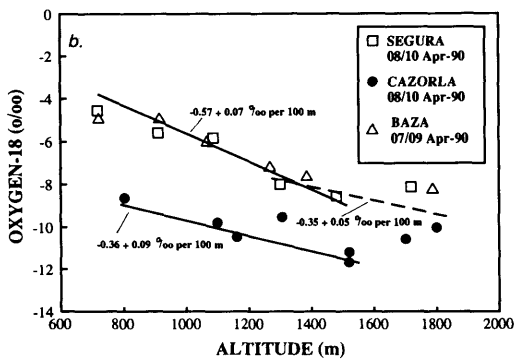
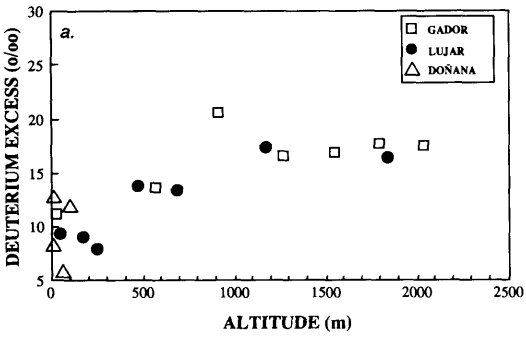


Fig. 4. $\delta^{18}O$ of precipitation samples collected during selected rain events, plotted versus altitude of the sampling site. The heavy lines represent the best-fit of the data points. The points labelled with a question mark (Fig. 4a), and others representing elevation higher than 1600 m (Fig. 4b) have been omitted in the calculations of the regression lines. Broken lines represent $\delta^{18}O$-altitude relationships in shallow groundwaters of the region. They were derived using data for springs with well defined local recharge. For location of the sampling sites, see Fig. 1.



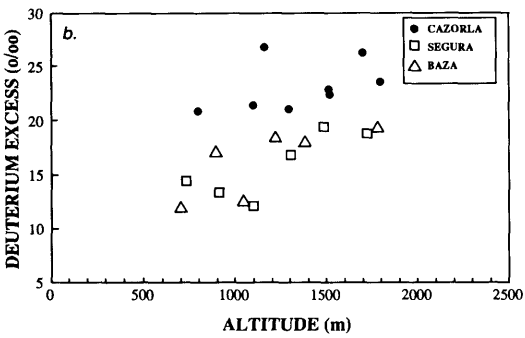


Fig. 5. Deuterium excess values of individual precipitation samples collected during selected rain events, plotted as a function of the altitude of the sampling site. The symbols represent the same rain events shown in Fig. 4a and 4b. For locations of the sampling sites, see Fig. 1.

progressively depleted in deuterium and ^{18}O. The isotopic composition of a newly formed condensate, after making several simplifying assumptions, can be expressed as follows:

$$\delta_p = \alpha_{eq}(\delta_{vo} + 1)\, F^{\alpha_{eq}-1} - 1, \qquad (1)$$

where

$$\delta_{vo} = \frac{1}{\alpha_{eq}} \frac{1-k}{1-kH} - 1 \qquad (2)$$

stands for initial isotopic composition of marine moisture (Merlivat and Jouzel, 1979). The parameter F describes the degree of rainout of the considered air mass and can be expressed as a ratio (W/W_o) of the total precipitable water in the atmospheric column over the site of precipitation to that over the source region (Sonntag et al., 1983). α_{eq} stands for the equilibrium fractionation factor between liquid and vapour, at condensation (eq. (1)) or evaporation (eq. (2)) temperature.

The isotopic composition of evaporated marine vapour is controlled by the temperature of the sea surface (via temperature dependence of α_{eq}), the humidity of the air, H, and the wind speed, which controls the value of the kinetic fractionation factor k. Analysis of eq. (2) reveals that the deuterium excess of the vapour mainly responds to changes in relative humidity. The modelling of isotope variations of precipitation and water vapour over Western and Central Europe, based

on equations (1) and (2), revealed that $\delta^{18}O$ and δD values of rain and vapour are controlled in first instance by the actual value of the F-parameter, i.e., the degree of rainout of the precipitating air mass. This parameter is a function of regional scale processes such as the evaporation conditions in the source region, the vapour flux variations in the atmosphere, and the precipitation-evaporation rates over the whole distance from the source region to the sampling point (Rozanski et al., 1982, Sonntag et al., 1983).

