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METEOSAT AND GROUND-BASED OPTICAL MEASUREMENTS OF DESERT DUST WITHIN EUROPEAN PROJECT MEDUSE

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ABSTRACT

We present here an overview of our remote sensing studies of African dust in the Mediterranean region, performed in the frame of the European MEDUSE (Mediterranean DUST Experiment). The data used include images from Meteosat VIS and IR channels, Sun photometer measurements of the aerosol optical thickness at three coastal stations, and lidar profiling of the aerosol vertical distribution. Operational products distributed daily from Meteosat data are presented. Those are a dust quick-look, and maps of a dust index over land and of the dust optical thickness over ocean. Monitoring of the spectral aerosol optical thickness using Sun photometer measurements shows relatively large background values due to submicronic particles and allows us to test our Meteosat inversion of dust optical thickness. Lidar measurements show that dust particles are present in well identified layers above the atmospheric boundary layer, up to 4-6 km in altitude. A case study of dust transport over the eastern Mediterranean combining Meteosat, Sun photometer and lidar data is discussed.

1. INTRODUCTION

An increasing trend in African dust export over the tropical North Atlantic has been observed over the last 30 years under the influence of climatic variations (Moulin et al., 1997a). Tegen and Fung (1995) suggest that anthropogenic perturbations of semi-arid soils have caused an increase of 30-50% in Saharan dust emissions. Meteorological satellites images of the North Atlantic region show the impressive direct radiative effect of dust particles in the solar spectrum (Jankowiak and Tanré, 1992; Husar et al., 1997) and they also affect the infrared radiative budget (Legrand et al., 1992; Tegen et al., 1996; Claquin et al., submitted). The atmospheric dust cycle appears to be strongly correlated with long-term climate variations such as glaciations (Jouzel et al., 1993). Dust deposition is also thought to sustain phytoplankton production in large oceanic regions (Martin et al., 1994) and also provides essential nutrients to soils (Muhs et al., 1990; Swap et al., 1992). Moreover, dust particles strongly decrease the acidity of precipitations (Loje-Pilot et al., 1986; Losno et al., 1991) and it has been recently shown that mineral dust particles in the eastern Mediterranean are often coated with sulfates, following processing of aerosols by cloud droplets. This converts dust

dramatic effects such as aviation accidents. It is therefore important to study and monitor the dust transport and its impacts.

Since March 1996, the objective of European project MEDUSE (Mediterranean DUST Experiment) is to develop an operational system for real-time monitoring and forecast of dust transport over the Mediterranean region. This system is based on (i) an operational meteorological model operated in forecast mode, including the atmospheric dust cycle from mobilization in source areas to surface deposition (Nickovic and Dobricic, 1996), and (ii) on a real-time analysis of VIS and IR Meteosat data (Dulac et al., 1994). It has proved to be helpful during recent field aerosol experiments such as a STAAARTE airborne campaign (June 1997, eastern Mediterranean) and ACE-2 (June-July 1997, North Atlantic). A set of measurements (mineral dust deposition, atmospheric concentration, optical thickness, vertical distribution) is performed on a regular basis or following dust transport forecasts, to evaluate and improve model- and Meteosat-derived products.

Here we report on MEDUSE aerosol passive and active remote sensing activities: (i) real-time monitoring of dust plume over both Africa and Mediterranean, using respectively Meteosat IR and VIS channels; (ii) measurement of the aerosol optical thickness in the visible and near-infrared using ground-based Sun photometers; and (iii) assessment of the vertical distribution of dust using ground-based lidars. Figure 1 displays the distribution of MEDUSE remote sensing facilities, i.e. a Meteosat receiving station (Gif-Sur-Yvette, France), three Sun photometers (Carloforte, Sardinia; Finokalia, Crete; and Thessaloniki, Greece) and two lidar systems (Observatoire de Haute Provence (OHP), France; Thessaloniki, Greece). Carloforte, Finokalia and Thessaloniki are coastal sites.

