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Monitoring and predicting Saharan Desert dust events in the eastern Mediterranean

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Under suitable synoptic conditions, dust from the north African desert can be mobilised and transported great distances away from the source region. The quantities of desert dust transported into the atmosphere during dust events are really impressive; D'Almeida (1986) estimates that on a global scale, one billion tonnes of desert dust is transported into the atmosphere per year. Such dust events adversely affect a number of weather-sensitive human activities such as aircraft operations due to the low visibilities which the dust in suspension normally induces. Also, in prolonged situations, dust suspended in the air, when inhaled, can cause respiratory problems to a sensitive group among the population. To a certain extent, the above dust-related problems can be considered as rather localised in character, affecting the immediate vicinity of the source region. Longer-range transports were long considered as having a rather passive character. However, the role of atmospheric dust as a source of mineral nutrients for plants must not be underestimated. Also, recent findings have revealed that the atmospheric dust transport plays a very important ecological role. Hedin and Likens (1996) argue that dust particles can neutralise acid rain. Combining directly with acidic gases or by dissolving into acidic cloud water droplets, dust particles neutralise precipitation; this is believed to lessen the effect of acid rain on forests.

The above are but a few of the effects of desert dust, certainly justifying the current interest and enhanced efforts in understanding the physical mechanisms underlying the mobilisation, transport and deposition of dust, as well as the endeavour in predicting dust events and their evolution in space and time. Several research groups are currently engaged in the study of a wide spectrum of desert-dust-related issues.

The present article outlines the spectrum of the available tools which are now available for monitoring and predicting dust events originating from the desert regions of north Africa and subsequently affecting the eastern Mediterranean region. All of these tools have been employed in a co-ordinated effort to understand, monitor and predict dust events taking place over the Mediterranean basin. Most of the operations described below were undertaken under the MEDUSE (the MEditerranean DUSt Experiment) project which was recently completed, and was funded by the European Union.

In order to demonstrate the employment of the available tools in the study of dust events, an illustration is given for a particular case-study regarding the significant dust event that affected the eastern Mediterranean from 20 to 22 March 1997. This case represents a typical springtime dust event which was initiated by the rapid advancement of a cold front deep into the north-eastern African coast. Under these synoptic conditions, widespread sandstorms were initiated mostly ahead of the advancing cold front. Sand lifted in the atmosphere on 20 and 21 March 1997 was subsequently transferred by the upper-level wind field to the east or north-east of the source region.

Synoptic evidence of dust events

Surface synoptic observations are customarily carried out every three hours. Synoptic observers are in a position to report duststorms and sandstorms during their genesis over or near the source regions. Also, subsequent dust transport away from the source regions, poor visibilities due to haze, dust or sand, whether at ground level or suspended in the air, can be quite adequately documented by experienced synoptic observers. It is true, however, that the sparsity of synoptic stations over the desert region or over the water body of the Mediterranean makes a close monitoring of the evolution of Saharan dust events difficult to sustain for long after the initial occurrence of individual events. Nevertheless, during the period of the project, it became evident that it is feasible to employ the synoptic network to monitor satisfactorily the progress of significant dust events for a period of up to two to three days.

Figure 1 displays the synoptic situation over the eastern Mediterranean at 1200 GMT on 21 March 1997. This situation led to a considerable rise of dust and sand mostly ahead of the cold front and consequently to a series of significant duststorms over Egypt. Evidence for this dust event is provided by the synoptic observation network. Several stations reported

