Tellus (1990), *42B*, 263–271

Patterns of the isotopic composition of precipitation in time and space: data from the Israeli storm water collection program

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(Manuscript received 14 March 1988; in final form 14 June 1989)

ABSTRACT

The data from a precipitation sampling program in Israel show the synoptic scale history of the air masses to be the predominant factor which controls the isotopic data. Within a single storm, the passage of a front is always associated with values most depleted in the heavy isotopes. Local factors and especially the enrichment of the heavy isotopic species resulting from partial evaporation of rain in low lying stations, are superimposed on these large-scale effects.

1. Introduction

The stable isotope composition of precipitation follows certain rules related to climatic and geographic factors, summarized as the effects of latitude, altitude, distance from the coast (the water source) and the amount of rain (Dansgaard, 1964). Based on the data from a world-wide monthly-averaged precipitation collection program, Yurtsever and Gat (1981) showed the changes in isotopic composition to be correlated with temperature; a Rayleigh law describes the depletion of the heavy isotopic species in the air moisture by rainout (Gat, 1980). The isotopic composition of the hydrogen and oxygen in water is expressed in units of δD and $\delta^{18}O$, respectively. The δD and $\delta^{18}O$ values of the precipitation, in most cases, follow a relationship such as $\delta D = 8 \cdot \delta^{18}O + d$, the so-called Meteoric Water Line (MWL) relationship. For a world-wide average $d = 10‰$ (Craig, 1961) but higher values of $d > 15‰$, are found in the Eastern Mediterranean Sea area (Gat and Dansgaard, 1972); d was named the "deuterium excess parameter" by Dansgaard (1964). The value of d is believed to relate to the conditions under which evaporation takes place at the source area for atmospheric moisture (Merlivat and Jouzel, 1979), implying that the subsequent rainout from such air-mass is invariant with regards to d. However, partial re-evaporation of water from falling rain droplets under dry conditions may perturb (decrease) the value of the deuterium excess parameter in the residual rainwater.

The dependence of the isotopic compositions in the meteoric water cycle, namely of both $\delta^{18}O$ and d, on climatic parameters has been utilized in attempts to reconstruct paleoclimates. For this purpose, one tries to reconstruct the mean isotopic composition of past precipitation based on the isotopic composition of proxy materials and compare it to that of present-day precipitation. A prerequisite for any such use, however, is the understanding of how the isotope data of rain events are related to either local or global climate parameters and how the individual rain data combine to form a seasonal and yearly average.

[1] The storm water collection program was initiated by Michael Rindsberger with the aim of a meteorological and, eventually, paleo-climatic interpretation. Due to the untimely death of Michael, this program was cut short. The data which have been obtained and their phenomenological evaluation are presented by his colleagues and teachers, in honoured memory of a devoted scientist and a dear friend.

The isotopic composition of individual rain events show very wide variations, possibly reflecting singular local factors such as the rain intensities. However, some preliminary work by Rindsberger et al. (1983) and Leguy et al. (1983) indicate that the synoptic history of the precipitating air masses was mirrored in the isotopic composition of the precipitation. The question then arises whether the control on the mean isotopic composition of precipitation (and on its variability in time) is exercised by local climatic factors such as the precipitation pattern and local temperature, or whether they are the result of the synoptic scale phenomena, the origin of the air-masses, etc. Clearly, a more detailed description of the isotopic composition of water from a single storm event in time and space, and the relationship to climatic and synoptic factors, would be desirable.