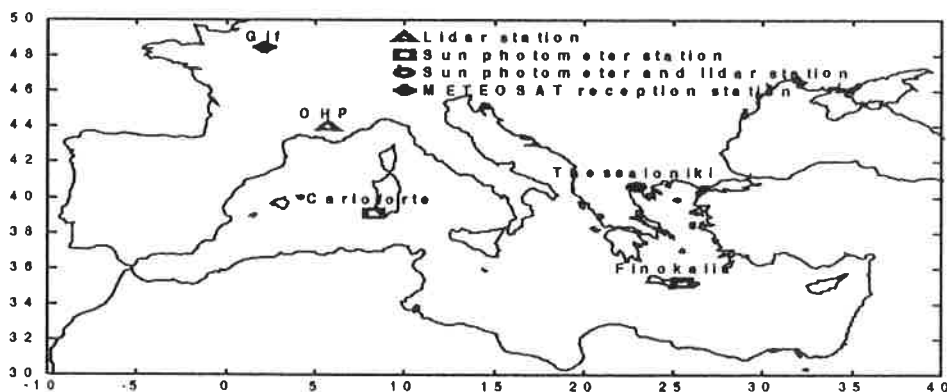


Figure 1: Distribution of MEDUSE remote sensing facilities.

2. METEOSAT REMOTE SENSING OF DUST

The methods used have been described in a previous work (Dulac et al., 1994). Developments made in the frame of MEDUSE essentially aimed at making products available daily on an operational way, using a Meteosat Primary Data Users Station operated since early June 1996. The station is composed of a 3.1-m diameter antenna and associated electronics, two Pentium PCs, respectively one receiver and one manager with an extra 4-Gb hard disk and a CD-recorder. The PCs are networked to a UNIX workstation equipped with a CD changer. We have developed routines for automatic acquisition, processing, archiving and network distribution of data. Bugs were fixed and since a secured power supply of the reception station has been installed, slot 24 (11:30-11:55) images are processed on a daily basis.

2.1. Dust quick-look

Numerical images of 2500 lines x 2500 pixels from both the VIS and IR Meteosat channels are acquired daily at 12:00 GMT. We subsample the data and perform a graphical processing of the combined VIS and IR data. This allows us to produce a colour quick-look image of 832 lines x 832 pixels (ISCCP-B1 format) of the Earth disk with enhanced clouds and enhanced dust plumes over the ocean, based on the IR and VIS numeric counts, respectively. The dust quick-look image is available in JPEG format at 13:00 GMT at the MEDUSE Web sites (<http://pentium.ccsem.infn.it> and <http://www.halo.hi.is/meduse>). Figure 2 gives an example of such a dust quick-look image. Backscattering by dust particles over the dark ocean tends to increase the VIS numeric count of ocean pixels. Ocean pixels with clear sky appear in dark blue. The concentration of airborne dust particles over seawater increases from light blue to yellow, orange and red. Land surfaces appear in dark grey, and clouds in white or grey. Note that coloured pixels on the border of the viewed Earth disk are not significant, and that coloured pixels in the Gulf of Guinea are due to sun glint on the sea surface. A large dust plume over the western Mediterranean is clearly seen on

image. Backscattering by dust particles over the dark ocean tends to increase the VIS numeric count of ocean pixels. Ocean pixels with clear sky appear in dark blue. The concentration of airborne dust particles over seawater increases from light blue to yellow, orange and red. Land surfaces appear in dark grey, and clouds in white or grey. Note that coloured pixels on the border of the viewed Earth disk are not significant, and that coloured pixels in the Gulf of Guinea are due to sun glint on the sea surface. A large dust plume over the western Mediterranean is clearly seen on figure 2. Many other intense dust events were observed in 1997, particularly in summer which is the season of maximum dust transport in the Mediterranean (Dulac et al., 1996; Moulin et al., 1997b). On the contrary, we observed only one intense event in the Mediterranean during summer 1996. The weakness in African dust export in 1996 can be attributed to unusual climatic conditions over the North Atlantic, associated with excess precipitations over northern Africa and southern Europe (Moulin et al., 1997a).

