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An illustration of the transport and deposition of mineral dust onto the eastern Mediterranean

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Abstract

The analyses of aerosol samples and deposition (wet) measurements during August 1991–December 1992 at Erdemli (36°N, 34°E) located on the Turkish coast of the eastern Mediterranean has shown higher dust concentration and total deposition during transitional seasons (spring and autumn) compared to summer and winter seasons. The data, complemented by three-dimensional (3D) air mass back trajectories and satellite observations suggest that North African and Middle East desert derived dust particles are transported to the region during transitional seasons. Transport events in the last part of March 1992 and early October 1992 are studied through combined analyses of ground based and satellite observations and modelling results. It is shown that dust transport constitutes a large fraction of the annual atmospheric deposition in the eastern Mediterranean, with two deposition events of short duration accounting up to 30% of the total annual flux. Therefore, the dissolved and particulate species associated with dust could be extremely variable in the mixing layer during large deposition events and could easily be missed in a short-term sampling program. The possible impact of large pulses on biological productivity of the sea also warrants consideration. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Mineral dust; Long-range transport; Atmospheric vertical motions; Wet/dry dust flux; Modeling; Satellite

1. Introduction

A number of case studies confirm the long-range transport of Saharan dust, towards the Black Sea (Kubilay et al., 1995); Netherlands (Reiff et al., 1986); across the northern Atlantic (Prospero and Nees, 1987) and toward the Amazon basin (Swap et al., 1992). Being a small enclosed basin, the Mediterranean Sea is susceptible to dust transport from desert sources in North Africa (Sahara) and the Middle East (Arabian Peninsula and Syria) on its periphery (Martin et al., 1990; Dayan et al., 1991; Ganor 1994; Kubilay and Saydam, 1995). Climatological conditions are favourable for the transport of dust from north Africa into the eastern Mediterranean atmosphere during the spring and from Middle East in the autumn (Dayan 1986; Alpert et al., 1990), other conditions favour transport into the western Mediterranean atmosphere in summer (Moulin et al., 1998).

Mineral dust transported from Africa to the Mediterranean influence the regional radiative budget by affecting cloud microphysical properties (Levin and Ganor, 1996) and the pH of the precipitation (Loye-Pilot et al., 1986). Dust deposition is likely to stimulate the surface marine productivity by providing nutrients (Dulac et al., 1996; Bergametti et al., 1992) and deposition to the sea bottom makes important contributions to the clay mineral content of marine sediments (Guerzoni et al., 1997).

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Unfortunately, accurate transport and deposition estimates are troublesome to obtain on a regional scale since they require observations over extended time and space scales. Satellite observations (Dulac et al., 1992) and modelling (Nickovic and Dobricic, 1996) offer opportunities to extrapolate local measurements from coastal sites into the rest of the domain of interest, making it possible to further assess the biogeochemical significance of deposition events on a regional basis.

In this paper, we focus on the long-range transport of African dust to the eastern Mediterranean, to describe the meteorological processes creating it, and the seasonal variability of its deposition on the Turkish coast. Ground-based measurements, satellite data and modelling are used to estimate the mass of desert dust in the eastern Mediterranean atmosphere for two different transport events during March 1992 and October 1992.

2. Materials and methods

2.1. Ground-based aerosol and deposition measurements

Samples of aerosol and rain were collected from a 21-m-high atmospheric collection tower located on the Turkish Mediterranean coast at Erdemli (34°15′18″E, 36°33′54″N) during the period August 1991–December 1992. Details of the methodologies for sampling and analysis can be found elsewhere (Kubilay et al., 1995; Kubilay and Saydam, 1995; Kubilay, 1996). Specific procedures are described here.

The aerosol samples were collected using a high volume ($70\,\mathrm{m}^3\,\mathrm{h}^{-1}$) sampler with Whatman 41 filters and the rain samples were collected on an event basis using wet and dry automatic collector (Andersen, standard "acid rain sampler") with a lid activated by the rain sensor. The rains were then immediately filtered through a 0.45 μm diameter membrane filter and refrigerated prior to analysis. The samples included 25 episodes of precipitation and 339 daily measurements of aerosols, with a few missing samples due to mechanical failure.

The Al concentration, used as a good indicator of dust in the aerosols and particulate fraction of the rain samples, determined by atomic absorption spectrometer (GBC model 906 unit with a FS3000 flame attachment) following hot HF/HNO_3 digestion method. Since the concentrations of the dissolved form of Al in precipitation samples were below the detection limit of the applied method, the results only apply to particulate in rains.

The particulate "wet" flux (F_w, $\mathrm{g\,m}^{-2}$) was calculated from $F_\mathrm{w} = (C_\mathrm{w} * P)/A$, where C_w is the particulate dust concentration ($\mu\mathrm{g\,l}^{-1}$) in precipitation samples, P the amount of rain in units of $\mathrm{g\,m}^{-2}\,\mathrm{mm}^{-1}$ and A the area of the sampler (490 cm^2). The "dry" flux (F_d, $\mathrm{g\,m}^{-2}$) was estimated from $F_\mathrm{d} = C \times V_\mathrm{d} \times t$, where C is the dust concentration in $\mu\mathrm{g\,m}^{-3}$ estimated from the Al measurements in the aerosol samples, V_d is the deposition velocity in $\mathrm{cm\,s}^{-1}$ and t is the sampling duration in seconds. Large particles make a greater contribution to the dry deposition of dust and the value of the deposition velocity used in the above calculation is of crucial importance. A deposition velocity of $1\,\mathrm{cm\,s}^{-1}$ was used, based on measurements of net transfer velocity of dust particles in the western Mediterranean (Dulac et al., 1992).

