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correlations during  
dust transport  
episodes**

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# Aerosol-ozone correlations during dust transport episodes

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## Abstract

Its location in the Mediterranean region and its physical characteristics render Mt. Cimone (44°11' N, 10°42' E), the highest peak of the Italian northern Apennines (2165 m asl), particularly suitable to study the transport of air masses from the North African desert area to Europe. During these northward transports 12 dust events were registered in measurements of the aerosol concentration at the station during the period June–December 2000, allowing the study of the impact of mineral dust transports on free tropospheric ozone concentrations, which were also measured at Mt. Cimone. Three-dimensional backward trajectories were used to determine the air mass origin, while TOMS Aerosol Index data for the Mt. Cimone area were used to confirm the presence of absorbing aerosol over the measurement site.

A trajectory statistical analysis allowed identifying the main source areas of ozone and aerosols. The analysis of these back trajectories showed that central Europe and North and central Italy are the major pollution source areas for ozone and fine aerosol, whereas the North African desert regions were the most important source areas for coarse aerosol and low ozone concentrations. During dust events, the Mt. Cimone mean volume concentration for coarse particles was  $6.18 \mu\text{m}^3/\text{cm}^3$  compared to  $0.63 \mu\text{m}^3/\text{cm}^3$  in dust-free conditions, while the ozone concentrations were 5% to 20% lower than the monthly mean background values. Our observations show that surface ozone concentrations were lower than the background values in air masses coming from North Africa, and when these air masses were also rich in coarse particles, the lowest ozone values were registered. Preliminary results on the impact of the dust events on  $\text{PM}_{10}$  values measured in the urban and rural areas of the Po valley are also presented.

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## 1. Introduction

Mineral dust is one of the greatest sources of natural aerosol and represents, with 2150 Tg/yr, about 37% of the total production of atmospheric primary aerosols by both natural and anthropogenic sources (Penner et al., 2001). When the weather conditions are favourable to lift dust material, dust particles rising in the free troposphere can be transported over long distances by the atmospheric circulation. The presence of mineral dust in the atmosphere may contribute to climatic variations and influence the behaviour of some tropospheric trace gases, changing the oxidizing capacity of the atmosphere (Arimoto, 2001). Atmospheric aerosol can modify the energy balance through scattering and absorption of light (Sokolik and Toon, 1996). The radiative effect of mineral aerosol from natural sources and disturbed soils contributes about 8% to total aerosol scattering of incoming solar radiation (Andreae, 1995). In particular, those mineral aerosol particles, which are characterised by very large surface area, can strongly absorb the shortwave solar radiation, influencing the radiative forcing of climate (Dickerson et al., 1997), or causing a photolysis rate reduction, thus inhibiting ozone production. In fact, in the lower atmosphere, mineral aerosol may strongly influence the balance of atmospheric trace gases, including ozone (Prospero et al., 1995; Dentener and Crutzen, 1993; Zhang et al., 1994; Dickerson et al., 1997). Dentener et al. (1996) in their modelling studies, suggested that the ozone destruction on mineral aerosol surfaces could lead to a 10% reduction of O<sub>3</sub> concentrations in the dust source areas. In fact, the large surface area of solid dust particles may play a significant role as a reactive surface on which heterogeneous chemistry can take place (Schmitt et al., 1988; Zhang et al., 1994). Recently, from a global modelling study (Bauer et al., 2004), have found out that during the year 2000 a decrease in global tropospheric ozone mass by about 5% could be due to the heterogeneous reactions on dust aerosol. Hanisch and Crowley (2003) have shown that the ozone loss can be due to decomposition, catalytic destruction or absorption on mineral oxides.

In order to find out whether air masses coming from the Sahara carry depleted O<sub>3</sub>

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concentrations during their travel towards or passage over the European continent, it would be necessary to know the ozone concentration in the desert source areas. Unfortunately, due to the lack of measurement sites in these areas the actual concentrations of background O<sub>3</sub> in the African deserts are not known. Only few measurements in the Lybian desert (Gusten et al., 1996), in Chad and Tunisia (Fabian and Pruchniewicz, 1977) were carried out in the past. Fabian and Pruchniewicz (1977) found that the lowest O<sub>3</sub> concentrations were associated with air masses coming from Central Africa, while Gusten et al. (1996), in spite of the limited measurement period (18 days), highlighted an interesting phenomenon. During their measurements, carried out in the western Lybia desert (30 km south of the Oasis of Dukhla), relatively small O<sub>3</sub> diurnal variations ranging between 45 and 50 ppbv were registered when northerly winds prevailed. On the contrary, under southerly winds coming from the desert, very low O<sub>3</sub> concentrations with a diurnal variation between 25 and 45 ppbv were measured (Gusten et al., 1996). Outside the African deserts, but close to the west coast of North Africa, trace gas measurements, carried out at the Izaña baseline mountain station (Canary Islands), showed marked surface ozone depletions during Saharan dust events (Prospero et al., 1995; Schmitt et al., 1998), which significantly influenced the annual mean ozone concentrations (Schmitt et al., 1998; de Reus et al., 2000).

Dust mobilisation over the African deserts supplies a large contribution to natural mineral aerosol in the atmosphere. Using the Total Ozone Mapping Spectrometer Aerosol Index (TOMS-AI), Prospero (1999) showed that the Sahara desert exports more dust than any other desert region. During dust storms, aerosol concentrations of more than 1000 µg/m<sup>3</sup> (Ganor, 1994) can be injected into the atmosphere. Although a great part of this mineral aerosol moves westward into the Atlantic Ocean and towards the American continent, another considerable part can be transported across the Mediterranean basin towards southern Europe and can occasionally even reach Central and Northern Europe (Franzen et al., 1994; Schwikowski et al., 1995; Moulin et al., 1998; Kubilay et al., 2000; Rodriguez et al., 2001). Ansmann et al. (2003) have recently documented the large spatial extent and three-dimensional structure

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of such a dust transport event using data from the European aerosol lidar network. Moulin (1997) estimated in his thesis that  $70 \times 10^6$  tons of dust are transported annually over the Mediterranean and  $350 \times 10^6$  tons of dust are transported over the Atlantic. This is in good agreement with work from Schütz (1980) and d'Almeida (1986) who estimated the North Atlantic transport at respectively 260 and  $190 \times 10^6$  tons and the Mediterranean transport at  $100 \times 10^6$  tons.

In Southern Europe, Mt. Cimone is one of the first high mountains that is passed by the Saharan air masses and where measurements of the chemical composition of the background atmosphere are regularly carried out. This has permitted to register several Saharan dust intrusions since 1991 (Bonasoni et al., 1996), showing that low ozone concentrations usually accompany these transport events. This fact was confirmed by soundings of ozone, humidity and temperature carried out in the lowland Po valley (Bonasoni et al., 1998). During the recent MINATROC EU project (Mineral Dust and Tropospheric Chemistry), in order to better characterize the influence of mineral aerosol on surface ozone concentration, high time resolution in situ measurements of surface ozone, aerosol size distribution and other parameters were carried out at Mt. Cimone from June to December 2000. This permitted to identify all the dust transport events reaching Mt. Cimone. The correlation between ozone concentration and coarse and fine aerosol was studied using back-trajectory and satellite data analyses.