2.2. Infrared-Derived Dust Index

We also process full resolution IR images to derive information on the atmospheric turbidity over land surfaces. During daytime, backscattering of incoming solar radiation by airborne dust particles leads to a decrease in ground temperature and thus of the reemitted long-wave radiation, which is further attenuated by the dust layer (Legrand et al., 1992). Therefore the presence of a dust plume over ground surfaces results in a decrease of the radiance measured in the thermal IR channel. Following the method of Legrand (1990), this property enables us to compute an infrared-derived dust index (IDDI) which was found to be well correlated to horizontal visibility (Legrand et al., 1994). The method consists in computing a "warm" reference image from a set of about 15 successive images obtained at the same hour. For each pixel, the clearest observation (i.e. the highest IR radiance) from the considered period is selected. The difference between the IR image and the reference image is then made to obtain the IDDI image. Pixels containing water clouds are discriminated based on their greater heterogeneity compared to dust plumes. The discrimination is based on cutoff values for both the mean and standard deviation on sets of running (3 x 3) pixels. The IDDI image is available in TIF format at MEDUSE Web sites 2-3 hours after image acquisition.

Figure 3 gives an example of such an IDDI image for August 8, 1997. Water surfaces are masked in light blue. White areas are clouds. Blue indicates clear areas over land. Dust concentration increases from green to yellow, orange and red. We see a large dust plume over central and North Sahara. Dust raise has indeed been reported by meteorological stations in North Sahara on August 7 and in Mauritania and South of Atlas mountains on August 8. The plume appears to be channeled towards the western Mediterranean. Meteorological maps from the European Meteorological Bulletin show that this is due to the presence of a low off Portugal and of a high off Tunisia. On the day after, dust covers most of the western and central Mediterranean (figure 2).

2.3 Dust optical thickness

VIS images are further subsampled in ISCCP-B2 format (416 x 416) for real time estimate of the dust optical thickness at 550 nm (DOT_{550}) over the Mediterranean and the northeastern Atlantic between 5N and 20N and from Africa up to 40W at low latitudes and 30W at mid latitudes. The method is described in Moulin et al. (1997b). It is based on the use of the radiative transfer model 5S (Tanré et al., 1990). The dust aerosol model is the background desert aerosol model of Shettle (1984) with a refractive index of 1.50 - 0.01i (Moulin et al., 1997c). The inversion is relatively sensitive to the sensor calibration and we rely on a calibration obtained from the monitoring of stable desert areas (Moulin et al., 1996; Moulin et al., submitted), which requires long series of images. In case of change of satellite or of sensor gain, only a rough estimate of the dust optical thickness can therefore be obtained during several weeks.

Figure 4 displays the results for August 9, 1997. Continents are masked in black and cloud areas in white. The area analyzed is limited by geometric observation conditions. The DOT_{550} reaches large values of more than 1 in the western Mediterranean. A large dust plume with smaller optical thicknesses is also found over the tropical Atlantic, with dust likely originating from Mauritania (figure 3). Due to the poor resolution in B2 format, a number of pixels are discarded by the cloud filter based on spatial heterogeneity. We thus plan to analyze full resolution data in the near future.

3. SUN PHOTOMETER MEASUREMENTS

Because strong hypothesis on aerosol optical properties are necessary to derive the aerosol optical thickness from satellite data, ground-truths are required to test and validate satellite-derived aerosol optical thicknesses (Jankowiak and Tanré, 1992; Ignatov et al., 1995; Moulin et al., 1997c). Moreover the determination of the DOT requires to take

into account the possible contribution from other aerosol species to the satellite signal. Indeed lidar observations indicate that dust are generally present in well defined atmospheric layers above the marine boundary layer (Swap et al., 1992; Chazette et al., 1997; Hamonou et al., 1997).