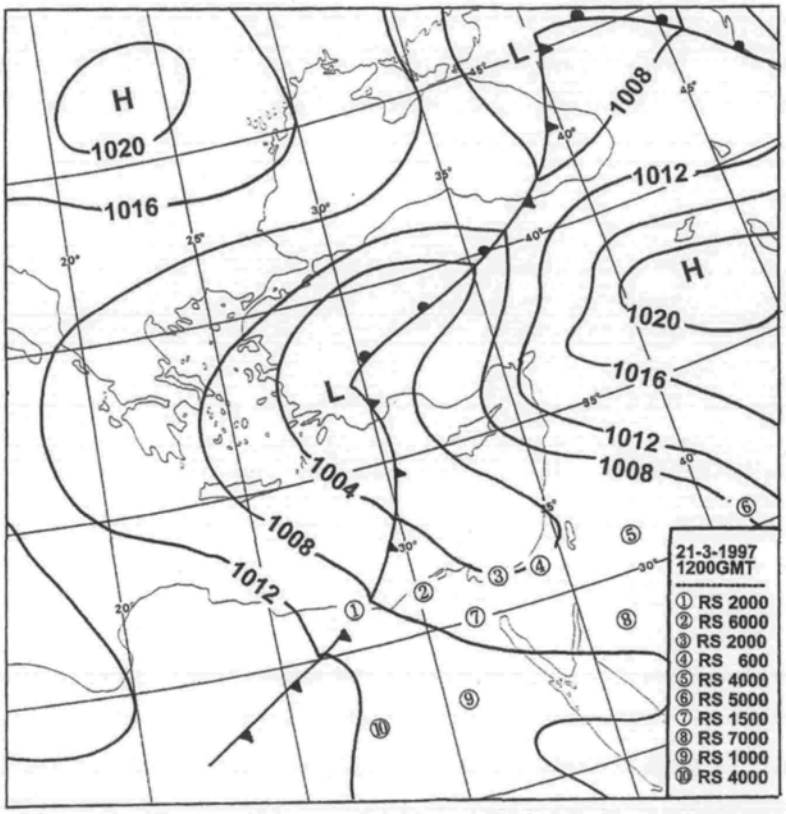

Fig. 1 Synoptic evidence of a dust event at 1200 GMT on 21 March 1997. Synoptic stations are indicated by circles. The reported dust-related phenomenon (RS=rising sand) and the horizontal visibility (m) corresponding to each station are shown.

rising dust or sand and a considerable reduction in horizontal visibility. Surface synoptic stations where rising sand is reported are marked accordingly, together with the respective horizontal visibility estimations. As mentioned above, this synoptic pattern constitutes a typical one favouring the onset of desert duststorms over the north-eastern African coast. An advancing cold front and the associated strong surface winds ahead of it penetrating south-eastwards from the Mediterranean Sea deep into the northern African desert region are traditionally considered by local weather forecasters as precursors of a significant dust event.

Satellite observation of dust

Remote sensing of extensive desert dust plumes by using observational data from satellites is largely based on the appropriate analysis of such data from the visible part of the solar spectrum. The philosophy underlying such an analysis is rather simple. In this respect, the radiance measured at the top of the atmosphere (reflected sunlight by the earth–atmosphere system), in the absence of cloud coverage, is considered to have contributions from the earth's surface, the atmospheric gas molecules and airborne solid particles. Bearing in mind that oceanic water surfaces have a low albedo and that the contribution from atmospheric gases is relatively constant in space and time, changes in the back-scattered solar light can be attributed to variations in airborne particles (see Dulac *et al*. 1996).

Due to their location, geostationary meteorological satellites of the Meteosat family have proved very consistent tools for the monitoring of dust transport over the area of the Mediterranean basin on a long-term and systematic basis (Moulin *et al.* 1997a). Polar-orbiting satellites can also be utilised for monitoring dust events. Images from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA orbital satellites have been routinely analysed to provide information about the presence of dust over the eastern Mediterranean. The potential of satellite-derived information for studying dust events is shown in Fig. 2 (see back cover). This is a processed satellite image obtained at 1200 GMT on 21 March 1997 and displays significant quantities of desert dust from the Egyptian coast being drifted northwards. This image clearly depicts the nature of dust transport over the Mediterranean waters in the form of distinctive dust plumes.

Sun photometers and lidars

Lidars (also known as laser radars and optical radars) are instruments used for the detection of suspended atmospheric particles (see World Meteorological Organization 1996). Typical lidars consist of a pulsed laser transmitting pulses of coherent light. Suspended particles scatter the electromagnetic energy transmitted by the lidar. A return signal is captured by an appropriately mounted optical telescope. The amount of the targeted atmospheric particles and the attenuation of the electromagnetic energy dictate the intensity of the signal received by the optical telescope. This signal is subsequently analysed to provide appropriate measurements of the presence of suspended particles. Lidars are considered to provide useful information for research studies on aerosol optical depth.

The aerosol optical depth can also be calculated from sun photometer data. The sun photometer consists of a narrow-band interference filter and a photovoltaic detector (World Meteorological Organization 1996). The net photometer employs an automatic sun-tracking system and is capable of performing optical depth measurements of the atmosphere at various wavelengths ranging from the visible to the infrared parts of the spectrum. Experience has shown that very careful operation is required to produce useful results, primarily because of the change in the instrument's response over short periods of time. Sun photometer measurements have been employed by Moulin *et al.* (1997b) in order to validate the procedure for satellite-derived optical thickness.