2.2. Air mass back trajectories

Three-dimensional, 3-day back trajectories, arriving at the sampling point at 12 UT at levels of 900-, 850-, 700- and 500-hPa have been computed, based on the operational model results at ECMWF (Reading, England). The trajectory model is somewhat similar to the method independently developed by Martin et al. (1987). Precipitation measurements were obtained from the Erdemli meteorological station of the Turkish Meteorological Service.

2.3. Model description

Modelling the atmospheric dust cycle is an approach which, along with observations provide more insight into the process. The NMC/Eta atmospheric model is used as the foundation for atmospheric dust concentration calculations. To perform dust calculations, the atmospheric part of the model is extended by a dust continuity equation following the method of Nickovic and Dobricic (1996); Nickovic et al. (1997) and Dobricic (1997).

The Eta model was developed as a result of joint effort over an extended period by the University of Belgrade, the Yugoslav Federal Hydrometeorological Institute and the National Centers for Environmental Prediction (NCEP), Washington (Janjic, 1979, 1984, 1990, 1994; Mesinger et al., 1988).

The dust concentration in the model is considered as a passive substance with a unique particle size of 2 μm. It has been shown that a major aerosol mode initially around 2.5 μm with a standard deviation of 2.0 plays the dominant role in long-range transport of mineral dust from Sahara to the Mediterranean (Schulz et al., 1998). Larger particles have short life times in the atmosphere and have therefore not been considered in the model. It should be noted also that a monomodal model of the size distribution of desert dust particles with a mass-median diameter (MMD) of 2.5 μm over the northwestern Mediterranean during transport events from Africa is reported by Dulac et al. (1992). Because of the lack of relevant quantitative data on the size distribution of dust during the present study we assumed single mode in the particle size for the desert dust transported over the Mediterranean.

The dust concentration equation consists of the following basic components: production of dust from the source areas, horizontal and vertical transport; wet and dry removal of dust to the ground; turbulent mixing in the vertical. For all deposition processes the soil is treated as a perfect sink; no remobilization of settled dust is considered. The potential dust source points in the model are pre-specified using the information on geographical distribution of deserts and semi-deserts. According to the state of the soil and dynamical and thermal atmospheric conditions in the surface model layer, the dust production scheme calculates the amounts of the dust mobilised from the surface and inject into the atmosphere. Once entered into the atmosphere, the dust starts its life cycle during which large amounts of mineral particles may transfer over long distances, thus affecting environment and climate.

The model horizontal resolution is approximately 35 km and vertical resolution of 25 levels between the Earth's surface and 16 km domain. In our experiments, the Eta model was initialised every 24 h, using meteorological data obtained from the European Centre for Medium-range Weather Forecasts, and dust concentration values from the previous run.

2.4. Satellite data

Daily Meteosat images of the solar (VIS) channel in ISCCP-B2 format (apparent resolution of 30 km × 30 km at nadir), taken at 11 : 45 UT, were analysed following the method of Moulin et al. (1997a). Pixels possibly contaminated by reflection from clouds, land and coastal waters were eliminated. For each clear-sky marine pixel, the satellite signal (numeric count) was first converted into radiance and the optical depth of desert dust at a wavelength of 0.55 μm has then been retrieved using a radiative transfer model. The contributions of tropospheric and stratospheric sulphates (especially resulting from the eruption of Mount Pinatubo) were subtracted using climatological information, and the mean optical properties of desert dust were validated by coincident sunphotometer measurements (Moulin et al., 1997b). The accuracy of aerosol optical depth was found to be within ± 25% of the clear-sky conditions. Desert aerosol mass was also estimated using a mathematical relationship between the aerosol mass density in a vertical column and aerosol optical thickness derived from the satellite signal using an earth–atmosphere radiative model (Dulac et al., 1992).

3. Results and discussion

3.1. General characteristics of the atmospheric dust transport and deposition

Atmospheric Al concentrations have often been used as indicators of the atmospheric dust load itself (Prospero and Nees, 1987). The method adopted for calculating dust concentration from a mean crustal Al abundance of 8.2% has yielded a mean dust loading of 15.5 ± 25 $\mu g\ m^{-3}$ for our samples. The wide range of