We used automated Sun photometers from CIMEL Electronique, Paris, to measure the atmospheric attenuation of the solar irradiance at wavelengths (λ) 437, 669, 871 and 1021 nm. Measurements were taken at three coastal sites at Carloforte (southwestern Sardinia), Thessaloniki (northern continental Greece) and Finokalia (northeastern Crete). Provided proper calibration and relatively easy corrections for contribution of absorption and scattering by air molecules to the total attenuation, Sun photometers provide direct measurements of the atmospheric aerosol optical thickness (AOT).

The wavelength Angström exponent (α) describes the spectral dependence of the AOT at visible wavelengths (Angström, 1964):

$$\alpha = \text{Ln}(\text{AOT}_{\lambda_1} / \text{AOT}_{\lambda_2}) / \text{Ln}(\lambda_2 / \lambda_1)$$

Its value depends mostly on the aerosol size distribution. Small or even negative value are found for large particles such as seasalts or desert dusts, whereas values between 1 and 2 are found for submicronic particles such as sulphates.

Results obtained in 1996 are presented in figure 5. The AOT_{443} shows a relatively large background with values not lower than 0.1 and often larger than 0.3. α is generally larger than 0.8, showing the predominance of submicronic particles. Values of AOT and α are found significantly larger in Thessaloniki than in coastal sites of Crete and Sardinia, which can be attributed to local urban and industrial pollution sources. Measurements stopped in September at these two latter stations due to technical problems with the instruments. A few likely dust events may be detected in these time series when α becomes lower than 0.5. In particular from September 10 to 14 (Julian days 253 to 257), an increase in AOT, together with a marked decrease in α down to null values is observed at Carloforte and Finokalia, due to the most intense dust event that we observed with Meteosat in 1996. For example, during day hours of September 11, the AOT_{443} at Finokalia decreased from more than 0.6 ($\alpha = -0.05$) to less than 0.15 ($\alpha = 0.6$) when the plume passed over. The AOT monitoring using Sun photometer will allow us to characterize the seasonal evolution of the background AOT.