Dynamic forecasting of dust events

In spite of the complexity of the respective physical processes, recent research on the mobilisation and transport processes which underlie a Saharan dust event has shown that such events can be predictable. In the light of these recent developments, a dust-prediction model was set up in an attempt to assemble the current scientific knowledge on this issue into a working meteorological model suitable for the prediction of large-scale dust events in the broader area of the Mediterranean.

The model that forms the basis of this endeavour is based on the eta/NCEP (National Centers for Environmental Prediction, USA) model which was originally formulated at the University of Belgrade. This is a regional-area model with eta as the vertical coordinate (from the Greek letter =eta). This distinct vertical coordinate is pressure-normalised and leads to a simpler solution of the equations of motions and to a step-wise representation of mountains. The eta surfaces are quasi-horizontal, an advantage that renders this model appropriate for use in areas with widely varying topography such as the Mediterranean basin. Further details on this model are given by Lazic and Telenta (1990).

The dust module recently incorporated in this model was developed to take into account the mobilisation of desert dust and its transport (Nickovic and Dobricic 1996). The model's input data consist of the daily grid point fields of temperature, wind components, specific humidity and geopotential height made available by NCEP on the Internet. The model in its present form was developed initially within the framework of the SKIRON forecasting system and runs operationally at the University of Athens in Greece (see Kallos *et al.* 1997). The SKIRON forecasting system was funded by the European Union and the Greek government, and various products of the system are routinely available over the Internet (the Internet web site is http://forecast.uoa.gr). In its current form, the model is upgraded so that now it is able to describe the dust cycle: dust uptake, transport and deposition (see Nickovic *et al.* 1997a, b and c). The appropriate modules required to represent these physical processes have also been developed at the University of Athens within the framework of the MEDUSE project. Customarily, the dust products are presented in the form of maps of spatial distribution of dust loading in the atmosphere and are available to users. Figure 3 (see back cover) depicts the predicted dust loading during the dust event of 21 March 1997 that was successfully predicted by the model.

It must be stressed at this point that validation of the model's performance regarding dust predictions, in the strict meaning of the term, is by no means an easy task. This requires direct and indirect measurements of dust parameters (*e.g.* dust flux, dust loading, dust deposition) in the atmosphere and comparison with the model's behaviour. However, during the experimental phase, it became evident that a number of existing practices can aid in the validation of the model, at least in a qualitative manner. The synoptic observation network discussed above comprises such an important (qualitative) source of dust-related information and is discussed in the following section. Quantitative validation is also possible to a certain extent by using surface measurements of dust deposition, and this practice is also discussed below. Also, satellite-derived information can aid in the near-real-time validation of dust-event predictions.

Synoptic monitoring of dust events

This section describes how the predicted dust events were verified on a near-real-time basis by using data from the Global Telecommunication Network and in particular surface synoptic observations. In order to monitor and verify the dust events predicted by the model discussed above over the eastern Mediterranean, predictions were evaluated in near-real time by using the surface synoptic network data.

December 1996 had a high frequency of dust events in the eastern Mediterranean and is considered here as an example for the validation of the dust forecast by using information from the synoptic network. Once a significant dust event was predicted by the model, the current and subsequent surface synoptic analyses prepared at the meteorological office at Larnaka Airport in Cyprus were utilised to evaluate the extent to which the predicted event was justified. The results, shown in Table 1, contrast the geographical areas in the eastern Mediterranean basin forecast to be affected by dust

Table 1 Evaluation of predicted dust events in December 1996 using the surface synoptic analyses