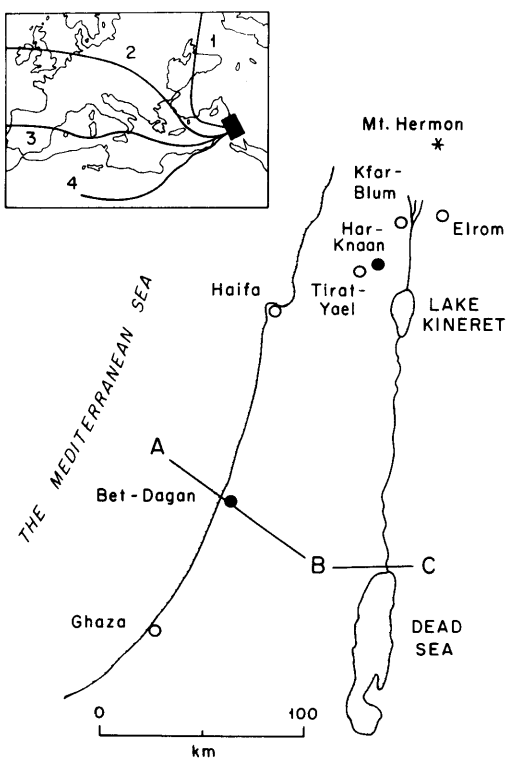

Fig. 1. Map of Israel, showing location of precipitation collection stations. ●: IAEA-WMO network stations; ○: special strom sampling stations. Location of the transect of Fig. 6, is indicated by line A-B-C. Inset: trajectories of precipitating air masses as classified by Gagin and Neumann (1974).

In this paper, we present data from a rather detailed storm collection program at a number of stations in northern and central Israel; their isotopic composition (the δD and δ^{18}O content) and a synoptic analysis of the air mass trajectories associated with these storms are discussed.

As a background to such a discussion, we may recall that in general most of the moisture which results in the winter precipitation in Israel derives from the interaction between the Mediterranean Sea and air masses which moved over the European continent. Four rather distinct types of trajectories have been identified by Gagin and Neumann (1974); only three of these seem to be represented in the suite of samples to be discussed. As shown in the inset of Fig. 1, trajectory type 1 originates from continental arctic or polar air, trajectory type 2 from maritime polar or arctic air and trajectory type 3 from either polar or tropical maritime air masses. As summarized by Gat and Rindsberger (1985), each of these pathways is associated with a distinctive isotopic composition, reflecting both the origin of the moisture and the subsequent interaction pattern with the waters of the Mediterranean Sea (Gat and Carmi, 1970).

2. Methodology of the storm sampling program

During the years 1981–85, precipitation was collected at a number of Israeli stations, with Bet-Dagan serving as a reference station. The location of the station network is shown in Fig. 1; the network consisted of a transect from the coast to the east, from Haifa to the Golan Heights, and of two more southern stations situated in the coastal plain. As a rule, the water accumulated by standard rain gauges during the collection periods of 8 am–8 pm and 8 pm–8 am, respectively, was sampled. Occasionally, during heavy showers, a shorter sampling interval was chosen. The samples were analysed mass-spectrometrically for their ^{18}O and ^{2}H content at Rehovot using conventional analytical techniques (IAEA, 1981b).

In order to ascertain the representativeness of a sample taken at a certain site, simultaneous collection was carried out during November and December 1982 at 4 rain gauges situated within

the perimeter of the Meteorological Service at Bet-Dagan. These stations were spaced about 200 m apart and the sample suite consisted of 30 sampling periods, during which the rain amounts ranged from 0.6–35 mms of water depth, and the stable isotope content from $\delta^{18}O = 0‰$ to $\delta^{18}O = 7‰$. The average deviation between data from the different rain gauges (for any given sampling interval) was found to be $\Delta(\delta^{18}O) = 0.22 \pm 0.2‰$ (average deviation of rain amounts for any given sampling interval was 6%) compared to the analytical reproducibility which was $\sigma(\delta^{18}O) = \pm 0.2‰$. The larger scatter (in 5 out of 6 cases where $\Delta > \sigma$) was from periods of small rain amounts, of less than 1.5 mm. We conclude that a local sample is a meaningful probe of the isotope composition at any sampling site.

3. Data from the 1982/83 season

Fig. 2 gives the isotopic data obtained for the 1982/83 season, including about 12 rainy periods. Data for two periods with more prolonged rainy spells (29 December 1982 to 6 January 1983 and 17 February to 28 February 1983) are shown in greater detail in Figs. 3 and 4. At first sight one sees a wide range of isotopic compositions (range of 12‰ in $\delta^{18}O$), as large within a single rainy spell as from storm to storm. Quite often the pattern of evolution in time during a rain-spell is V or W shaped: a sharp decrease of the δ values initially, with a minimum value sometime in the middle of the shower. Similar paterns were traced in the Negev by Levin et al. (1980). We note that in general the progression of the data from different stations is in parallel, underlain by some characteristic differences between stations.