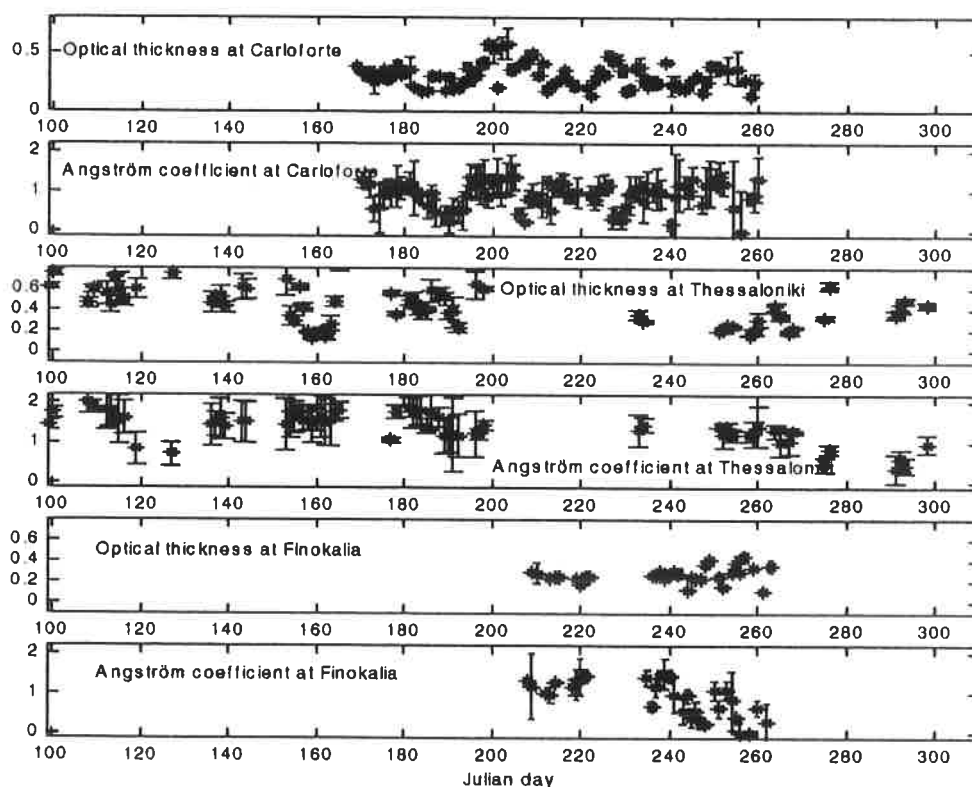


Figure 5: Evolution of the aerosol optical thickness at 443 nm and of the visible Angström exponent at the three Sun photometer stations in 1996. Daily means are represented by stars and vertical bars give the daily standard deviation.

4. COMPARISON BETWEEN METEOSAT AND SUN PHOTOMETER MEASUREMENTS

We derived from Meteosat VIS data the daily evolution of AOT_{550} near Carloforte. Values are averaged over a square of 3×3 marine pixels close to the measurement station. When no pixel is available due to cloud cover, values of AOT are missing. Most days were clear in summer and the cloud coverage markedly increased from October (day 273 on). In the absence of ground measurements at large spatial scale, Moulin et al. (1997b) used a climatological value of the background AOT, derived from the model sulfate concentrations of Langner and Rodhe (1991), to account for the contribution of sulphate aerosols in the Meteosat VIS signal. Corresponding values are of the order of 0.02-0.04 which appears underestimated compared to our Sun photometer measurements. Indeed, as noted by Moulin et al. (1997c), the northern Mediterranean coast exhibits very specific background conditions due to the European pollution. Our measurements enable us to refine Meteosat results in this region, using a background AOT due to marine aerosol of 0.15. Figure 6 displays a comparison between Meteosat-derived and photometer-derived AOT_{550} at Carloforte. Dust events around day 210, 230 and 255 are more or less captured. The high aerosol optical thickness episode around day 200 observed in Carloforte with values of about 1 does not seem due to a dust event but to a pollution episode. When more dust events will have been observed coincidentally by both systems, a statistical comparison between Sun photometer- and Meteosat-derived AOT will allow us to constrain the dust aerosol model used, following the procedure of Moulin et al. (1997c).

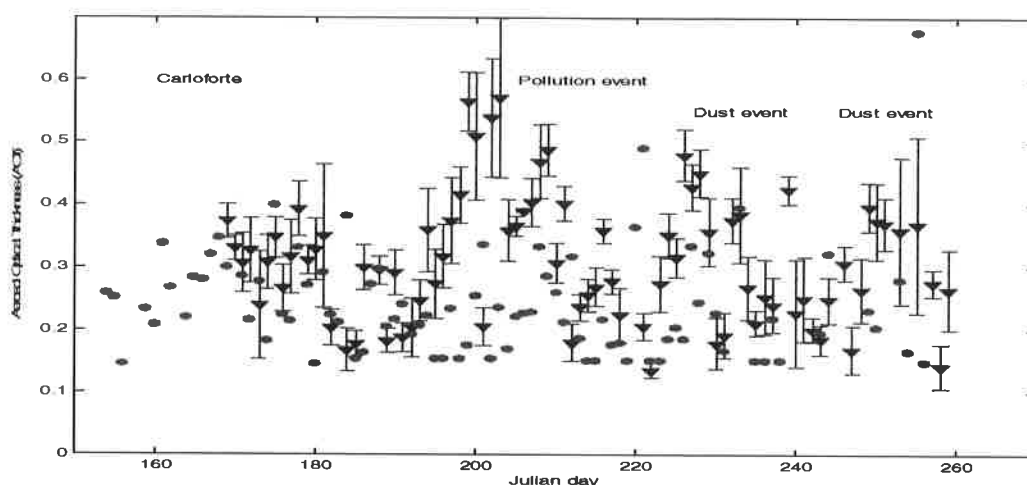


Figure 6: Comparison between the aerosol optical thickness at 550 nm retrieved from Sun photometer measurements (triangles and bars as in Figure 5) and from Meteosat noon observations (filled circles) above Carloforte in 1996.