Forecast date (Dec. 1996)	Forecast area	Present weather and horizontal visibility
2nd	Crete	Crete (HZ, 7–9)
3rd	Crete, Cyprus	Crete (RA 10), Cyprus (TS 12)
4th	Cyprus, Egypt	Cyprus (TS 5), Sinai (HZ 7), north Egypt (widespread RS 200 m)
10th	Tunis, Libya	Tunis (HZ 8), Libya (RS4, HZ 8)
11th	Cyprus	Cyprus (RA 10)
12th	Sicily, Crete, north Africa	Sicily (locally 10), Crete (RA, TS 8), north Africa (HZ 8)
23rd	Italy, Adriatic	Italy (HZ 2, RA 4), south Balkans (HZ 3), north Greece (HZ 3)
24th	Crete, Greece	Libya (RS 5, HZ 8), Egypt (HZ 6), Crete (locally 10)
25th	Cyprus	Cyprus (HZ 6), north Egypt (HZ 6)
26th	Red Sea	East Egypt (RS 6), Sinai (HZ 6)
28th	Crete, Cyprus, south of Sinai	Crete (TS 3), Cyprus (RA 15), Egypt (widespread RS 200 m)
29th	Syria, Sinai	Syria (HZ 10), Egypt (RS 6), Israel (HZ 2500 m)
30th	Greece, Libya	Greece (locally 10), Libya (HZ 5–7), Egypt (RS 8)

Explanation of abbreviations in parentheses: TS = thunderstorm, RA = rain, HZ = haze, RS = rising sand; numbers represent horizontal visibility (km), unless otherwise stated.

events with the geographical areas for which a dust-related phenomenon had been reported in the respective surface synoptic observations. Due to the reporting limitations inherent in the current reporting practices, one is bound to look for synoptic stations reporting phenomena that are thought to be related to dust/sand rising or transportation (*e.g.* reduced visibilities, haze, rising dust/sand). Obviously the comparison of the dust-model output and the synoptic network data can only be qualitative in nature. Direct comparison between the synoptic records and the model output is not possible. Extremely poor visibilities recorded at ground level, especially in the source regions (*e.g.* widespread visibility reductions to 200 m over Egypt on 4 and 28 December 1996 shown in Table 1), cannot readily be anticipated by using the model's output. Nevertheless, the results in this table clearly indicate that the dust model was capable of predicting dust events over the eastern Mediterranean satisfactorily.

Measurement of dust deposition

Dust raised by the winds and transported away from the source region is eventually deposited on to the earth's surface. Deposition can be either dry (through gravitational sedimentation) or wet (washing-out of dust particles by precipitation). To quantify the actual amount of dust and other solid particles in the atmosphere a direct measurement of such suspended solid material is required. To achieve this objective, solid particles in the atmosphere can be collected by a suitable aerosol-sampling device. The system comprising the aerosol-sampling equipment is rather simple. It basically consists of a high-volume centrifugal air pump which draws air through a filter matrix. Aerosols are collected on the surface of this special filter matrix. Any unwanted water entrained in the air or condensed on the intake of the hose is properly removed. Also the equipment can be adjusted so that air is sampled from a specific 'acceptance sector' by allowing the pump to operate only when the wind blows from a predetermined sector. The weight of the material deposited on to the filter provides a direct estimate of the atmospheric aerosols deposited at ground level. The material can also be used for further chemical or other analyses.

For the purposes of the project, such an aerosol-sampling device was installed at Kalopanayiotis in Cyprus (35°00′N, 32°50′E, 575 m above mean sea-level) which measured dry and wet deposition of dust on a daily basis. As most of the desert dust reaches the island of Cyprus from the south-east to west, the acceptance sector of the aerosol sampler excluded northerly winds. Figure 4 shows the course of the daily aerosol measurements at this site during the second half of March 1997. The peak in these measurements on 21 March 1997 clearly depicts a considerable increase of the deposited material associated with the serious

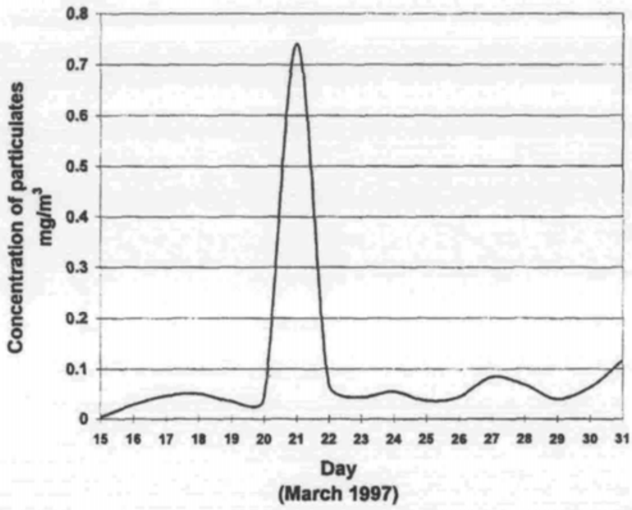

Fig. 4 The course of the daily aerosol measurement at Kalopanayiotis in Cyprus during the second half of March 1997

dust event that started on the previous day over the north African coast and subsequently affected the eastern Mediterranean including Cyprus.