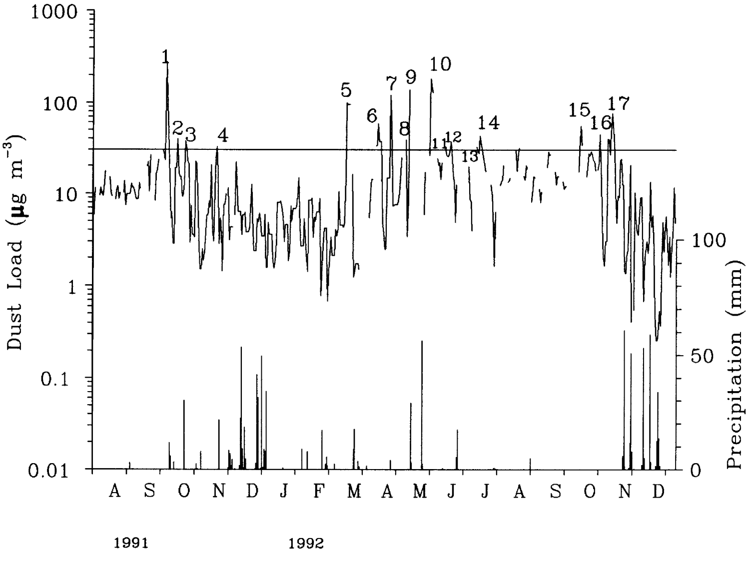
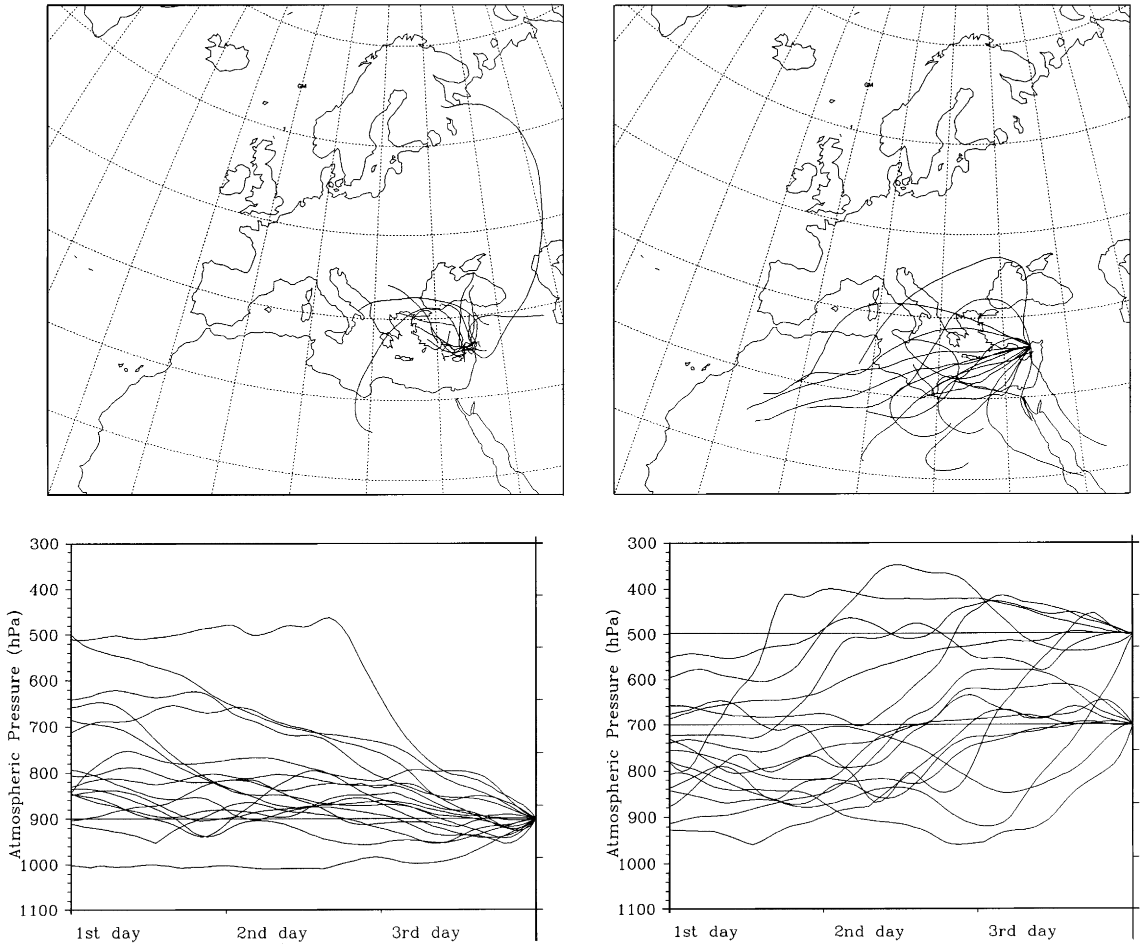


Fig. 1. Temporal variation of dust loading and local event-based precipitation amounts between August 1991 and December 1992. Peaks (> 30 $\mu g\ m^{-3}$) representing major desert dust outbreaks are numbered.

the dust load values (0.25–279 $\mu g\, m^{-3}$) observed during the study period corresponds to episodic pulses of dust from North Africa and Middle East. Consequently, to quote a mean concentration of dust could be too simplistic. To counter bias from episodic high concentrations, the geometric mean of our observations has been calculated as 8.4 (3.1) $\mu g\, m^{-3}$.

Time series of mineral dust concentration is displayed in Fig. 1, together with precipitation corresponding to wet deposition. Substantial variability is indicated both on daily and seasonal time scales. During the extreme dust intrusion events, atmospheric concentrations occasionally exceed the background levels by up to two orders of magnitude. It is also evident that the precipitation is usually followed by an abrupt decrease in the dust concentration due to washout by rain. For example during a Sahara dust intrusion in October 1991 (the first sharp peak in Fig. 1), a high value (279 $\mu g\, m^{-3}$) was followed by a rather low concentration (5.3 $\mu g\, m^{-3}$) accompanied by rainfall (Kubilay et al., 1994).