5. LIDAR PROFILING

Structural properties of dust plumes transported over the Mediterranean basin are of great importance to assess their geophysical impacts: both horizontal and vertical structure are key parameters to estimate dust radiative forcing and deposition to seawater. Passive instruments such as Sun photometer or Meteosat provide only a vertically integrated information. Active instruments such as lidar systems enable a time resolved investigation of the atmosphere from which the position of the backscattering layers can be retrieved.

To determine the vertical distribution of dust, we have performed lidar measurements at two different sites in the Mediterranean basin which are Observatoire de Haute Provence (OHP) and Thessaloniki (figure 1). These two lidars use Nd:Yag laser sources at 532 nm. Intensive measurements were performed when a dust event was likely to be observed above the station, according to Meteosat observations and model forecasts. Atmospheric backscattering profiles were retrieved from lidar measurements using Klett's (1981) solution. We then used the same dust aerosol model than for Meteosat analysis to derive the extinction coefficient profile. During MEDUSE project, we observed several dust events with the lidar systems at OHP and Thessaloniki. All of them showed a well defined vertical structure, the altitude of the dust layer varying between about 1.5 and 6 km. A similar pattern was observed over the Azores region (Chazette et al., 1997) and the tropical Atlantic (Swap et al., 1992). For instance, during a dust event over France on 14-17 May 1997 associated with a low over the Iberic peninsula, several aerosol backscattering maxima were detected within a dust layer extending between less than 2 (maximum not seen due to lidar telescope

field of view) to more than 6 km in altitude. Another case on 11 July 1997 showed a dust layer from 2 to about 4.5 km, with stratus clouds on top of the dust layer.

Figure 7 is an example of a lidar profile that has been measured above Thessaloniki on May 8, 1997, at 10:20 GMT, during a dust event. The relative humidity profile from the local meteorological sounding is also shown. The top of the Planetary Boundary Layer (PBL) is at an altitude of 550 m (maximum in relative humidity). The sharp drop in relative humidity between 550 and about 700 m corresponds to a temperature inversion (not shown). The sounding indicates southerly winds in the PBL and above. In the absence of dust plume the lidar signal usually follows the theoretical molecular (Rayleigh) extinction profile above the PBL (figure 7). Here we have a strong deviation to the Rayleigh due to the scattering by dust particles present in the dry air layers above the PBL. The dust extinction presents two maxima. The bottom maximum in extinction below 1 km in altitude is not fully seen due to the field of view of the lidar telescope. The second maximum appears at about 4 km in another relatively dry layer with constant humidity above 3 km and up to 4.5 km in altitude.

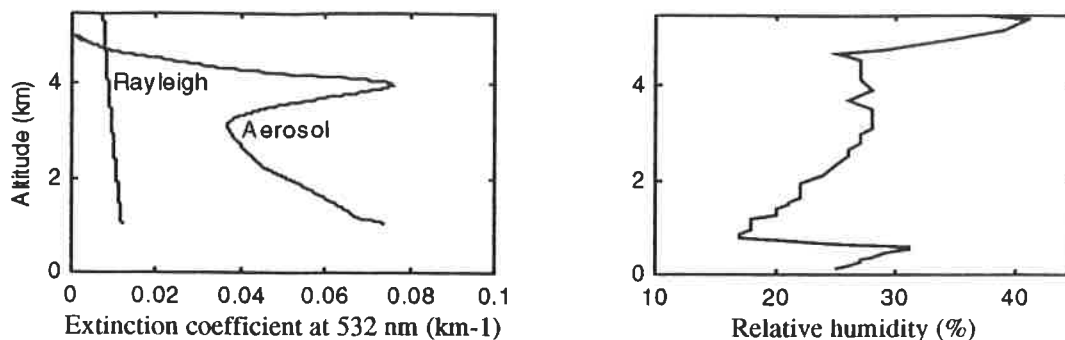


Figure 7: Vertical profile of (left) aerosol extinction coefficient retrieved from lidar measurement at Thessaloniki on May 8, 1997 10:20 GMT (13:20 local time) and theoretical molecular extinction profile, and (right) relative humidity from meteorological rawindsonding (14:00 local).