## 2. Site, experimental procedures, and methods

### 2.1. Site and measurement description

In order to investigate the relationship between trace gases and mineral aerosol in the free troposphere, an extended field campaign, with measurements of  $O_3$  and  $PM_{10}$ , particle size and mass distribution and meteorological parameters, was carried out at the Mt. Cimone baseline station ( $44^\circ 11' N$ ,  $10^\circ 42' E$ , 2165 m asl) from June to December 2000. Mt. Cimone (MTC) is the highest mountain peak in the northern Apennines.

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It is considered representative of the European continental background conditions (Fischer et al., 2003; Bonasoni et al., 2000) and due to its altitude (2165 m asl) and geographical position (44°11' N, 10°42' E) to the South of the Alps and the Po valley and to the North of the Mediterranean Sea, this measurement site is suitable to study a wide spectrum of atmospheric processes. Particularly, the Apennines are the first mountain chain met by Saharan air masses on their way to Europe. Usually, dust transport events occur with strong synoptically forced south-westerly winds that, even during the summer season, prevent the development of the valley breeze wind regime, which could potentially bring locally polluted air masses up to MTC. In fact, during the considered period, the hourly mean wind velocity recorded at MTC during the dust transport events (10.1 m/s) was more than twice that during “normal” conditions without dust transport. Located at a distance of about 1600 km from the African deserts, the Saharan air masses can directly reach the measurement site in a few days. As obtained from back-trajectory analysis, during the period of the present study (June–December 2000) the mean air mass travel time from the North African coast to MTC was 64 hours, but in about 50% of the cases it took less than 48 h and in the fastest transport events (13–14 October, 16–17 November) it took only 18 h.

During the MINATROC project (Mineral Dust and Tropospheric Chemistry) an intensive measurement campaign took place at MTC during the summer of 2000 (see companion papers in this issue). After the intensive campaign from the 1st of June to the 5th of July, measurements of surface ozone and aerosol size distribution were continued till the end of the year. Ozone was measured with an UV-absorption analyser (Dasibi 1108) with an accuracy of better than 5% and one minute time resolution. The air inlet was placed at 8 m above the ground. Aerosol concentrations and size distributions of particles with aerodynamic diameters between 0.30 and 20  $\mu\text{m}$  were measured with an optical particle counter (OPC) (Particle Size Analyser Grimm Mod. 1.108) in 15 size channels with one minute time resolution. A built-in flow-controlled pump was used to draw in the air sample through the sampling head. These measurements permitted us to distinguish between coarse ( $1 \mu\text{m} < D_p < 20 \mu\text{m}$ ) and fine ( $0.3 \mu\text{m} < D_p < 1 \mu\text{m}$ ) aerosol

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particles (see Hanisch and Crowley, 2003) which – as we shall show below – have a quite different relationship with ozone. This extensive data set of aerosol size distribution constitutes the first continuous dust record with high time resolution (interrupted only from July 6th to August 4th 2000) carried out in the free troposphere in this part of the northern Mediterranean area.

## 2.2. Trajectory model description and application to field concentration

We used the Lagrangian model Flextra (Stohl et al., 1995) to calculate three-dimensional 10-day back-trajectories arriving at MTC every three hours. Flextra uses meteorological analysis fields (every 6 h) plus 3-h forecast fields produced by the numerical weather prediction model of the European Centre for Medium Range Weather Forecasts (ECMWF). Position information along the trajectories was available every 3 h. Typical trajectory errors are about 10–20% of the travel distance (Stohl, 1998), but individual trajectories can have much larger errors depending on the meteorological situation. Further errors in tracing the air masses can be caused by the difference between the real topography and the model topography around MTC, which can be quite large.

To investigate the correlation between air mass origins and the ozone and aerosol (fine and coarse) concentrations recorded at MTC, we applied the trajectory statistics method of Seibert et al. (1994). This simple method has the potential to determine the source regions of measured substances using only the measurement data and the trajectories, without involving a detailed model of the emission, transformation and removal processes occurring in an air mass. Thus, it also avoids the errors associated with these complex models and yields a measurement-based and receptor-oriented estimate of the sources of atmospheric trace species. In order to identify the source areas of a specific species (in our case ozone or aerosol concentrations) monitored at the measurement site, a so-called concentration field on a geographical grid is calculated with this method by attributing a measured concentration to every point along the trajectory arriving at the time of measurement. Considering all the trajectories and all

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the data recorded during the period of study, a mean concentration is obtained for each grid cell of the concentration field.

Assuming  $m, n$  to be the indices of the horizontal grid,  $l$  the index of each trajectory,  $M$  the total number of the applied trajectories,  $c_l$  the concentration recorded at the arrival of trajectory  $l$  and  $\tau_{mnl}$  the time spent in the cell  $(m, n)$  by the trajectory  $l$ , the mean concentration was calculated by using the following formula:

$$\log(\bar{C}_{mn}) = \frac{1}{\sum_{l=1}^M \tau_{mnl}} \sum_{l=1}^M \log(c_l) \tau_{mnl} \quad (1)$$

The concentration field obtained in this way can be interpreted as the distribution of sources contributing to the measured values at MTC. In order to eliminate small-scale variations in the concentration field which are not statistically significant, a 9-point smoothing operator was applied for each cell. To avoid that significant features are removed, the smoothing procedure was applied only for those values exceeding an interval calculated on the 95% confidence level for a  $t$ -statistic. The statistic was applied to the number of trajectories passing across each cell, assuming that individual measured values were independent from each other.

The concentration field method by Seibert et al. (1994) is known to underestimate the spatial gradients of the source fields, since the concentrations measured at the receptor location are smeared out along the segments of the associated trajectory, while actual emissions may take place only in some segments (Wotawa and Kröger, 1999). However, as we focus on the contributions of a large area (i.e. North Africa) a high spatial resolution of the concentration field is not required in our case. Moreover, the resulting concentration fields have to be interpreted as source fields contributing specifically to the concentration at MTC. The actual spatial distribution of the considered species or its sources may be different because the meteorological conditions (and thus also the emission, transformation and removal processes) are specific for the pathway towards MTC (Stohl, 1998). Furthermore, the density of the trajectory information and thus the

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reliability of the method decreases with distance from MTC. For another receptor site the source field may therefore look slightly different.

### 2.3. TOMS aerosol index

The absorbing aerosol index (AI) from the Total Ozone Mapping Spectrometer (TOMS), defined as the difference between the backscattered radiation measured in two ultra-violet channels, provides a linear relationship with the aerosol optical depth for smoke and dust: the larger the aerosol index, the higher the optical depth. Although negative AI values are usually related to non-absorbing particulate matter for which aerosol scattering dominates over absorption (Torres et al., 1998), small negative values (i.e. AI > -2) could also be indicative for a weakly absorbing particle layer not far from the Earth's surface. The AI archive by TOMS constitutes an easy-to-use satellite data set available for the entire globe. Maps of the aerosol index are available with a resolution of 1.25° in longitude by 1° in latitude. The "Earth Probe" satellite, which hosts the TOMS spectrometer, has a polar orbit with a local passing time around 11:00 am over MTC, with a shift of about 30 min varying from year to year. Although the absorbing AI has severe drawbacks in terms of quantitative validation of the dust emissions, recent studies suggest that useful information can nevertheless be retrieved with a reasonable accuracy (Chiapello and Moulin, 2002; Torres et al., 2002). In fact, in order to highlight persistent dust sources and typical dust transports in atmosphere, a 13-year climatology (1980–1992) of TOMS-AI was systematically examined by Prospero et al. (2002).