A mean value of $7.2 \pm 9.7\ \mu g\, m^{-3}$ in rainy winter period (November–February) could be considered a background for the region. Alpert et al. (1990) have shown that during these three months, the Mediterranean cyclones in the region lead to trajectories originating from the northern sector. We expect local dust to be important in summer, during the dry season when agricultural activity is at its peak in the southern part of Turkey. In summer (June–September), the lack of precipitation and cyclones (Alpert et al., 1990) result in a mean dust concentration of $15.8 \pm 7.8\ \mu g\, m^{-3}$. The



(a) (b)

Fig. 2. Air-mass back trajectories arriving at Erdemli. Vertical motions along trajectories are given at the lower panels. (a) Trajectories arriving at 900 hPa level. (b) Trajectories arriving at 700 and 500 hPa levels.

highest mean dust concentration of 28.5 ± 43.3 μg m^{-3} was observed in the transitional periods, March–May and October. Although precipitation scavenging was still effective in these periods (Fig. 1), the dust load was increased by transport with cyclones originating from North Africa, which are known to be the main agents in the eastern Mediterranean (Alpert et al., 1990). The seasonal variation of dust in the eastern Mediterranean as summarised above is consistent with the monthly distributions of dust optical thickness obtained from an analysis of the Meteosat data (Moulin et al., 1998). Moreover, the air-mass flow patterns obtained from the partitioning of the trajectories into geographical sectors for the sampling period (Kubilay, 1996) appeared to be representative of the mean annual conditions when compared with the air flow climatology of the eastern Mediterranean (Dayan, 1986).

Much of the Saharan and Middle Eastern mineral dust is transported in pulses, superposed on background reflecting the trace metal composition of local sources. The identification of these pulses together with air-mass back trajectory analyses (offers a possible method of isolating the desert derived component of the eastern Mediterranean aerosols) applied to select major events (Kubilay, 1996). During the sampling period, 17 such pulses of high dust input (30 μg m^{-3} of dust load concentration) have been identified at the Erdemli site. About 90% of the events are observed between March and October with the most intense cases occurring between March and May (Fig. 1). The seasonality found is consistent with 33 years of measurements in Israel indicating more frequent transport of desert dust in the transitional seasons of spring and autumn compared to the other seasons (Ganor, 1994).

The computed trajectories (see Fig. 2) of the 17 dust pulses marked in Fig. 1 indicate the origins of the air masses arriving at the selected final barometric levels. The shallower trajectories (900 hPa) identified air masses coming from non-desert sources, except for the outstanding cases originating from Libya and from the Polar circle at around 60°N (Fig. 2a). On the other hand, the trajectories arriving at the upper barometric levels (700 or 500 hPa) mostly originated from Africa during all peak events, except one case which originated from the Arabian Peninsula (Fig. 2b). The slope of the vertical component of trajectories shown in the lower panel of Fig. 2a, b provides information on prevailing meteorological conditions during the transport (Martin et al., 1987). One observes that the trajectories arriving at 900 hPa started from the upper levels, representing anticyclonic motion, and the trajectories arriving at 700 and 500 hPa started from lower levels, representing cyclonic motion. At synoptic scale, there is significant upward motion for the upper level trajectories and in contrast, a notable downward motion for the lower level trajectories, characterising frontal systems previously described by Reiff et al. (1986); Martin et al. (1990); Dulac et al. (1992) in the content of dust transport reaching the western Mediterranean and European regions.

Fig. 3 presents the temporal variations of the dust flux, atmospheric dust concentration and rainfall in Erdemli. Our deposition estimates indicate a marked seasonal cycle. The highest dust concentrations and deposition rates occur predominantly in the transitional months,

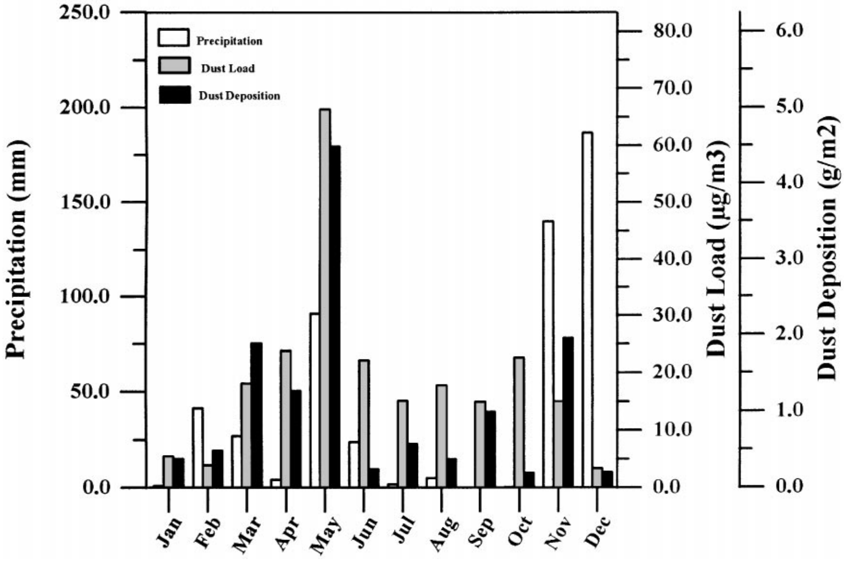


Fig. 3. Temporal variations of the dust flux, atmospheric dust concentration and the precipitation at Erdemli in 1992.