6 A CASE STUDY WITH METEOSAT, LIDAR, AND SUN PHOTOMETER OBSERVATIONS

In figure 8 Meteosat-derived dust optical thickness distributions on May 8 and 9, 1997 clearly show a dust plume over the eastern basin. The plume was present over Thessaloniki on May 8. Meteosat-derived DOT_{550} at 11:45 in the Gulf of Thessaloniki was of the order of 0.4. By integrating the lidar-derived dust extinction coefficient shown in figure 7, we find an optical thickness of about 0.2 for the Saharan air layer at 10:20 GMT. This value does not account for the contribution of the part of the bottom dust layer which is not seen by the lidar (below 1050 m). The evolution of the optical thickness and Angström exponent on May 8 and the day after, as derived from Sun photometer measurements, is shown in figure 9. AOT_{332} was of the order of 0.5 in the morning, in satisfying agreement with the Meteosat-derived value to which the boundary layer aerosol AOT has to be added. Between 9:00 and 12:00 GMT, α decreased from 0.7 to 0.45 due to the arrival of the dust plume and to the major contribution of mineral dust particles to the solar extinction. In the afternoon between 15:00 and 16:00 GMT, the values of AOT_{332} and α were stable at 0.43-0.44 and about 0.4, respectively. In the following morning, α was of the order of 0.9-1, AOT_{332} has decreased to about 0.2. Indeed, the lidar-derived aerosol extinction profiles plotted in figure 10 show that the dust layer in altitude has disappeared after 6:00 GMT. Assuming that the background AOT due to aerosol particles in the PBL was also 0.2 on the morning of May 8, this indicates by difference that the dust optical thickness was about 0.3. The different measurements are therefore consistent, and their combination allows to get a good view of the regional, vertical and temporal evolution of the dust plume, which will be very helpful to validate model simulations of dust transport.

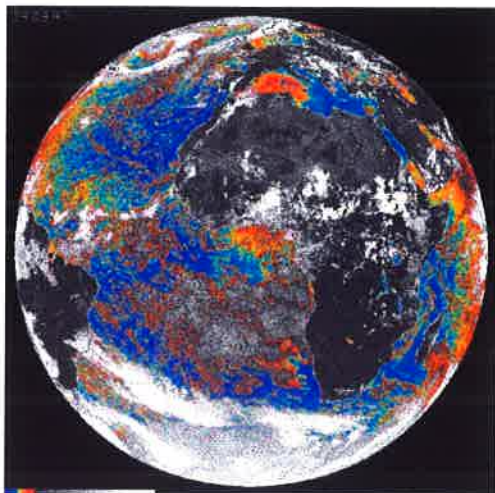


Figure 2: Dust quick-look image, from Meteosat VIS and IR images of August 09, 1997.

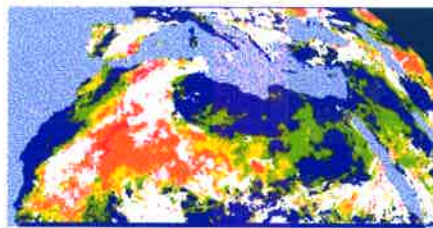


Figure 3: Dust index image, from Meteosat IR image of August 08, 1997.

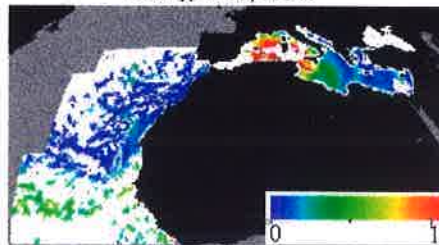


Figure 4: Meteosat-derived dust optical thickness over seawater on August 09, 1997.