3.1. 29 December 1982–6 January 1983

Let us examine the occurrences during the period of 29 December 1982–6 January 1983 in greater detail. During this period samples were collected from two stations in the south (Bet-Dagan and Ghaza) and two more in the far north (namely Kfar-Blum in the Hula Valley and Elrom on the ascending slopes of the Golan). The isotopic and rain data are shown in Fig. 3. On 29 of December, we witnessed a rainy spell of moderate intensity of about 24 h duration, with about equal rain amounts throughout the country.

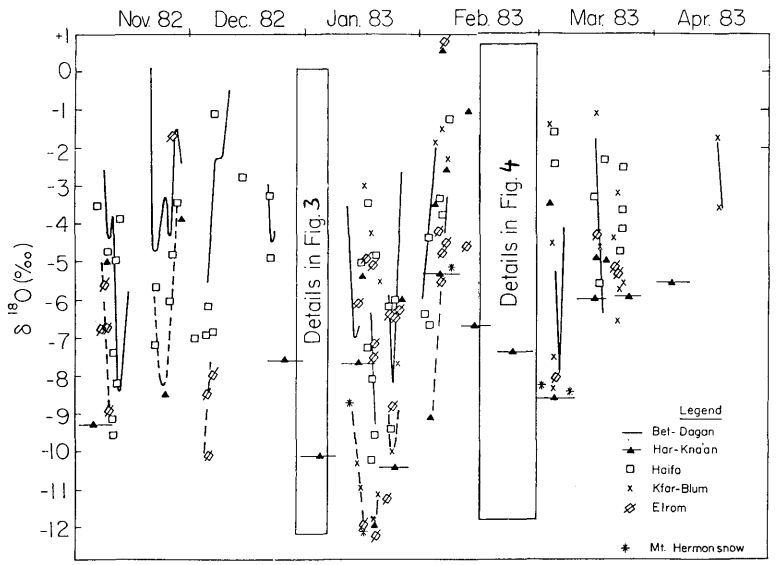

Fig. 2. ^{18}O data of short term precipitation samples from Northern Israel. Sampling duration was usually about 12 h, except for the Har-Kna'an data which represent a 10-day averaged sampling period. Data points from Bet-Dagan are not marked individually.

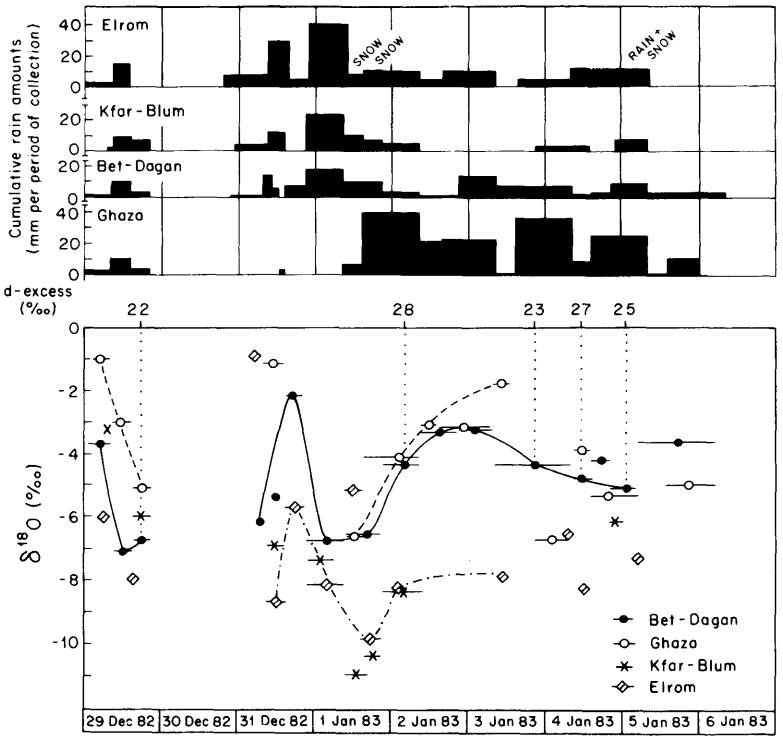

Fig. 3. The march of isotopic values during a rainy spell from 29 December 1982–6 January 1983. The distribution of the rain amounts during the sampling intervals is shown on top. Value of the *d*-excess parameter (in ‰) for Bet-Dagan samples is shown on top of the bottom diagram.