## 3. Results and discussion

### 3.1. Analysis of aerosol during dust transport episodes

Saharan dust episodes brought about pronounced changes in the aerosol size distribution and in the chemical composition of aerosols compared to dust free conditions

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at MTC (Van Dingenen et al., 2001). This is illustrated in Fig. 1, which shows average aerosol number size distributions during dust events and under dust-free conditions at MTC. The episodic appearance of the coarse (dust) mode aerosol during the period June–December can clearly be seen in the time series of the aerosol volume size distribution in Fig. 2. It can also be seen that dust events occurred most frequently from June to October but were relatively rare during November and December.

Differences in average aerosol number size distributions permitted us to identify dusty from non-dusty periods. In order to corroborate the identification of dusty periods at MTC, we used three-dimensional back-trajectory analysis as well as satellite images from SeaWiFS – Sea viewing Wide Field-of-view Sensor (McClain et al., 1998), model results of dust optical depth from NAAPS - Navy Aerosol Analysis and Prediction System (Hogan et al., 1991a, b) and aerosol loading from IcoD/DREAM – Dust Regional Atmospheric Model (Nickovic et al., 2001). Dusty periods were then identified using all this information.

In order to identify the major dust production areas during our period of study, we used the TOMS-AI data. Figure 3 shows a map of the average of all positive AI values for the June–December 2000 period. The areas of maximum mean AI likely correspond to the main source regions for mobilized dust and match well with a five-year TOMS-AI analysis for the Mediterranean region (Israelevich et al., 2002). The Chad basin (about 16° N; 16° E) and the Eljoug basin in Mali (about 19° N; 6° W) appeared as the main dust source areas, while minor source areas can be identified in Libya, between Algeria and Tunisia, in the Arabian Peninsula and in northern Sudan. In spite of the short period of investigation, it is evident that enhanced positive AI values extend into the Mediterranean region, indicating active dust transport.

In order to confirm the transport of aerosol in the troposphere over the MTC area, we retrieved the daily TOMS-AI value for the MTC pixel area (pixel size 1.25° Lon., 1.00° Lat.) and combined these data with the back-trajectories ending at MTC. For our purpose we made the assumption that the daily AI values are representative for 24 h, attributing the same measured value to all the eight daily trajectories. We furthermore

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assumed that usually the trajectories ending at the altitude of MTC are representative for the dust transport. This is not an unlikely assumption, because the dust is frequently transported in layers in the lower free troposphere at about the MTC altitude (Hamonou et al., 1999). In order to identify the dust sources contributing to the dust in the MTC pixel (as indicated by the TOMS-AI), trajectory statistics were applied to the combined data set. The results of this analysis (Fig. 4) clearly show that positive TOMS-AI values at the location of MTC are associated with transport from North Africa, with the principal source region being located in Algeria.

In order to determine the main source regions for the aerosols measured in situ, we applied the trajectory statistics method to both coarse and fine fractions of the particle concentrations measured at MTC during the period June–December 2000. The concentration field for the fine particle numbers is shown in Fig. 5. The highest number concentrations of fine particles, which are mostly produced by transformation of gaseous compounds into the liquid or solid phase (Hering et al., 1998; Raes et al., 2000), are mainly related to regions with strong anthropogenic sources of precursor gases like the Po Valley, central Italy, North-eastern France, and North and South-western Germany. In these areas the contribution of fine particles directly emitted by combustion processes and produced by photochemical reactions is very important, because they take place in an atmosphere rich in ammonium nitrate and ammonium sulphate (Bowman et al., 1995). Enhanced values in the concentration field are also found over Northern Africa, possibly indicating dust mobilization as a secondary source for fine-mode aerosols. In fact, as evidenced in Fig. 2, Saharan dust events are often associated not only with enhanced concentrations of the coarse-mode aerosols, but also with enhancements in smaller aerosols (Gomes et al., 1990).

Figure 6 shows the concentration field for the coarse fraction. The highest coarse aerosol number concentrations measured at MTC are usually associated with low latitude air masses originating in North Africa, particularly in Algeria (Fig. 6). This result is in good agreement with the similar analysis carried out for the TOMS-AI data (Fig. 4) and confirms that North Africa is the principal source region for coarse aerosol mea-

sured at MTC. The close agreement between the concentration fields for the TOMS-AI and the coarse particle number concentrations is understandable as a consequence of the strong correlation between the time series of these two parameters (Fig. 7a and b).

During Saharan dust events recorded at MTC the air masses often also moved further northward and eastward and reached Northern Italy, where they could influence the PM<sub>10</sub> aerosol concentrations in the Po Valley. In fact, several environmental monitoring stations of the “Agenzia Regionale Prevenzione e Ambiente – Emilia Romagna” (ARPA) sited in the Po Valley area (i.e. Parma, Modena, Ferrara, Cesena) detected clear increases in the PM<sub>10</sub> concentrations during or shortly after Saharan dust events at MTC (Fig. 8). The dust episodes in the Po Valley are confirmed by the back trajectory analyses (not shown) and underline the importance of the mineral aerosol contribution to the PM<sub>10</sub> concentrations in the lowland urban and rural areas.

### 3.2. Ozone analysis and aerosol correlation during dust episodes

Because of its high mountain location, no ozone diurnal variations are normally recorded at MTC, except for some periods during the warm season when a small reverse diurnal variation can be caused by the local upslope winds, indicating that the station samples the free troposphere most of the time (Bonasoni et al., 2000). The seasonal ozone concentration ranges from about 40 ppbv in winter to 65 ppbv in summer. A concentration field for O<sub>3</sub> source areas has been obtained by applying the trajectory statistics method to the MTC ozone data for the period June–December 2000 (Fig. 9). High ozone values are associated with air masses coming from populated and industrialised areas in North and North-Eastern Europe, low ozone concentrations are associated with air masses coming from the South and South-West. The same analysis (not shown) has been applied for warm (June–September) and cold (October–December) seasons showing similar results, even if in respect to the cold, the warm season is characterised by higher O<sub>3</sub> values.

