CLIMATE PROCESSES RELATED TO SAHARAN DUST IN THE MEDITERRANEAN

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Introduction

Saharan dust, carried into the Mediterranean region by Scirocco and Khamsin winds or winds generated by mid-latitude atmospheric depressions, is probably one of the most important factors modifying climate in the region, both in the local and the global sense. Firstly, it modifies the incoming radiation at the earth's surface, and therefore effectively modifies the heat budget of semi-enclosed seas such as the Mediterranean Sea (Gilman and Garrett, 1994). Secondly, it can contribute to marine primary productivity by iron fertilization. This, on the other hand, is one of the most important feedback mechanisms regulating the radiation balance of the earth, because primary productivity in the ocean mediates carbon dioxide fluxes between the atmosphere and the ocean, and leads to increases in cloud albedo as a result of sulfate aerosols (DMS) production.

The major source of iron present in the remote areas of the ocean is deposition of atmospheric dust particles. (Duce *et al.*, 1991; Donaghey *et al.*, 1991). The deposition of iron on the ocean surface can have important implications for marine productivity. Recently, Martin's hypothesis on iron limitation of phytoplankton productivity has been tested in an artifically iron enriched area of the equatorial Pacific Ocean, indicating a doubling of the plant biomass, chlorophyll and plant production following the introduction of iron (Martin et al., 1994).

It has further been emphasized that the speciation of iron deposited on the surface water is important, since the bioavailability of iron for marine production depends on the relative enrichment with Fe(II) (Johnson *et al.*, 1994; Zhuang *et al.* 1994). The photoreduction and photooxidation reactions with short reaction times (on the order of minutes) determine the balance of Fe(III) to Fe(II) in cloud droplets (Faust, 1994). A balance in favor of Fe

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(II) is maintained during the daytime, especially when humidity is present together with sunlight. Johnson *et al.* (1994) have confirmed the diurnal characteristics of bioavailable iron in surface waters. The mineral dust deposited during nighttime consists of a higher percentage of Fe(III) which sinks rapidly, and can be reduced in water by longer wavelength light, only before they reach below the photic zone (Sulzberger *et al.*, 1993).

A positive feedback exists during the ocean deposition of atmospheric iron (Zhuang *et al.*, 1994): photoreduction of Fe(III) to Fe(II) increases the release of dimethyl sulphide (DMS) from the ocean to the atmosphere, and this creates further radicals motivating photoreduction.

DMS released during primary production constitutes most of the volatile sulfur originating from the oceans, and is a significant source of sulfate aerosols in the atmosphere other than the anthropogenic sources (*e.g.* Holligan *et al.*, 1993; Liss *et al.*, 1994; Charlson and Wigley, 1994). Its oxidised form is a major contributor to acidic rain. It is known that DMS forms cloud condensation nuclei and increases cloud albedo, thereby counteracting the greenhouse effect.

Recent experiments in the Pacific have pointed out the link between iron and sulfate aerosols, indicating an increase of 50-80 % in DMSP (a product of DMS) levels as a result of plankton blooms initiated by iron fertilization (Martin et al.,1994). One of the main sources of atmospheric organic sulfur is coccolithophorid blooms, with dominant species *Emiliania Huxleyi* (Holligan et al., 1993; Brown *et al.*, 1994). Timmermans *et al.* (1994) have demonstrated that the addition of iron enhances nitrate reductase activity in *Emiliania Huxleyi* such that the growth rate doubles. Yet, the factors responsible for inducing these blooms are not well known. It is suggested in the following that the flux of desert dust is one of the most important sources contributing to such blooms.

Eastern Mediterranean Dust Events and Plankton Blooms

A long term atmospheric sampling program of mineral dust is being carried out at IMS-METU since August 1991. An aerosol sampling tower (20 m) on the harbour jetty of the Institute (34o15′18″E, 36o33′54″N) collects daily aerosol samples on filter paper, utilizing a hi-vol pump. The samples are used for characterizing the temporal variability of atmospheric aerosols.

For the Mediterranean region and the Northern hemisphere in general the main sources of the dust are the Sahara and Arabian deserts. The results of the chemical analysis performed on samples collected on the southern coast of Turkey indicate sporadic dust intrusions into the Eastern Mediterranean, originating from these deserts (Kubilay and Saydam, 1995b). Each pulse is associated with an order of magnitude increase in the atmospheric concentrations of crustal elements like Al and Fe. 90 % of the total deposition of Fe is transported by dust pulses.

These observations are supported by satellite data (AVHRR and visible NOAA) received locally through an HRPT receiving station operated at the IMS-METU. Corresponding 3-D air-mass back trajectory analyses are made with the help of the Land-3 Project of the World Laboratory in Erice, Italy, which has excellent facilities to carry out such analyses (Kubilay, Dobricic and Nickovic, 1995). Furthermore, we are now able to model dust uplift and transport with a regional scale atmospheric model, including dynamical and transport components (Nickovic and Dobricic, 1995a,b).