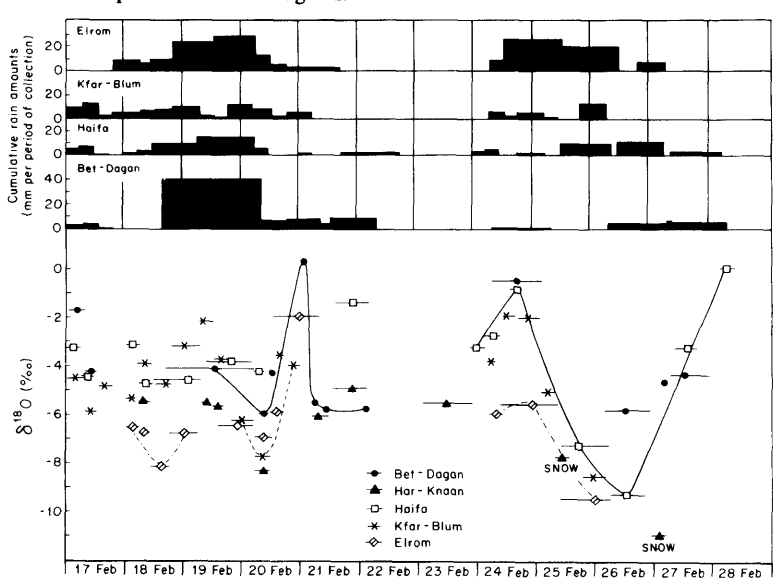

Fig. 4. The march of isotopic values and the rain amounts during the period from 17–28 February 1983.