These results are consistent, at least qualitatively, with pictures of European ozone source and production rates obtained by Wotawa et al. (2000) by applying both a sta-

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tistical trajectory source analysis and a Lagrangian photochemical box model. This agrees with the existence of a North-South gradient of ozone across the Mediterranean region, as reported by Balkanski et al. (this issue). The areas characterised by high ozone concentrations are very similar to those identified as the source areas for fine particles measured at MTC (Fig. 5). Particularly, the areas of North-Western Europe, the Po Valley, central and South Italy as well as the Balkan peninsula show the highest levels of both fine particles (Fig. 5) and ozone (Fig. 9), likely due to anthropogenic emissions of the precursors for the formation of both ozone and particles. On the contrary, low ozone concentration values are associated with air masses coming from the Southern Mediterranean and North-Africa regions, which are characterised by relatively small anthropogenic emissions, but strong dust sources (North-Africa and Sahara areas), as shown by the TOMS-AI maps (Fig. 4). It is of interest to look more in detail into the anti-correlation between the spatial distribution of the sources of O<sub>3</sub> (Fig. 9) and coarse particles (Fig. 6).

In order to investigate the ozone behaviour during Saharan dust events at MTC and to study the possible influence of coarse aerosols on the ozone concentrations, we analysed the relationship between the hourly data of the de-trended concentrations of ozone and the concentrations of coarse particles (Fig. 10). We de-trended the ozone data in order to remove the strong seasonal variation of ozone. The de-trended ozone is obtained by:

$$O_3^{DET} = O_3^{MTC} \frac{O_3^{period}}{O_3^{rm}} \quad (2)$$

where  $O_3^{DET}$  is the ozone concentration value corrected for the seasonal variations,  $O_3^{MTC}$  is the hourly ozone concentration measured at MTC,  $O_3^{period}$  is the averaged concentration for the period June–December 2000 and  $O_3^{rm}$  is a running mean concentration. Since the phenomena on which we focused occur on synoptic time scales (i.e. a few days), a 21 days running mean was used (Vukovich, 1997; Weischet, 1977).

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During the 12 dust episodes, the de-trended ozone concentrations (Fig. 10) were on average between 5% (25–27 October) and 20% (13–17 November) lower than the detrended mean value. The hourly  $O_3$  minima during the strongest dust events (20–24 August, 12–15 October) were even about 35% below the mean value. The lowest ozone concentrations were measured simultaneously with the highest coarse aerosol values so that an anticorrelation between coarse particle and ozone concentrations is evident (Fig. 10). During the few cases when a high concentration of coarse particles was not due to Saharan air mass transports (e.g. an episode on 10 November when the air came from the Gulf of Genoa), an ozone increase was recorded.

The relationship between the values of the detrended ozone concentration with the fine and coarse aerosol volume has been analysed using a box-and-whiskers plot. The boxes and whiskers denote the 10, 25, 50, 75 and 90 percentiles, and the bold lines the mean values of the ozone distributions for different classes of the fine- and coarse-mode particle volume concentrations (Fig. 11). The whole distribution of the detrended ozone concentrations shifts towards higher values with increasing aerosol volume concentrations of the fine-mode particles. Particularly the highest  $O_3$  values, which occur in polluted air masses, are associated to high fine aerosol volume concentrations ranging between 2 and  $10 \mu\text{m}^3/\text{cm}^3$ . In contrast, Fig. 11 shows the lowest ozone values for high values of the coarse-mode aerosol volume concentrations which are typical for the intrusions of Saharan dust, with the lowest ozone values recorded for coarse-mode aerosol volumes of  $5\text{--}10 \mu\text{m}^3/\text{cm}^3$ . In fact, the high aerosol volume classes ( $>2\text{--}5 \mu\text{m}^3/\text{cm}^3$ ) occurred only during the Saharan dust events.

To further explore the relation between ozone concentrations and dust loading, three cases were distinguished, based on coarse-mode particle volume concentrations and the source region of back trajectories: (a) North African origin during dust events, (b) North African origin without dust loading, (c) all the other data. In order to select air masses coming from North Africa, we considered back-trajectories originating from a geographical box roughly coincident with the major dust production areas ( $10^\circ\text{N}\text{--}35^\circ\text{N}$ ;  $15^\circ\text{W}\text{--}30^\circ\text{E}$ ) as shown in Fig. 3. During the period of our study 18% of the calculated

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back-trajectories were characterized by a North African origin, and only the 30% of these were not accompanied by dust transport. In average the trajectories coming from North Africa are characterised by travel altitude of 2000–2500 masl. Figure 12 shows the mean ozone concentrations for the three classes and different months. Due to the few cases available for condition (b) in September and November, the ozone averaged values were not calculated for this case. In all months, (b) and (c) have comparable de-trended  $O_3$  concentrations, whereas for (a) the  $O_3$  level is significantly lower. Although there is a large variability in the ozone data during “dust events” (see Fig. 11), this analysis confirms that ozone concentrations during dust events are systematically reduced. In fact, air masses coming from the North Africa region during dust events are characterised by high values of the aerosol mean volumes (greater than about  $6.15 \mu\text{m}^3/\text{cm}^3$ ) and low detrended ozone concentrations ( $50 \pm 8$  ppbv) compared to mean values of  $0.92 \mu\text{m}^3/\text{cm}^3$  and  $54 \pm 6$  ppbv for African air masses without dust and  $0.63 \mu\text{m}^3/\text{cm}^3$  and  $55 \pm 6$  ppbv for all other data.

In summary, there is a clear statistical relationship between high dust loadings and low ozone concentrations. It is likely that this statistical relationship is due to the physical destruction of ozone on the surfaces of the dust aerosols, a mechanism that several authors (Schmitt et al., 1998; Zhang et al., 1994; Dentener et al., 1996) have suggested to be important. It cannot be ruled out entirely that this relationship is caused by differences in the source regions of the air masses and accompanying differences in the chemical composition of these air masses. Perhaps the dust-laden air masses already carried lower ozone concentrations before they received the dust injections. However, as the air masses arriving from the same North African source regions without dust had higher ozone concentrations than the dust-laden ones, this is an unlikely scenario. Furthermore, Saharan air masses usually travel at altitudes above about 800–700 mb (Sancho et al, 1992; Hamonou et al., 1999) and are very dry (Charlson and Prospero, 1972), as also seen in vertical profiles of humidity, temperature and ozone carried out at the S. Pietro Capofiume WMO station, which is located close to MTC (Bonasoni et al., 1998). Therefore, ozone destruction by homogeneous chemical reactions is very

slow in these air masses. Our air mass analysis thus provides independent confirmation of the hypothesis put forward in other studies (Hanisch and Crowley, 2003; Bauer et al., 2004) that significant heterogeneous ozone destruction occurs on the surfaces of the dust aerosols.

#### 5 4. Conclusions

In this paper we have investigated the relationship between tropospheric ozone and mineral aerosol in the free troposphere of the Northern Mediterranean basin during an experimental campaign performed at the Mt. Cimone baseline station in the period June–December 2000. Saharan dust transport episodes, occurring during this period, were identified using three-dimensional backward trajectories, TOMS aerosol index analysis, aerosol size and mass distribution concentrations. A statistical analysis of the back trajectories combined with the ozone, coarse and fine aerosol measurements as well as the TOMS aerosol index at the location of MTC was done. The result of the trajectory statistics are so-called concentration fields of the respective parameters, which indicate their source regions.