when the eastern Mediterranean is under the influence of the Sharav depressions carrying dust from north Africa and the Middle East (Kubilay, 1996). The maximum monthly deposition rate is estimated to occur in May 1992 (Fig. 3). About 30% of the annual deposition for the year 1992 occurred during two Saharan dust episodes in May. This indicates that a major fraction of the annual deposition can occur in a few days, as observed also by Prospero and Nees (1987) for Saharan dust deposited in Miami (FL) and by Guerzoni et al. (1997) in the northwestern Mediterranean. Although the mean dust concentration in summer was about two times higher than in winter (see Section 3.1), the amount of dust deposited within these two seasons were almost equal in 1992. The higher winter deposition rate is attributable to the fact that in 1992, 70% of the annual rainfall occurred in the winter months, whereas only 5% occurred in the summer months. High dust deposition rates require the co-existence of the dust and rain, which is achieved in the transitional season at our sampling site.

Finally, our data set allows us to estimate the annual total dust deposition rate at the Erdemli station to be around 13 t km^{-2} yr^{-1} for the year of 1992. Percentages of the wet and dry deposition relative to the annual deposition are 44 and 56%, respectively. Our results show that the dry deposition flux is dominant on a seasonal basis. In the dry summer season of 1992, only 7% of the total deposition were in wet form whereas the remaining 93% were in dry form.

3.2. Case studies to compare the model results with satellite and ground truth deposition measurements

Making use of satellite data, transport modelling and three-dimensional air-mass trajectories give a more precise description of the long-range dust transport. The two cases of Saharan dust transport into the eastern Mediterranean in March 1992 and October 1992 were simulated, and compared with measurements at Erdemli and with satellite observations.

The sequence of visible satellite images from 27 to 30 March 1992 show the transport of dust in the central and

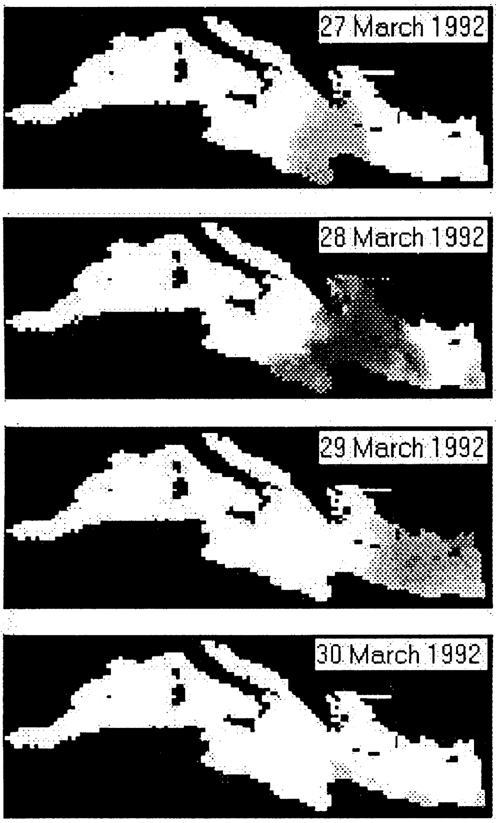


Fig. 4. The daily distribution of the dust mass loading as derived from Meteosat, shows an African dust event over the Mediterranean at the end of March 1992.

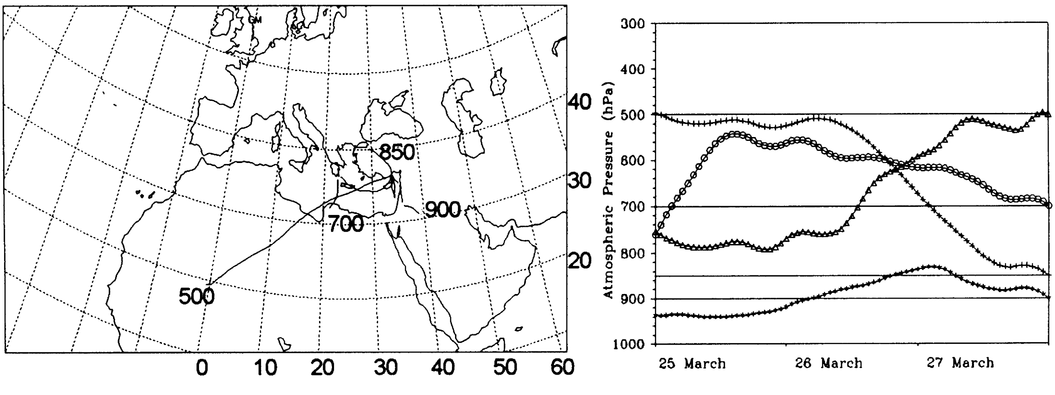


Fig. 5. Three dimensional, three days backward trajectories arriving at Erdemli, at 900, 850, 700 and 500 hPa levels on 27 March 1992. The pressure profile is shown at the right-hand side of the figure.