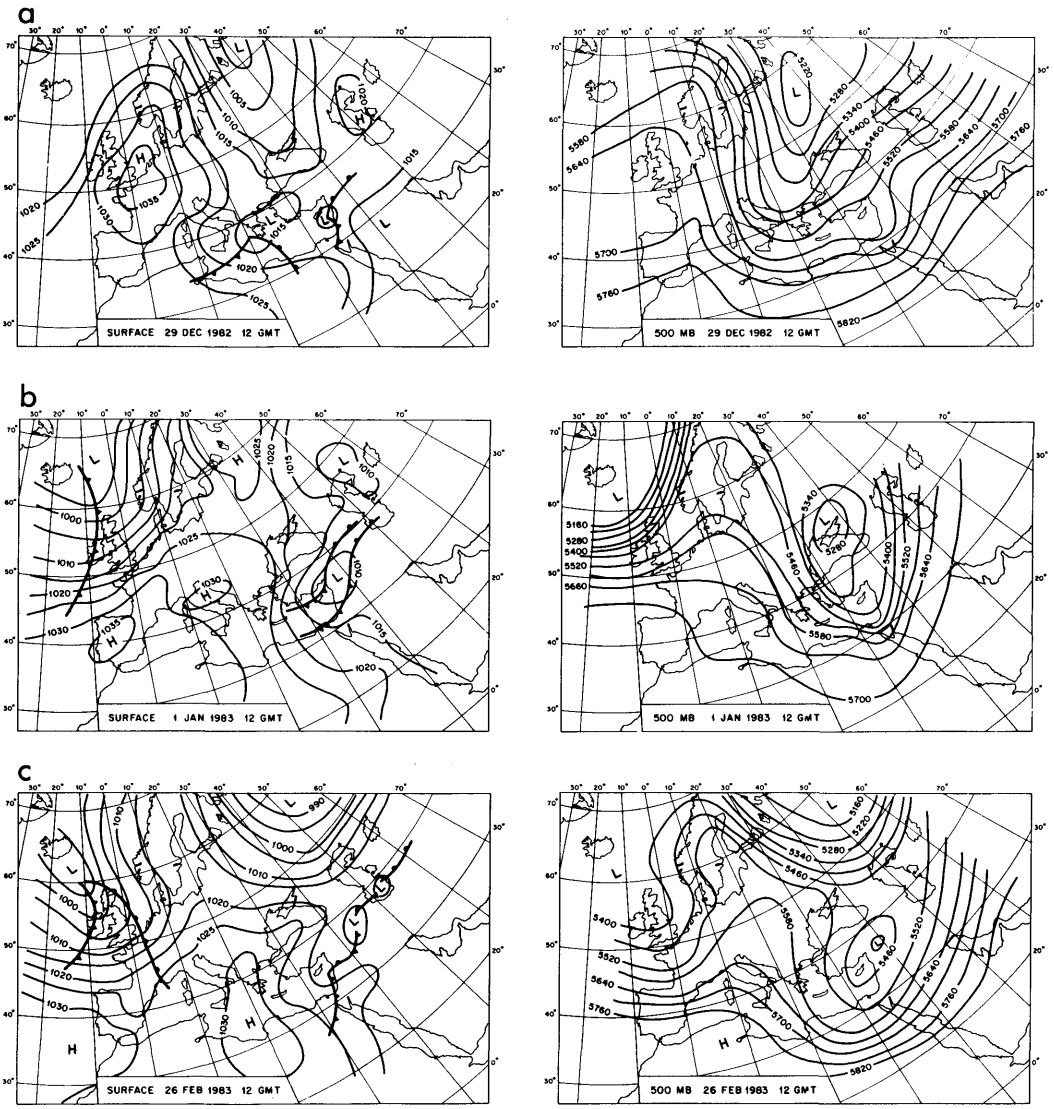

Fig. 5. (a) Surface and 500 mb synoptic maps for 29 December 1982. (b) Surface and 500 mb synoptic maps for 1 January 1983. (c). Surface and 500 mb synoptic maps for 26 February 1983.

Peak intensities at Bet-Dagan were recorded around 14:00 and these correspond to the nadir in isotopic composition. The isotopic values and their progress in time from the different stations is remarkably similar, except for the data from Ghaza which are more enriched by about 3‰ in $\delta^{18}O$ but describe a parallel curve. The weather maps for that day (Fig. 5a) show the classical pattern for rain in Israel, associated with the noon time passage of a cold front related to a "Cyprus Low". The minimum in $\delta^{18}O$ values corresponds to the time of passage of the front; the peak rain intensity also occurred at that time.

The air masses were found by synoptic back-tracking (Fig. 6) to have originated in the Atlantic maritime regions, approaching Israel on a trajectory along the Eastern Mediterranean (trajectory type 2, as shown in the inset of Fig. 1).

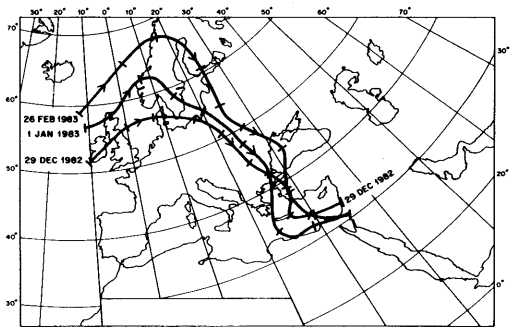

Fig. 6. Backtracking of the precipitating air masses at the 850 mb level, starting at 12:00 GMT on each of the dates indicated on the trajectories; the position on each trajectory for 12-h intervals is indicated by cross bars.

Rain resumed one day later on 31 December 1982, first in the north and spreading to the south; high rain intensities were recorded at Ghaza from mid-day of 1–4 January 1983. By that time, precipitation in the north had dwindled, but very cold weather resulted in a number of snow falls at Elrom. From the synoptic maps we learn that this period of precipitation was triggered by the passage of the tail-end of a cold front over Israel on 31 December. This front, however, was associated with a weather system located farther to the north (over Anatolia) than the "Cyprus Low" which was effective 2 days before. A further front passed one day later on 1 January 1983 and once again negative δ values result.