The ozone concentration field showed a positive gradient from North Africa to Europe, mainly due to the large differences between the anthropogenic emissions of ozone precursors, which characterise the two continental regions. In fact, the industrialised regions in North-central Europe and North–central Italy appear as the main source regions for both fine particles and surface ozone. Indeed, a significant positive correlation between surface ozone and fine aerosol concentrations has been found. On the contrary, the Saharan desert is the main source region for coarse particles, clearly suggesting desert dust as the main contributor to coarse-mode aerosols. Furthermore, we found a strong anticorrelation between the concentrations of coarse particles and ozone. When southerly winds transported dust clouds from North Africa to MTC, the concentrations of surface ozone at MTC showed a marked decrease compared to normal free-tropospheric conditions. On the other hand, there was only a slight reduction

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in the O<sub>3</sub> concentrations when air masses arriving from the South carried no dust. This suggests that high concentrations of coarse mineral aerosol in the atmosphere may lead to significant heterogeneous ozone destruction on the particle surface, thereby affecting the ozone concentrations even in areas very far away from the dust mobilization regions.

Finally, the close correlation between baseline (MTC) and urban (Po Valley) aerosol measurements shows that these dust transports can strongly affect the PM<sub>10</sub> concentrations in the urban and industrialized area of the Po Valley. In fact, the highest PM<sub>10</sub> concentrations in the Po Valley during the period of our study were almost all due to Saharan dust events, showing the significant influence of Saharan dust events on the air quality even in a polluted region of Southern Europe. This fact should be taken into account in the analysis of environmental pollution monitoring, when dust transport can contribute to the exceedances of the European air quality standards for PM<sub>10</sub> in urban and rural areas.

*Acknowledgements.* This work was supported by the European Commission (DG XII) within the framework of the MINATROC (EVK2-1999-00003) and STACCATO (EVK2-1999-00316) projects. We thank the “Ufficio Generale per la Meteorologia” of the Italian Air Force and P. Giambi, C. Magera, D. and P. Amidei for their support in the Mt. Cimone MINATROC field campaign. The authors would like to thank the “Agenzia Regionale Prevenzione e Ambiente – Emilia Romagna” (ARPA – ER) for their cooperation providing PM<sub>10</sub> data in the Po Valley. TOMS data were provided by NASA/Goddard Space Flight Center from their Web site. Images of SeaWiFS-NASA satellite as well as DREAM (Euro-Mediterranean Centre on Insular Coastal Dynamics – IcoD) and NAAPS (Naval Research Laboratory – NRL) analysis were provided by the Naval Research Laboratory (Monterey) from their Web site.

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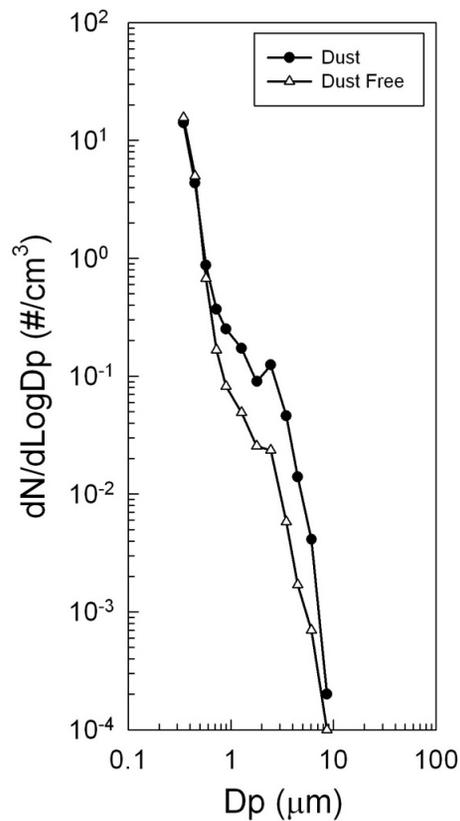
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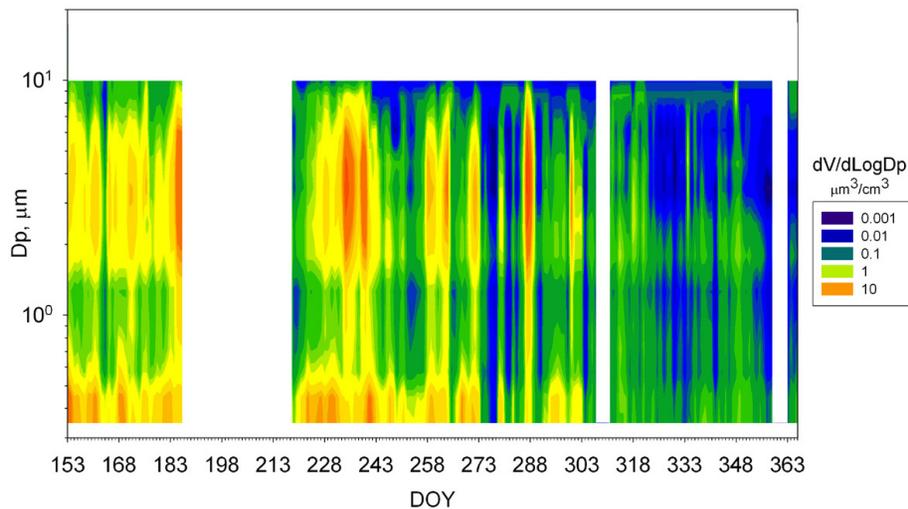


**Fig. 1.** Average aerosol number size distribution at MTC during dust events and dust-free conditions.

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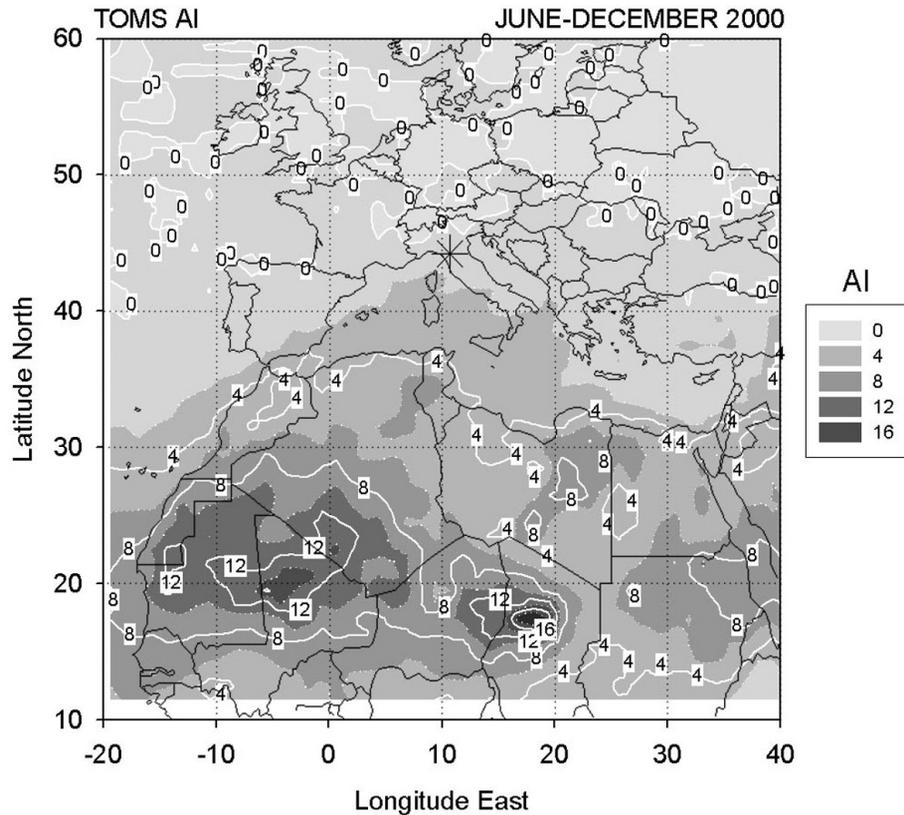


**Fig. 2.** Time series of the aerosol volume size distribution at MTC during the period June–December 2000.

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**Fig. 3.** Average spatial distribution of positive TOMS-AI over North Africa and Europe for the period June–December 2000.