The models outlined above also yield reliable estimates for the linear relationship between deuterium and ^{18}O contents in precipitation. Assuming that the subtropical ocean is the major source of vapour on a global scale (sea surface temperature of 25°C, relative humidity of 80%), Merlivat and Jouzel (1979) were able to reproduce the global relationship observed in precipitation, $\delta D = 8\delta^{18}O + 10$, called the Global Meteoric Water Line (GMWL).

4.1. δD-$\delta^{18}O$ relationship

Precipitation collected at Segura and Cazorla on 30 November and 27 December 1989, represents a typical example of NW circulation. Rain is heavily depleted in both oxygen-18 and deuterium, with a d-value close to $+10‰$. This suggests a long travel distance of air masses (high degree of rainout) and Atlantic origin of the water vapour. A similar event was recorded on 12 February 1990 at Gádor and Lújar. The isotopic data suggest a slightly smaller degree of rainout of the air masses compared to that observed in November and December at Segura and Cazorla. The isotopic composition of precipitation collected at Segura and Cazorla on 3 February 1990, suggests an entirely different origin of atmospheric moisture. Relatively enriched ^{18}O and deuterium as well as d-values close to $+20‰$ point to the western Mediterranean as the predominant source of water vapour.

The rains sampled at all six locations between 6 and 10 of April were associated with a presence of the deep depression at the Gulf of Cádiz. It is worth noting that, whereas the rain collected in Doñana suggests Atlantic origin of water vapour (d-values close to $+10‰$), precipitation at the remaining sites has a typical Mediterranean character (d-values close to $+20‰$). Apparently, part of the air masses from the subtropical Atlantic crossed the Atlas mountains, where part of the initial moisture load was removed by precipitation. Then, the air masses were probably reloaded with moisture over the Alborán sea (west Mediterranean) and produced precipitation on the coastal ranges of Granada and Almería. Although the travel distance over the Mediterranean was rather short, the d-excess signature of the water vapour was substantially modified. The moist air masses of Mediterranean origin, advected by the anticyclonic circulation, possibly also contributed to precipitation over the eastern coast of Spain during the discussed time period.

One single sample collected in the Gádor area on 6 April is extremely enriched in heavy isotopes ($\delta^{18}O$ more than $3‰$ higher than in the remaining samples collected on the same day). The location of this sample on the $\delta D/\delta^{18}O$ diagram excludes substantial evaporation effects. The origin of this extreme isotopic composition remains unclear.

The presence of two entirely different sources of atmospheric moisture contributing to the formation of precipitation over southeastern Spain is seen also in Monzón precipitation (Table 2). The samples collected on 7 January 1990 were isotopically depleted with low d-values, whereas the rain of 31 January 1990 is isotopically much heavier, with the d-value close to $+20‰$. Precipitation collected in Barcelona on 25 September 1990 has a typical Mediterranean character.

4.2. $\delta^{18}O$-altitude relationship

The decrease of the heavy isotope content of precipitation with increasing elevation of the collection site, known as the altitude effect, results mainly from gradual rainout of orographically uplifted air masses. The magnitude of this effect depends on the morphology of the area and on specific meteorological conditions leading to formation of precipitation. The slopes of $\delta^{18}O$-altitude relationship reported in the literature vary between -0.15 and $-0.7‰$ per 100 m for $\delta^{18}O$ and -1.2 and $-5.6‰$ per 100 m for δD (Moser and Stichler, 1974; Gat, 1980; Niewodniczanski et al., 1981; Holdsworth et al., 1991).

The $\delta^{18}O$-altitude relationship found for individual rain events sampled in April is presented in Fig. 4. In the Gádor and Lújar areas (Fig. 4a) the data points cluster around the line with a slope of $-0.3‰/100$ m, with substantially

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higher spread for the rainfall on 6 April at Gádor. The two outliers marked by question marks have not been considered in the calculation of the regression line. The plot of *d*-excess versus altitude (Fig. 5a) confirms common origin of precipitation for both events; the *d*-values are very similar, with a slight tendency to raise with increasing altitude.