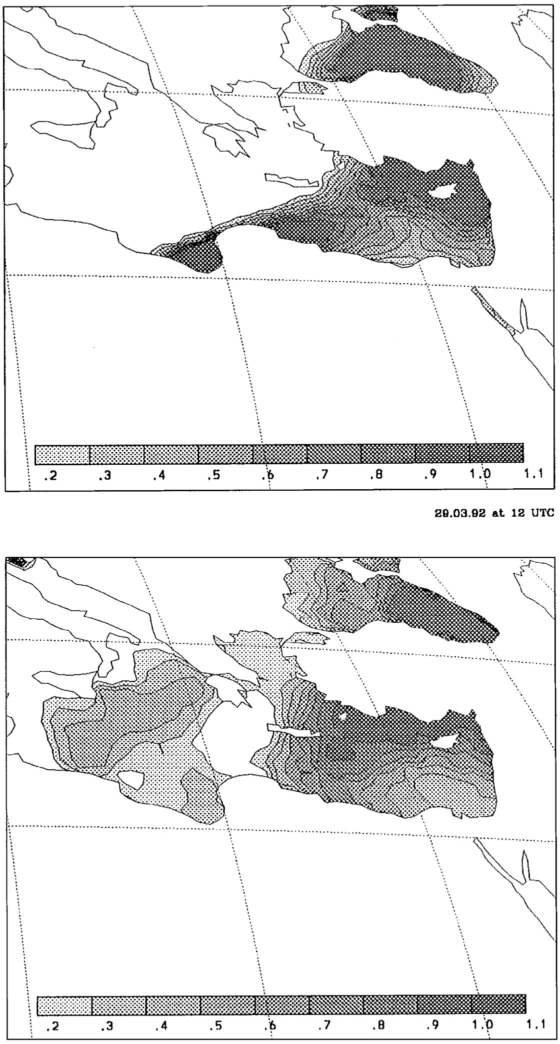


Fig. 6. Vertically integrated model dust concentration (upper panel) in g m^{-2} at 12:00 UT and computed desert aerosol columnar density (g m^{-2}) over the eastern Mediterranean at 11:45 UT (lower panel) on 29 March 1992.

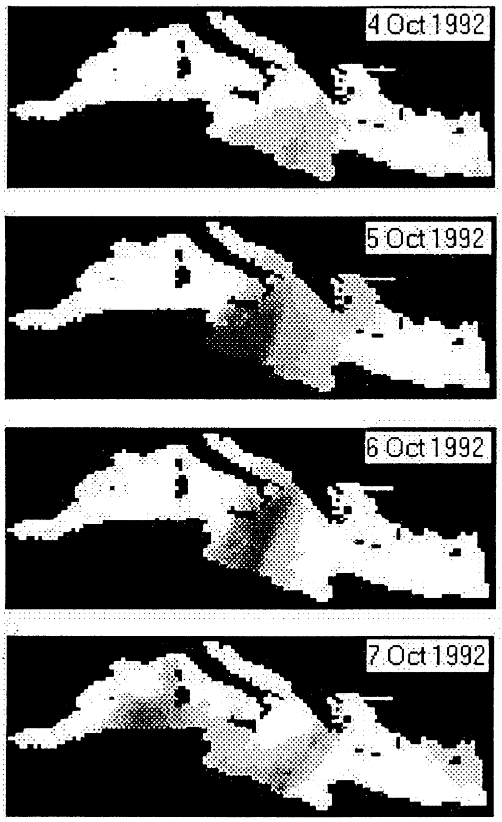


Fig. 7. The daily distribution of the dust mass loading as derived from Meteosat, shows an African dust event over the Mediterranean at the beginning of October 1992.

eastern Mediterranean regions (Fig. 4). The beginning of the period is characterised by moderate dust load in the central Mediterranean (27 March), hardly recognised because of cloudiness in the same area. A dust cloud, with high reflectance appears over the eastern Mediterranean on 28 March 1992. It consists of two branches: one covering the area between Greece and Libya and the other one extending along the Turkish and Egyptian coasts. During the next 24 h, the dust cloud moves east, covering the Levantine Basin. Rain on the night of 29 March resulted in washout of dust, clearly visible from images on 30 March. Unfortunately, concurrent ground measurements of aerosols are not available in the same period, because of technical difficulties with the sampling pump, resulting in a gap in measurements from the 24th till the end of March (Fig. 1). The only measurement during this event is based on the rainwater collected on 30 March. The precipitation experienced on the night of 29 March 1992 at the sampling site exhibited typical characteristics of Saharan dust, reflected in the abnormal pH (7.8) and particulate Al concentration (8020 μg l^{-1}) values (Kubilay, 1996). These values are higher than the mean pH of rainwater (4.93) and the Al concentration (540 ± 730 μg l^{-1}) in precipitated particulate at Antalya, 400 km west of Erdemli (Al-Momani, 1995). The appearance of the particulate material was also unusual, being distinctly reddish in colour.

The computed air-mass trajectories arriving at Erdemli (Fig. 5) on 27 March suggest very different origins of the air masses depending on final barometric level. The lower level air masses arrived from internal parts of Turkey and the Middle East, while the trajectories ending at 700 and 500 hPa levels indicated Saharan origin.