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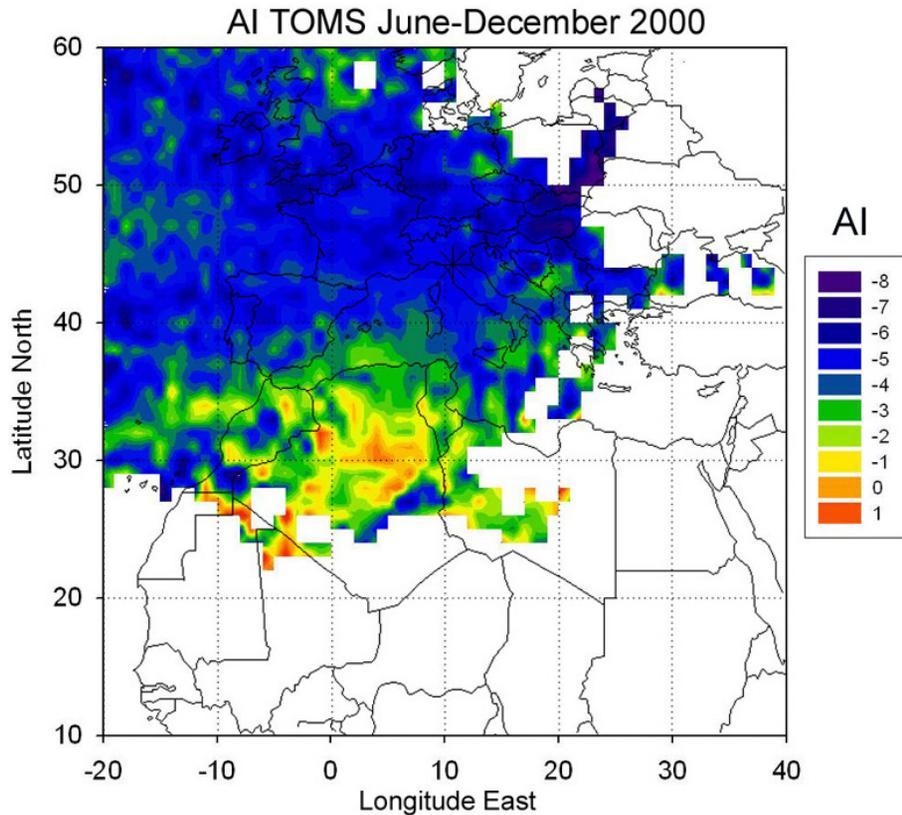
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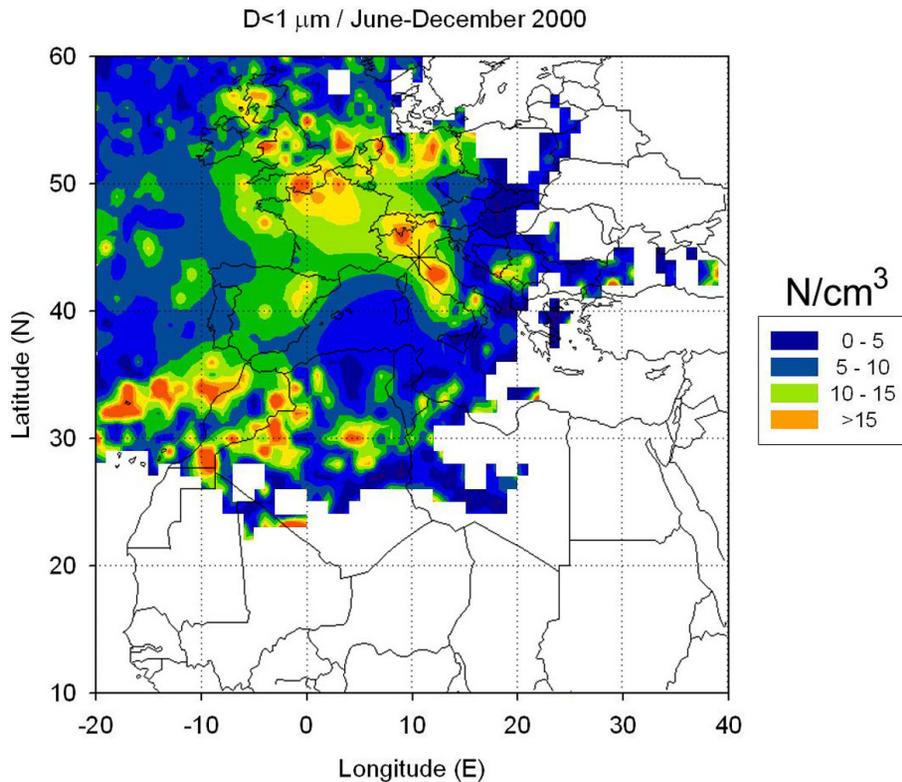


**Fig. 4.** Concentration field for TOMS-AI retrieved for the MTC pixel area as obtained by the trajectory statistical analysis, June–December 2000.