Concluding remarks

The transport of Saharan dust from over the north African coast into the Mediterranean basin displays a seasonal shift which is largely influenced by the presence of low pressure systems over the area. Dust events are most commonly reported over the eastern Mediterranean during the spring season and are largely associated with the prevailing distribution of low pressure systems during this period (see Alpert *et al.* 1990; Dayan *et al.* 1991). Such dust events have long been identified by using the available network of synoptic observations. The traditional synoptic observational network still has a major role to play in monitoring dust events. The frequency of the synoptic observations (every three hours) renders the synoptic network an indispensable tool in the monitoring of dust events both in the source region and in the areas affected by the subsequent transport of dust.

With the advent of satellite technology these synoptic-scale phenomena have been better monitored and even quantified by using appropriate methodologies. Despite its inherent limitations, the radiometric estimation of dust loading by using satellite-borne equipment proved to be a useful tool in localising duststorms initiated near the earth's surface and also for tracking dust transported by the upper-atmospheric air currents. It is anticipated that further progress in this field will make this technology an essential component of a universal dust-monitoring and prediction scheme.

It is evident that the physical processes for lifting desert dust, its transport and deposition can be modelled mathematically and therefore the prediction of the onset and further progress of dust events is now feasible. However, validation of such a dynamic model for forecasting dust events should involve a representative comparison with measurements made in both space and time. In this respect, the observations carried out from space-borne platforms are promising and challenging tools.

The use of dust-deposition measurements for the validation of a dust-prediction model is of great importance. However, the current network of such measuring sites renders the technique of rather limited importance. It is anticipated that a denser network of dust-deposition measuring sites, coupled with a comprehensive procedure for registering and disseminating the dust-deposition measurements, can help in understanding the spatial character of dust events and become a useful tool for validating dust-prediction models.

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Meteorologist's profile – Eleanor Anne Ormerod

Mick Wood

Bracknell, Berkshire

Eleanor Ormerod, first Lady Fellow of The Meteorological Society, was born on 11 May 1828, "a sunny Sunday morning",* at Sedbury Park, the youngest of the ten children of George and Sarah Ormerod of Sedbury Park, Gloucestershire, and Tyldesley, Lancashire. She was five years younger than her next eldest sister and enthusiastic collaborator, Georgiana.