A notable change in air-mass characteristics as from 1 January 1983 is inferred from the synoptic maps. Up to that time the whole country was under the influence of air-masses with similar characteristics (of the type classified as continental polar (cP) or continental arctic (cA)); as of 1 January there is evidence of a convergent flow system (Fig. 5b). Continental air masses reach the northern part of Israel, whereas the southern part of the country comes under the influence of easterlies, whose origin can be traced to maritime polar regions (Fig. 6). This pattern is apparently reflected in a difference of about 5‰ in $\delta^{18}O$ between southern and northern stations on 1 and 2 January. During the following three days (i.e., 2 January 1983 to 6 January 1983) no clear pattern in the isotope data can be singled out even though, on the average, the geographical gradients remain in force. By 2 January 1983 the surface low had filled up and no marked frontal systems are to be seen. Upper air masses changed gradually resulting in a shift to less negative $\delta^{18}O$ values during that day. In the Mediterranean air space, we then note residual pockets of cold air, hence presumably the variability of isotopic values in time and space during the period from 4 January 1983. Throughout this period, no significant changes in the *d* parameter were noted (Fig. 3).

3.2. 17 February 1983–28 February 1983

During the period of 17–28 February 1983 (Fig. 4), we have data from a detailed 4-station transect in the northern part of the country from the coast at Haifa to the Golan Height, with just one southern reference station at Bet-Dagan. A continuing rain spell throughout five days (17–21 February), rather evenly distributed throughout the country, is accompanied by snowfall in the northern mountain region and the passage of a cold front around noon-time on 20 February. A second weaker rain spell started after a 2-day interval, generally with smaller rain amounts particularly in the south.

During the first five days (17–21 February), we note the absence of a clear and consistent pattern of the isotopic composition although the inland gradient from Haifa to Elrom is very marked (Kfar-Blum which is situated in the northern Jordan Valley shows isotopic values in between those from the coast and the mountains to the east and west). This pattern can be explained by the fact that during this period one witnesses a rather rapid change of air masses of varied origin, resembling the situation reported above on 3 January. Indeed the only clear isotopic signal of the data is seen on 20 February, in accompaniment of the passage of a cold front.

In contrast, the rain during the final period of 24–27 February 1983 is associated with the passage of a cold front in the afternoon of the 26th. A notable feature is the relative southward deflection of the upper air circulation compared to the situation on 29 December 1982 and 1 January 1983 (Fig. 5c). During this phase, the isotopic pattern is quite regular with a pronounced minimum of isotopic values during the passage of the front, and relatively small differences in the isotopic composition at the different locations.

4. Discussion

The data set presented here shows that most of the times the progression of δ values in precipitation from various stations throughout the country runs roughly in parallel. The temporal changes are dominated by the large scale synoptic patterns, in particular the history of the moisture in the air masses concerned, and do not relate to local factors such as rain intensities. This confirms previous findings by Rindsberger et al. (1983). It is quite surprising that the seasonally averaged isotopic composition of precipitation converges to a rather well-defined value, in spite of the large differences in the δ value of the individual precipitation events which show a range of 12‰ in $\delta^{18}O$ (Fig. 2). At Bet-Dagan, which is the rain collecting station of the network established by WMO and the International Atomic Energy Agency (the IAEA) and from which we have a long record (IAEA, 1981a), the amount weighted annual average is $\delta^{18}O = -5.07 \pm 0.62$‰ for the 19-year period of 1965–86. Indeed, the scatter of ± 0.6‰ in the 19-year long series is to a significant degree the result of a 4 year period with lower δ values, namely the years 1971–75 when the averaged values were $\delta^{18}O = -5.7 \pm 0.2$‰ (Carmi and Gat, 1978). That period was one of worldwide climate anomalies (Kukla and Kukla, 1974). Evidently the synoptic pattern associated with the precipitation events controls both the mean isotopic values of the precipitation and its variability.