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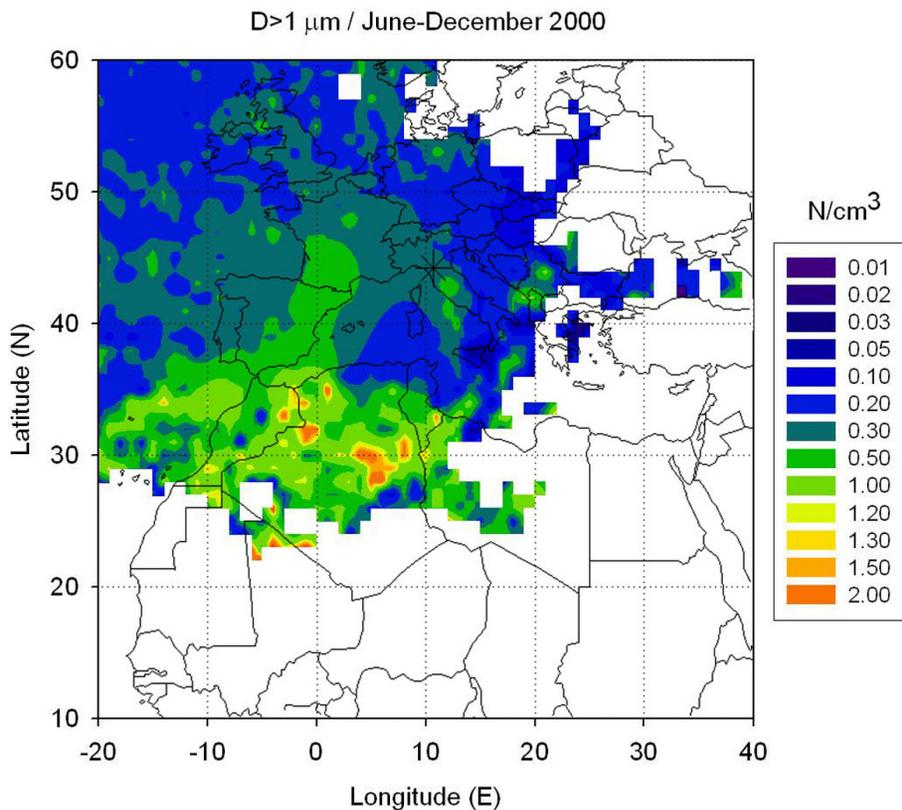


**Fig. 5.** Number concentration ( $\text{N}/\text{cm}^3$ ) field for fine aerosol ( $D_p < 1 \mu\text{m}$ ) as obtained by the trajectory statistical analysis. June–December 2000.

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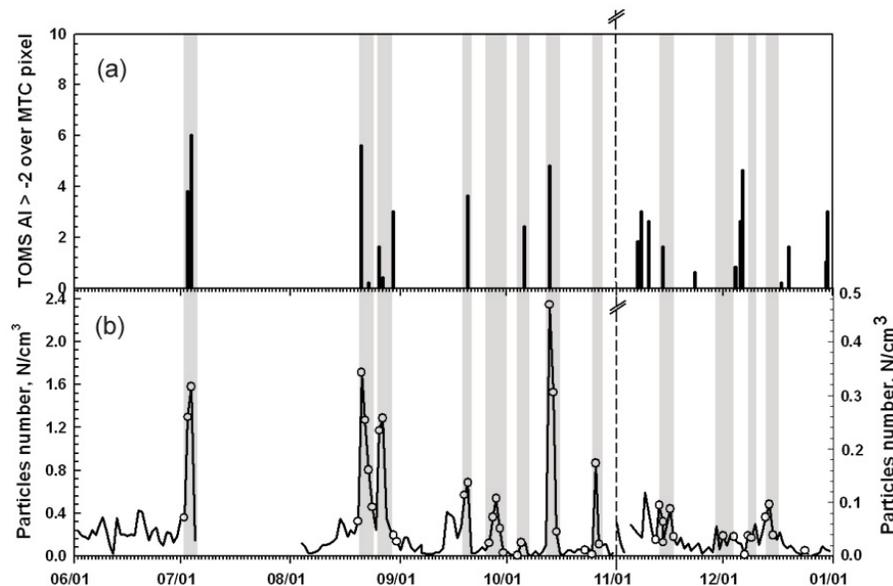


**Fig. 6.** Number concentration ( $\text{N}/\text{cm}^3$ ) field for coarse aerosol ( $D_p > 1\ \mu\text{m}$ ) as obtained by the trajectory statistical analysis. June–December 2000.

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**Fig. 7.** Daily positive values of TOMS-AI for the MTC pixel area **(a)** and coarse aerosol concentration recorded at Mt. Cimone **(b)** during the period June–December 2000 (November–December right scale). White circles represent days during which back-trajectories originated from North Africa. Grey bars represent the duration of the dust transport events.

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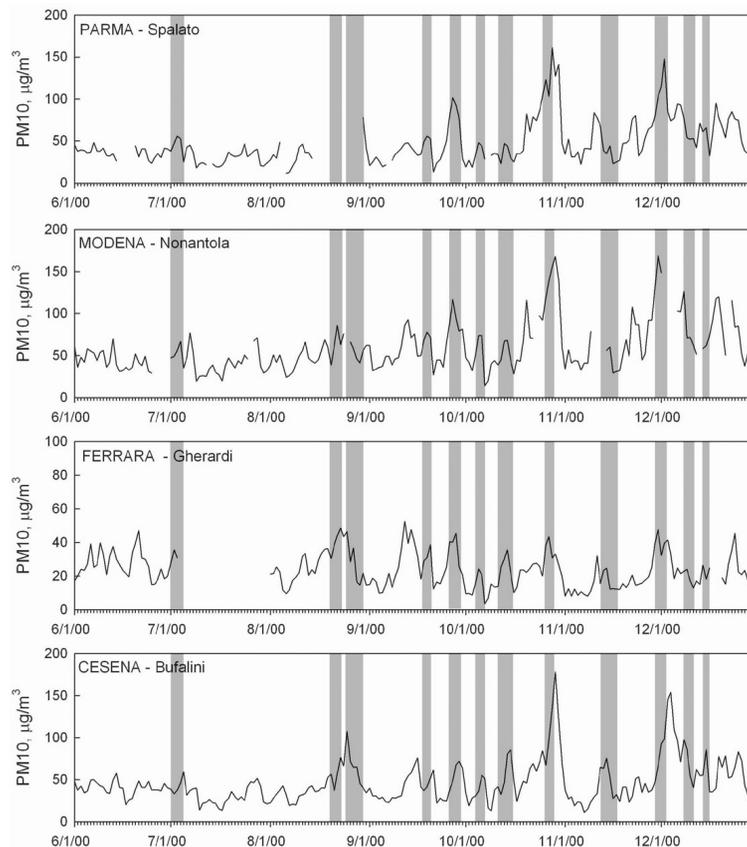
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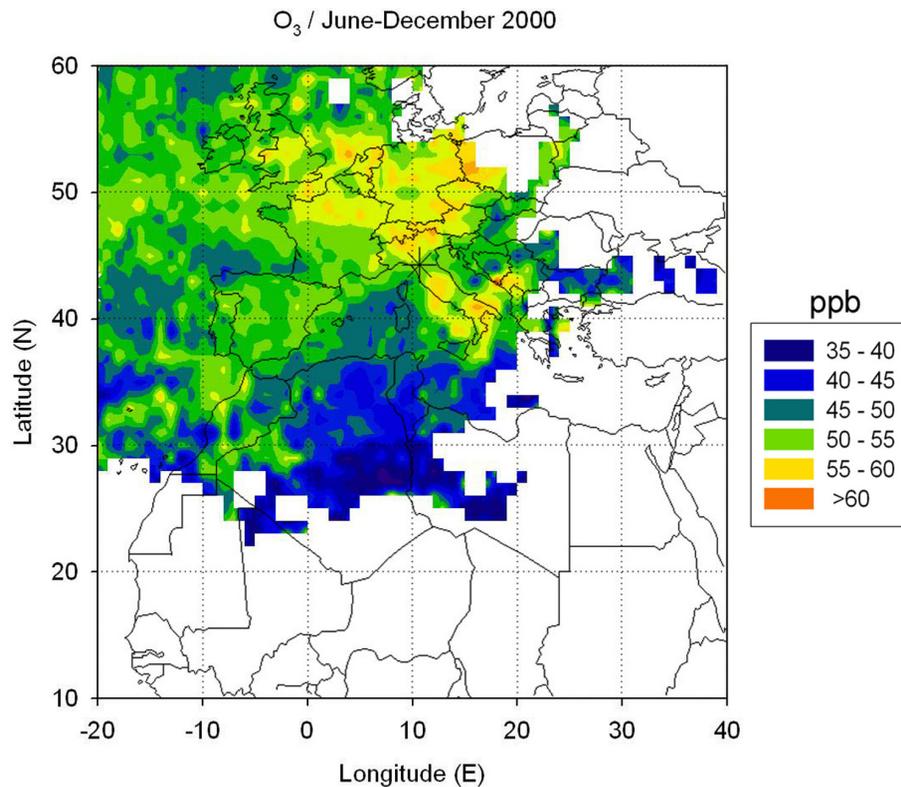