Fig. 4b summarizes the δ^{18}O-altitude relationship found for three other collection sites (Segura, Cazorla and Baza). Precipitation was collected between 7 and 10 April during predominant easterly circulation. Whereas the data points for Segura and Baza reveal a practically identical relationship, the ^{18}O content of rain samples collected at Cazorla is shifted towards more negative δ^{18}O values by approximately $2‰$, forming almost a parallel line. If one assumes that precipitation collected at Cazorla represent a continuation of the rainout process of the same air masses which precipitated before over Baza and Segura, the observed shift might be understood. However, the *d*-excess values of rain samples collected at Cazorla are distinctly higher than those observed in Baza and Segura precipitation (Fig. 5b). This practically excludes the hypothesis of a common source of precipitation for these three sites. The *d*-excess values suggest that two different air masses contributed to the precipitation event: one with a very distinct Mediterranean character (high *d*-excess) and relatively high degree of rainout (longer travel distance?), which produced precipitation over Cazorla, and the other, precipitating over Segura and Baza, with lower *d*-excess (between $+12$ and $+20‰$) and higher δ^{18}O values, pointing to formation of water vapour closer to the precipitation site, at higher relative humidity.

It was interesting to compare the δ^{18}O-altitude relationship observed in individual events, with those found in local groundwaters, indicated by broken lines in Fig. 4. These lines were established using only data for springs with well defined local recharge. They should reflect an average δ^{18}O-altitude relationship in precipitation, characteristic for the given region. The slope of this relationship reaches about $-0.28‰\,\delta^{18}$O per 100 m for Gádor and Lújar areas, and $-0.35‰\,\delta^{18}$O per 100 m for Segura, Cazorla and Baza.

An interesting feature of the data points presented in Fig. 4b is an apparent change of the δ^{18}O-altitude relationship, for the highest collection sites (between 1500 and 1800 m.a.s.l.). In the case of Segura and Baza, δ^{18}O remains roughly constant whereas for Cazorla it seems to increase with altitude. Although such an effect has been reported in the literature (Holdsworth et al., 1991) it is usually observed at much higher elevations, between approximately 3.5 and 5 km. In our case this irregularity most probably reflects complex meteorological conditions between 7 and 10 April 1990, with air masses of different origin and/or different degree of rainout contributing to the formation of precipitation.

4.3. Deuterium excess versus altitude

The correlation between *d*-excess values of the rain samples collected in April and altitude is shown in Fig. 5. In addition to the above discussed differentiation of *d*-excess values due to different origin of precipitating air masses, an apparent increase of this parameter with increasing elevation of the sampling site can be noted in Fig. 5. This fact suggests that evaporation of raindrops below the cloud base may play an important role at these latitudes. The lower *d*-excess values recorded at sea level would then be a consequence of the longer distance between the average cloud base level and the sampling point and resulting higher degree of evaporation of raindrops. The intensity of evaporation of falling raindrops depends on several factors: distance between the cloud base and the ground, relative humidity, character of precipitation event, average size of raindrops, etc. These effects probably contribute substantially to the observed seasonal fluctuations of the *d*-value in the mid-latitude precipitation. This effect is known in the literature as a pseudo-altitude effect (Moser and Stichler, 1971; Fritz et al., 1987; Rindsberger et al., 1990).

4.4. Local groundwater

The range of the isotopic composition of shallow groundwater in the six study areas has been marked by clusters in Fig. 3. They fall in all cases on the meteoric water line with the *d*-value close to $+10‰$, contrary to the $d = +20‰$, characteristic for the majority of spring precipitation collected in this region. Also, the groundwater is isotopically depleted compared to the Mediterranean-derived precipitation. This fact suggests that local recharge is produced mainly by Atlantic-derived winter precipitation, similar to

those precipitation events observed in November, December and February in Segura, Cazorla and Gádor, respectively.

5. Concluding remarks

The present study demonstrates the presence of Mediterranean-type precipitation in southern and eastern Spain during springtime. Precipitation of this type is relatively enriched in heavy isotopes and has a characteristic d-excess value around $+20^{o}/_{oo}$. Analysis of weather charts showed that this type of precipitation over eastern Spain is related to the depression systems situated in the Gulf of Cádiz and associated easterly winds over the western Mediterranean.

Comparison of isotopic analyses of precipitation and local groundwater in the study area showed clearly that groundwater recharge results mainly from Atlantic-derived precipitation (westerly circulation). Mediterranean-derived precipitation, although present in the record, seems to be of minor importance to the water balance.

The apparent correlation between the d-value and the altitude of the sampling site confirms earlier suggestions of the possible role of evaporative effects below the cloud base on the isotopic composition of precipitation collected at the ground level.

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