An extraordinary dust storm event originating from Sahara was observed on 6 April 1994, yielding a maximum dust loading of 1600 $\mu g m^{-3}$, the largest ever recorded since the beginning of long term continuos sampling program. The Sahara origin of the dust pulse event has been been verified by the 3D backtrajectory analyses. A secondary dust pulse was evidenced on 11 April 1994 in the AVHRR data, affecting the Adriatic and the central Mediterranean. The Eastern Mediterranean region enjoyed calm weather conditions during both dust storm events, apart from a cyclonic depression moving north from Africa to the Balkans during the first event.

Satellite data from the Eastern Mediterranean obtained about a week after the dust events indicated high reflectance of visible light from the sea surface at regions coinciding with dust intrusions, suggesting the creation of coccolith blooms in these areas. The high reflectance areas always appear about a week after the dust events, because the formation of detached coccoliths requires about 6-8 days to develop after the initiation of a bloom (Balch *et al.*, 1992, 1993). Coccolithophore blooms in the detached phase increase the reflectance of the water column by as much as 25 % or greater, readily detected by contemporary AVHRR sensors in the visible band (*e.g.* Ackleson *et al.*, 1989).

The fact that the blooms were simultaneously observed in the vastly differing environments of the Eastern Mediterranean, the Sea of Marmara and the Western Black Sea (with salinity differences of up to 23, temperature differences of up to 10°C) can only result from a common source associated with a synoptic scale meteorological event.

By coincidence, the research vessel R/V BILIM of IMS-METU was in the Sea of Marmara during same time when a high reflectance patch was observed in the satellite images of 14 and 15 March, with observations reporting a very unusual and very thick red tide. Analyses confirmed the presence of Noctilucua Miliaris being the dominant type of red tide. The presence of Emiliana Huxleyi could not be confirmed, however, because the samples could not be analysed on board, and were destroyed during storage with addition of formaldehyde, resulting in dissolution of carbonate shells.

The observations were also consistent with the notion that the blooms are initiated by the photoreduction of dust Fe(III) to the bioavailable form Fe(II) during day time either by interaction with atmospheric humidity (clouds) or in water, after they are deposited on the surface. It is possible that the diel differences in the balance between different forms of iron, combined with the dust transport and humidity patterns of a moving storm can lead to the patchy distribution of blooms.

Another synoptic scale meteorological event carrying dust was detected on 29-30 August, 1994 in the western Mediterranean, and again was followed by the formation of strong reflectivity patches on 4 September 1994 in the Gulf of Tarranto and the Adriatic Sea region where the dust intrusion reached about a week earlier.

The observations were also consistent with the notion that the blooms are initiated by the photoreduction of dust Fe(III) to the bioavailable form Fe(II) during day time either by interaction with atmospheric humidity (clouds) or in water, after they are deposited on the surface. In most cases the high reflectivity areas were found in the same regions where clouds and dust existed together about a week earlier. It is possible that the diel differences in the balance between different forms of iron, combined with the dust transport and humidity patterns of a moving storm could lead to the patchy distribution of blooms observed in the Mediterranean.

Another case in which a dust episode whose back-trajectories could be traced to the Saharan region coincided with the observations of "milky water" during the July 1992 surveys in the Black Sea (Kubilay and Saydam, 1995). The event was undoubtedly a coccolithophore bloom, but this was not evident to us during the cruise.

Global Change Implications

It is also expected that the dust transport and its interaction with water vapour can lead to global effects. The increased cloud albedo due to enhanced production of cloud condensation nuclei (CCN) during coccolithophore blooms could potentially decrease radiation in the higher latitudes, where clouds are more abundant. On the other hand, the suspension of dust into the atmosphere by erosion from the desert regions is itself a function of the degree of aridity in these regions, and, would decrease with southerly shifts of rain associated with the polar front. Furthermore, there is some evidence that the coccolithophore blooms release CO_2, decreasing the absorption of carbon dioxide by the ocean (Balch, 1993), so that the atmospheric carbondioxide would tend to increase with increasing dust induced blooms. As a result, a negative feedback is suggested between atmospheric dust flux and global temperatures, leading to cyclic regulation of climate such as during interglacial periods.

There is evidence that during the 'Younger Dryas', the near-glacial period before the last deglaciation, dust loading reaching Greenland increased abruptly, and later dropped to a minimum when the near-glacial conditions ended Mayewski *et al.* (1993). The conditions during the Younger Dryas, as well as during various shorter term oscillations before and after this period suggest increased aridity or increased catchment area for dust, possibly indicating an expansion of the polar cell. Our suggestions based on the effects of dust induced plankton blooms are consistent with the ice core records, but possibly need further critical evaluation.

As concerns our region, support for our hypothesis is found in Nasrallah *et al.* (1993), who suggest that the atmospheric temperature changes in the Middle Eastern region in the last 40 years are well correlated wit desertification and atmospheric sulfate concentrations over the whole region.

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