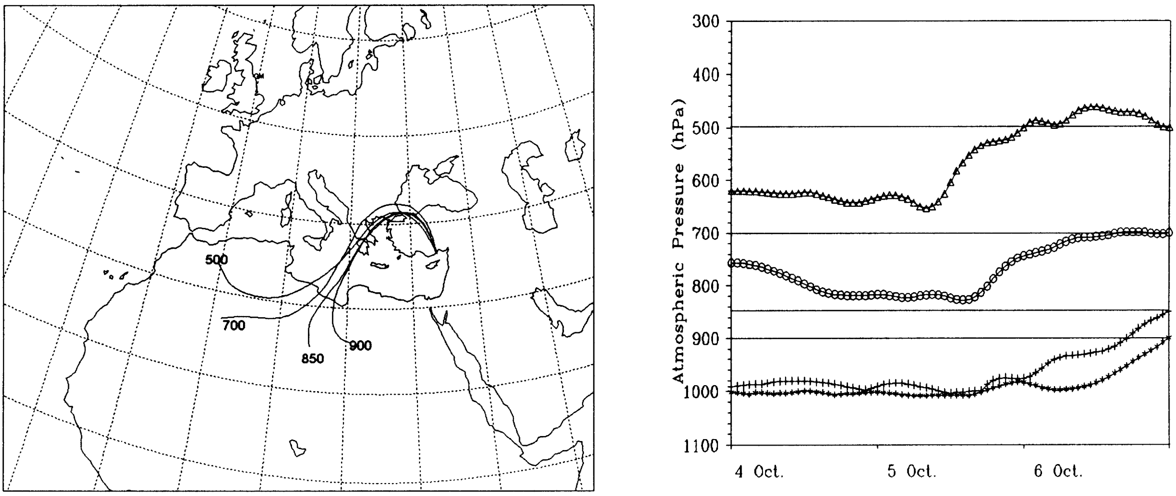


Fig. 8. Three dimensional, three days backward trajectories arriving at Erdemli, at 900, 850, 700 and 500 hPa levels on 6 October 1992. The pressure profile is shown at the right-hand side of the figure.

The vertical components of the trajectories reveal significant upward motion (700 and 500 hPa), allowing the dust to ascend and consequently to be taken in the cyclonic system.

In order to get more insight into the features of March 1992 dust storm, the model is run between 23 and 30 March. To provide better comparison of columnar dust load produced by the model and the estimate based on satellite-derived aerosol optical thickness, the data are plotted using the same "satellite view" and the same shading interval. Fig. 6 show simulated and observed (estimated from Meteosat derived aerosol optical thickness) columnar dust loading for 29 March. The Black Sea area is also partly affected by the dust during the considered period. The simulated fields generally coincide with the observed pattern, although some differences can be noticed. The model has a tendency to produce larger dust coverage with higher concentrations, although differences in values are not substantial. The model fails to reproduce the lower concentrations over the central Mediterranean as observed from satellite data.

Visible satellite data do not show any significant dust load over the sea on 3 October at the beginning of the considered period. During the next 24 h, dust penetrates the central Mediterranean as a result of moderate dust transport from probable sources in Tunisia and western Libya (Fig. 7). The maximum dust transport for the considered case can be clearly observed on the maps of 5 and 6 October, with a rather stationary position of the leading dust pattern. The dust transport cycle finally weakens on 8 October.

There is a good correspondence between satellite observations and trajectory calculations ending at Erdemli on 6 October (Fig. 8). The air-mass back trajectories had their origin over the African continent and continuous upwelling of the air masses lifted dust into the upper troposphere where it was transported to the Erdemli site. Ground-based aerosol measurement coincident with this event verified the transport of dust (event no. 15 in Fig. 1).

As in the March 1992 case, the model was run several days during the beginning of October 1992. Starting with a marginal dust load close to the Tunisian and Libyan coasts on 3 October, the transport is observed to be intensified during the next three days. The position of dust during these three days is in general well predicted, although the model gives lower compared to observed values as in the March case. On 8 October, the dust load almost completely disappears from the Mediterranean Sea region. Fig. 9 shows columnar dust load based on the model and satellite observations on 7 October, respectively. Both maps show SW–NE orientation of the dust cloud pattern in the Mediterranean Sea area between Libya, Italy and Greece. The maximum dust load is observed offshore of the Libyan coast, but the model predicts the maximum towards the northeast. Both products indicate a dust load over the Black Sea, with the higher values in the simulation.

For the October 1992 case, the estimated daily accumulated dust depositions at Erdemli show increased values on 6, 7 and 8 October (Fig. 10 dot–dashed line) with a maximum on 7 October. The simulated daily accumulating deposition at Erdemli compares well with the estimated fluxes from ground-based aerosol measurements (Fig. 10; solid line). However, a maximum value that is somewhat higher than the observations are produced by the model. The daily accumulated dust