There are characteristic interstation differences in the isotopic composition. Comparing for example the isotopic data for precipitation at Har-Kna'an and Bet-Dagan (the two stations with the longest record), where the difference in $\delta^{18}O$ is 1.6‰ on the average, we find that for individual rain periods the differences between these two stations range from slightly negative to positive values which are more than twice that average. In Fig. 3, we note inter-station differences (e.g., between Bet-Dagan and Elrom) which range from 0 to +3‰ in $\delta^{18}O$. One of the local factors which may be important is the evaporative enrichment from falling raindrops at low-lying (valley) stations, especially when rain amounts are sparse (the so-called pseudo-altitude effect, Moser and Stichler, 1971). Fig. 7 exemplifies this effect for stations situated on a transect from the Mediterranean coast to the Jordan Rift Valley; the best fit line for these data has a slope of $\Delta\delta(^2H)/\Delta\delta(^{18}O) \sim 3.8$, which is a typical isotopic evaporation line for this region (Gat and Dansgaard, 1972). Evidently the fractionation by evaporation plays a role in the case of the valley stations.

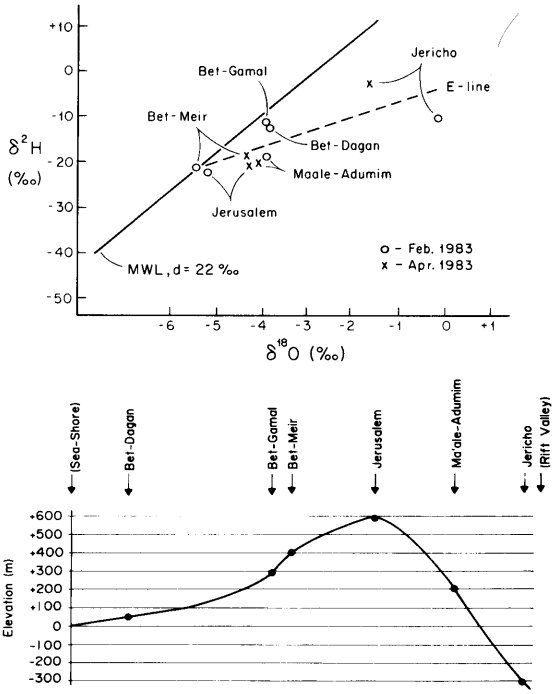

Fig. 7. The "inland"-isotope effect in precipitation, on a transect from the Mediterranean coast to the Jordan Rift Valley. Upper graph: monthly data for February and April 1983. Lower graph: elevations of the sampling stations. Location of the transect line is shown on the map of Fig. 1.

The data taken as a whole suggest however, that interstation differences in isotopic content are also, to a large extent, synoptically controlled; rains triggered by the passage of a cold front, for example, show rather similar δ-values throughout the country (except for the ever present evaporation effect in the Rift Valley). Convergent circulation as during the period from 1–5 January 1983, on the other hand, engenders more depleted isotopic values in the northern parts of the country. For sure, the magnitude of the average

inter-station difference in isotopic composition has only statistical validity.

We commented above on the V-shaped pattern of evolution (in time) of the isotopic composition during a rainy spell, especially noted for rains associated with the passage of a frontal system (in the case of successive passages of such fronts, a multiple, e.g., W-shaped, pattern is encountered). Peak rain activity then corresponds to the most depleted isotopic values, seemingly at variance with the synoptic control on the data. However, in fact, the following description of the course of events can be given.

- Initially, in advance of the storm with the cyclonic center situated to the north-west, surface air is advected which represents a pristine (Mediterranean) air mass without much of a rainout history; the isotopically enriched values may be further enhanced by some evaporative isotope fractionation, since at this stage these air masses are rather dry and the cloud base is at higher elevations.

- At the peak of the storm, during the passage of the front, the strong convective motions result in mixing of surface with higher altitude air (partially depleted in heavy isotopes). This period is, of course, usually also a period of maximum rain intensities.

- In the wake of the front, the very variegated air mass histories (often quite changeable in time and space) is reflected in the rather scattered nature of isotopic data.

It appears that not only the isotopic values, but also the amount effect is controlled primarily by the large-scale motion of the air masses and in particular by the degree of vertical mixing of the air layers above the Mediterranean. In this latter respect, orography plays a role, and the interstation differences do in part also reflect different degrees of mixing of the air layers at the various locations. Thus the apparent paradox between the overall correlation of the isotope data with the large scale synoptic history of the air mass, on the one hand, and the large intra-storm variations of isotopic content, on the other hand, can be resolved.

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