**Fig. 8.** Time series of PM<sub>10</sub> concentration measured in the Po Valley urban areas: Parma, Modena, Ferrara and Cesena from June to December 2000. Grey bars represent the duration of the dust transport events as identified at the MTC station.

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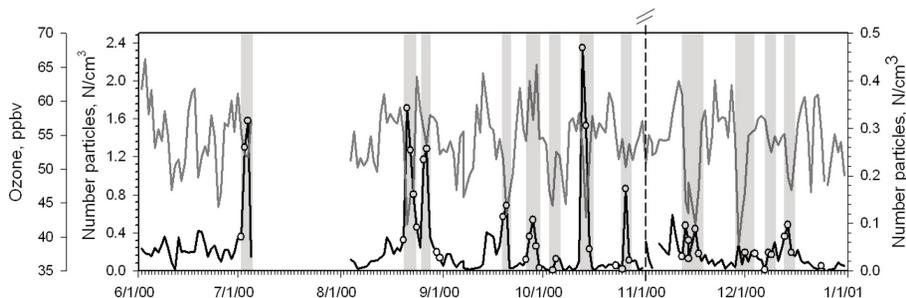


**Fig. 9.** Concentration field for ozone (ppb) as obtained by the trajectory statistical analysis, June–December 2000.

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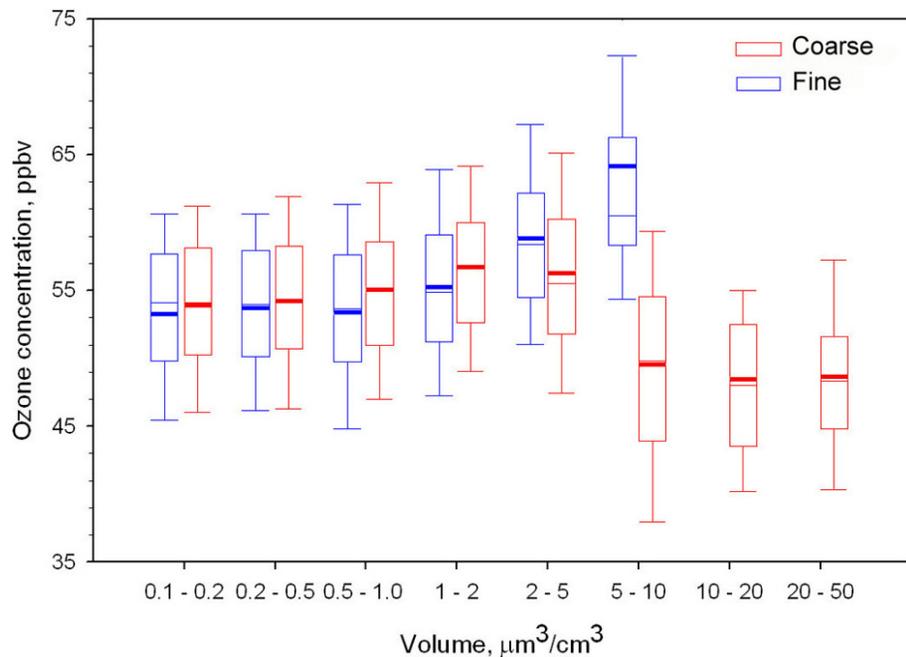


**Fig. 10.** Coarse aerosol concentration (black line) and de-trended ozone (grey line) recorded at MTC during the period June–December 2000 (for coarse aerosol: November–December right scale). White circles represent days during which back-trajectories originated from North Africa. Grey bars indicate the periods of the dust transport events. See text for the definition of the de-trended ozone concentration.

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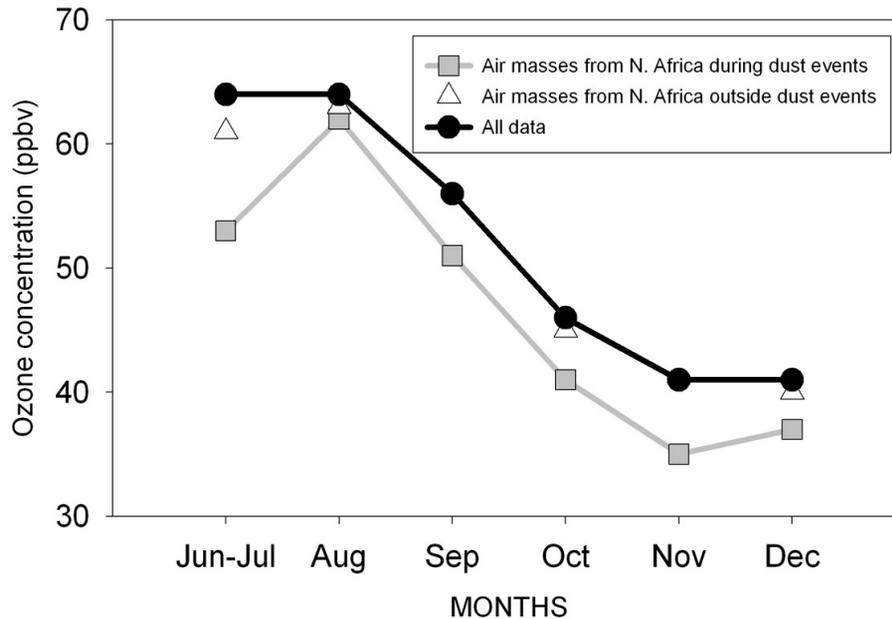


**Fig. 11.** Box-and-whiskers plot of de-trended ozone versus coarse and fine aerosol volume at MTC for the period from June to December 2000. The box and whiskers denote the 10, 25, 50, 75, and 90 percentiles and the bold lines the mean values of the ozone distributions. The statistics are based on the hourly mean values. The x-axis denotes the aerosol volume classes. Low ozone concentrations for high values of coarse volume are evident.

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**Fig. 12.** Monthly average values of ozone at MTC for three different situations, considering data for: air masses coming from North Africa during dust event (grey squares), dust-free air masses coming from North Africa (white triangles); all other air masses excluding transports from North Africa (black circles).

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