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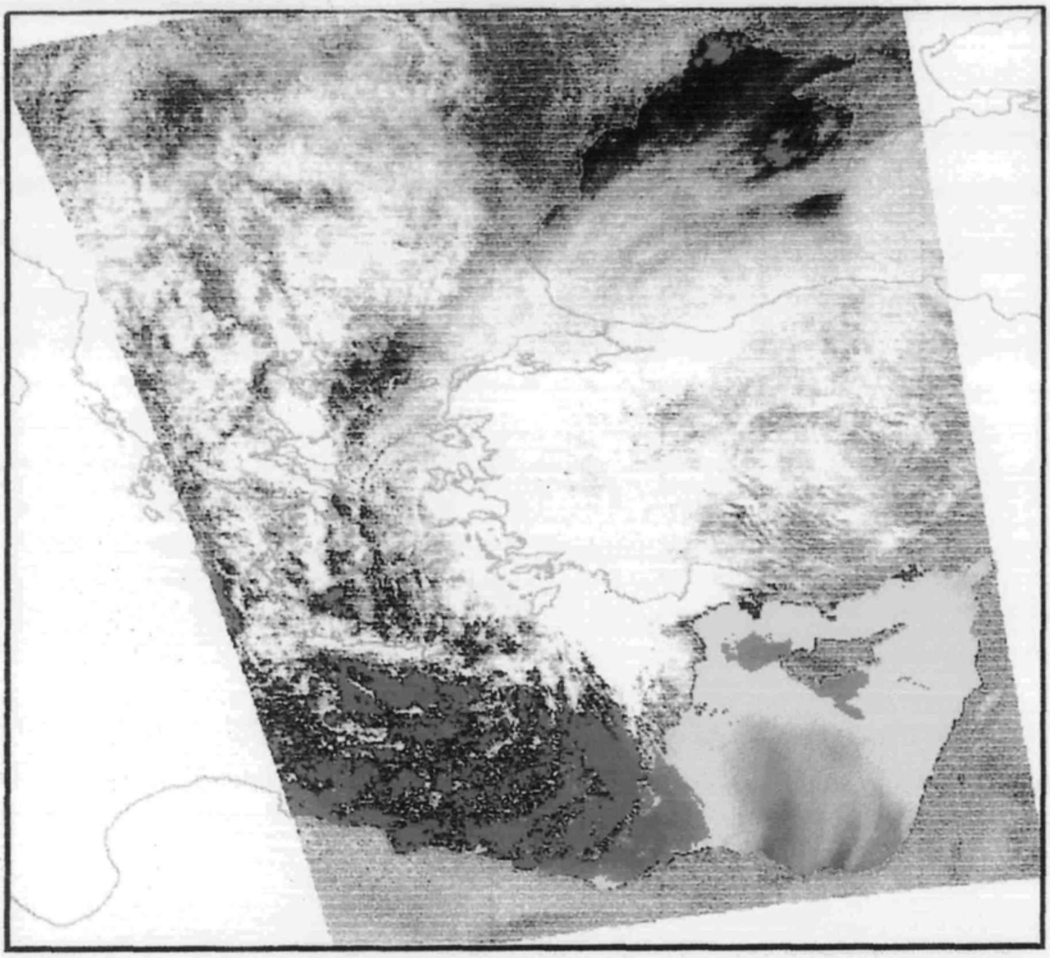
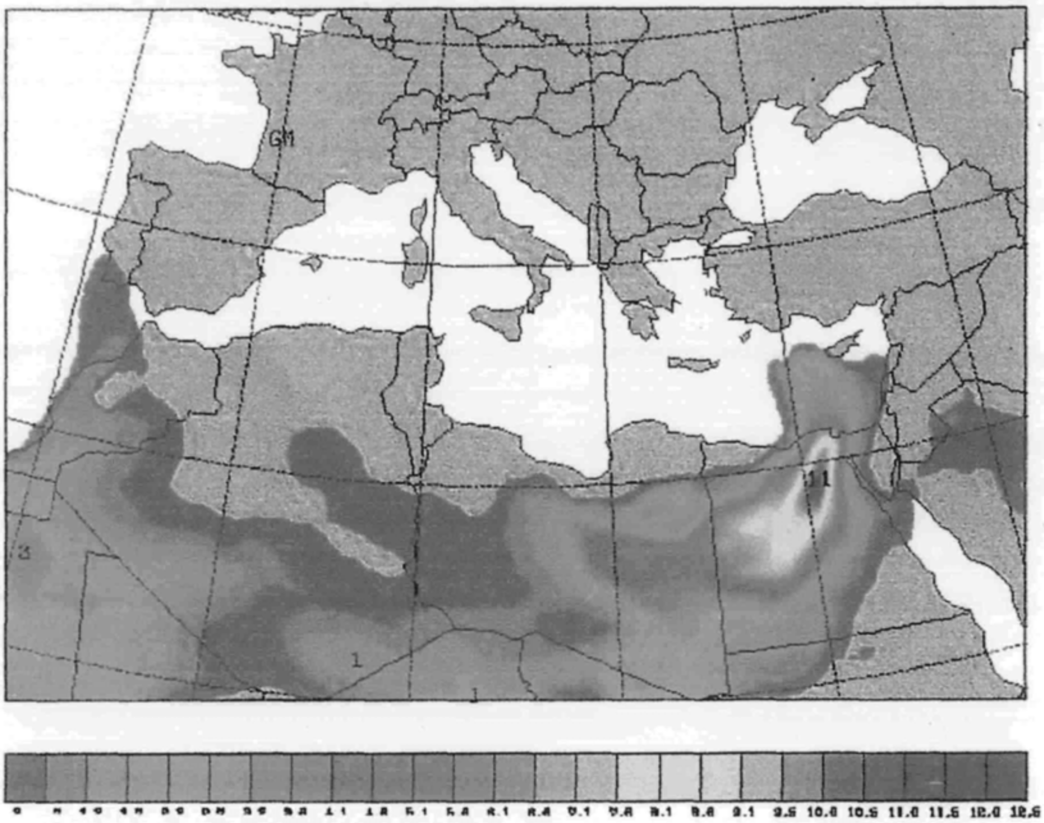
* This quotation (together with many others in this article) was taken from the edited biography of Eleanor Ormerod by Robert Wallace (1904).

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