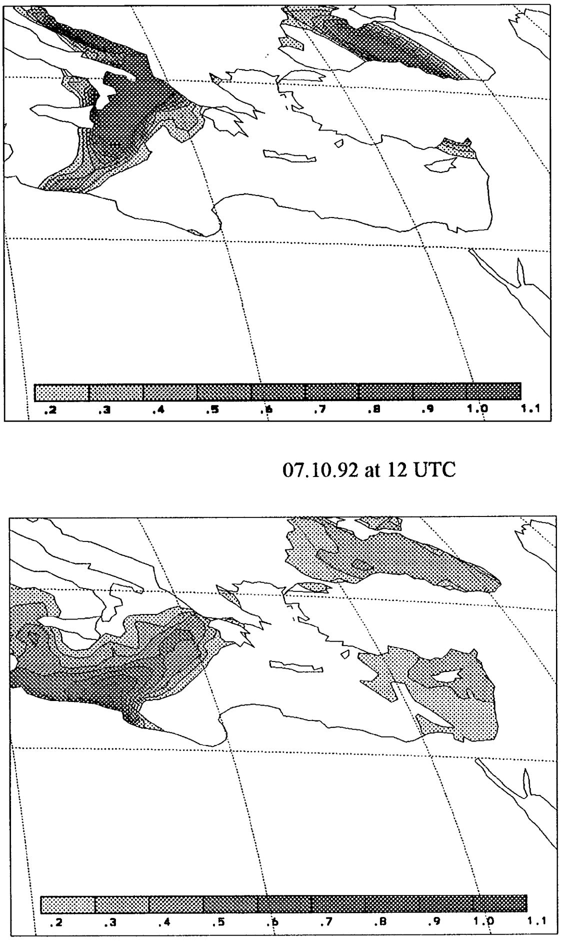


Fig. 9. Vertically integrated model dust concentration (upper panel) in g m^{-2} at 12:00 UT and computed desert aerosol columnar density (g m^{-2}) over the eastern Mediterranean at 11:45 UT (lower panel) on 7 October 1992.

simulated by the model on 7 October shows intense spatial variability even for a small basin like the eastern Mediterranean (Fig. 11). An important result derived from the satellite and model is the inhomogeneous spatial distribution of dust fallout over the basin, which means that care must be taken when extrapolating the fluxes established at the sampling site to the whole eastern Mediterranean basin.

The above analyses of the selected case shows that more insight into the features of dust transport events may be obtained by combining different approaches, observations and modelling. The trajectory model addresses general flow features responsible for the long-range dust transport. The three-dimensional Eulerian modelling offers more detailed description of the atmospheric dust cycle. The NMC/Eta dust model yielded reasonably successful simulations of the major features of dust load for the selected cases. The availability of the satellite observations and ground-truth measurements are of crucial importance for further refinement and tuning of the models.

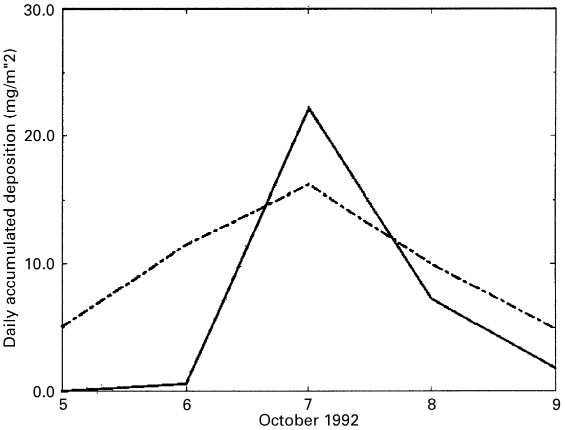


Fig. 10. Estimated dust deposition accumulated over 24 h at Erdemli (dot–dashed line) and simulated dust columnar density (solid line) at the coordinates of the Erdemli station.

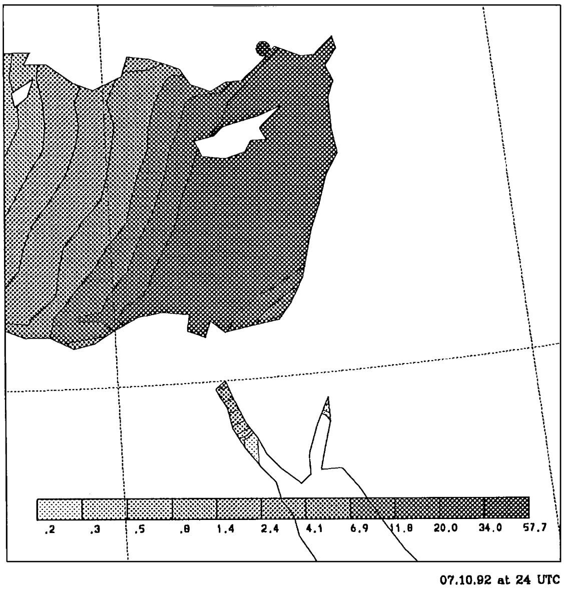


Fig. 11. Simulated daily accumulated dust fluxes (mg m^{-2}) onto the eastern Mediterranean on 7 October.

4. Conclusion

The atmosphere over the eastern Mediterranean is very dynamic and the concentration of dust is highly variable in space and time. This variability ranges from rapid day to day changes in dust concentrations as a result of meteorological and removal processes. Ground-based measurements yield a temporally varying record of the dust load, while modelling and satellite remote sensing complement the observations, indicating high spatial variability in the fluxes. We found that about 30% of the annual mineral dust deposition occurred in two dust events observed in May 1992. This means that the distribution of dust-related nutrient elements on the surface of the seawater could be extremely variable and that the significant deposition events could be easily missed in any short-term sampling program.

Dust loading in the atmosphere of the eastern Mediterranean is highly variable in space and time, so that its actual distribution and basinwide impact is difficult to quantify. The impact of dust on the climate and biogeochemical cycles would probably be underestimated if the annual or seasonal mean dust concentrations in the atmosphere were assumed to be given by those measured at coastal observing sites. Instead, regional- and event-based variations in the dust distribution are likely to be important in the identification of dust impact on the environment. In this paper we have presented that NMC/Eta model realistically reproduces the daily position of the Saharan dust plume extending from the African coast to the eastern Mediterranean and successfully describes the spatial variability.

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