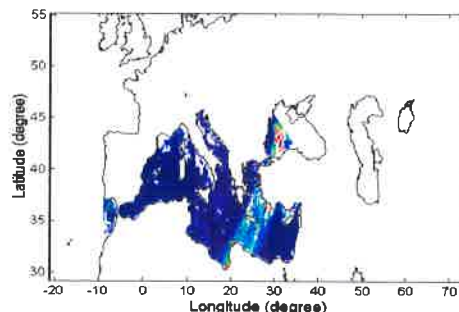
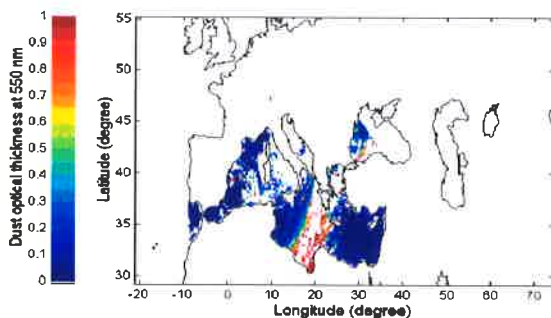


Figure 8: Distribution of AOT_{550} as derived from Meteosat on May 8 (left) and 9 (right), 1997.

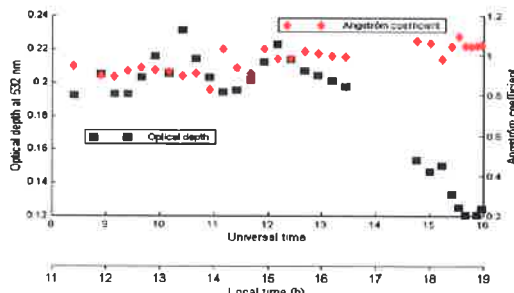
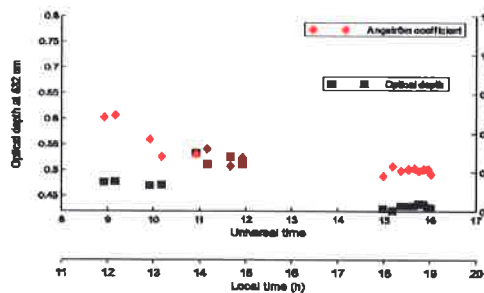


Figure 9: Evolution of AOT_{532} and α on May 8 (left) and 9 (right), 1997 from sun photometer measurements at Thessaloniki.

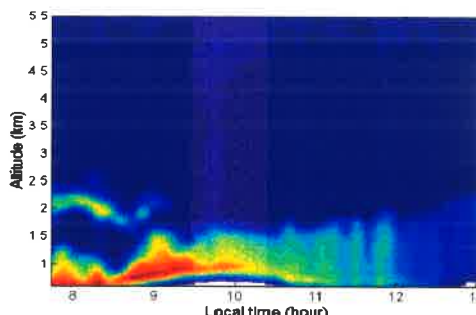
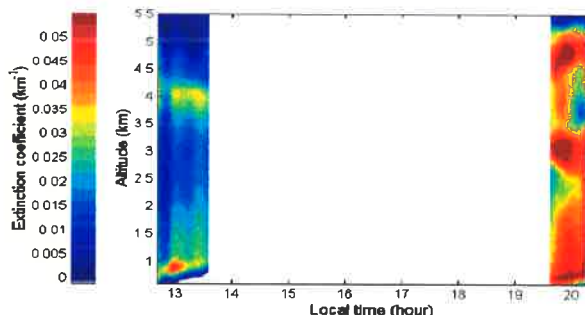


Figure 10: Evolution of aerosol extinction profiles on May 8 (left) and 9 (right), 1997 from lidar measurements at Thessaloniki.

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