Ground-based assessment of Total Ozone Mapping Spectrometer (TOMS) data for dust transport over the northeastern Mediterranean

Nilgün Kubilay, Temel Oguz, and Mustafa Koçak
Institute of Marine Sciences, Middle East Technical University, Erdemli, Turkey

Omar Torres
Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, Maryland, USA

Received 16 September 2004; revised 11 January 2005; accepted 31 January 2005; published XX Month 2005.

[1] Multiyear daily surface aerosol aluminum (Al) concentration and sunphotometer measurements at Erdemli (Turkey) sampling station were used to assess the performance of Absorbing Aerosol Index (AAI) and Aerosol Optical Thickness (AOT) retrieved from the daily Total Ozone Mapping Spectrometer (TOMS) over the northeastern Mediterranean. A total of 98 moderate-to-high intensity dust events with durations from 1 day to 1 week were identified by aerosol Al concentrations and/or TOMS-AAI above their threshold values of 1.0 $\mu g\ m^{-3}$ and 0.5, respectively. Only 15 events were found to bring appreciable dust load into the northeastern Mediterranean, predominantly below the 850-hPa pressure level, and therefore were not detected effectively by TOMS. Eight of these events corresponded to short-range high intensity intrusions ($Al > 3.0\ \mu g\ m^{-3}$) from nearby dust sources of the Middle East and Arabian deserts, the rest (seven events) represented moderate-to-high intensity ($Al > 1.0\ \mu g\ m^{-3}$) long-range transport from North Africa. Given the highly complex dynamics of the region, the use of TOMS-AAI data is justified for monitoring Saharan dust transport characteristics in the northeastern Mediterranean. Moreover, the TOMS-AOT data were found to covary linearly with its counterpart obtained by the ground-based measurements (correlation coefficient 0.86, significant at <0.001), which lies within the range of estimates suggested by earlier studies.

Citation: Kubilay, N., T. Oguz, M. Koçak, and O. Torres (2005), Ground-based assessment of Total Ozone Mapping Spectrometer (TOMS) data for dust transport over the northeastern Mediterranean, *Global Biogeochem. Cycles*, *19*, XXXXXX, doi:10.1029/2004GB002370.

1. Introduction

[2] Being highly oligotrophic and limited with nutrient supply from rivers, atmospheric deposition in general and Saharan-based mineral dust in particular constitute an essential component of the biogeochemical cycle in the Mediterranean Sea. The Aeolian input of nutrients (phosphate and iron) acts as the most effective external source for promoting enhanced biological production locally and episodically in the sea [*Krom et al.*, 2004]. The measurements in the western basin [*Guieu et al.*, 2002a, 2002b] indicated that the contributions of phosphorus and iron from the Saharan dust account for ~30–40% and ~96% of their total atmospheric fluxes, respectively. Although the impact of Saharan dissolved inorganic phosphate for the new production at basin and annual scales may not be significant, its contribution on event timescale represents an important part of the integrated new production, as indicated by measurements in the western Mediterranean [*Ridame and Guieu*, 2002], in the central Mediterranean (Crete) and the eastern Mediterranean (Erdemli) [*Markaki et al.*, 2003] during stratified (summer-autumn) periods. Estimation of dust associated atmospheric nutrient fluxes indirectly by means of remote-sensing-derived products is an area of growing interest because of their capability of providing continuous time series data at different spatial resolutions.

[3] Total Ozone Mapping Spectrometer (TOMS)-Absorbing Aerosol Index (AAI) constitutes one of the most useful space-borne data sets, offering long-term daily and global information on UV absorbing aerosol (black carbon, desert dust) distributions [*Herman et al.*, 1997; *Torres et al.*, 1998]. A compilation of nearly 2 decades of data has already provided a more precise identification of tropospheric aerosol characteristics surrounding distinct source areas [e.g., σ, 2002; *Prospero et al.*, 2002; *Washington et al.*, 2003], and long-range transport over continents and oceans [e.g., *Hsu et al.*, 1999; *Chiapello et al.*, 1999; *Chiapello and Moulin*, 2002; *Moulin and Chiapello*, 2004]. It is therefore regarded as one of the potential sources for monitoring the dust transport characteristics in the

0886-6236/05/2004GB002370$12.00

Mediterranean region as well. In addition to the TOMS AAI, an aerosol optical depth product derived from TOMS observations is also available.

[4] TOMS-AAI data were used for the North Africa and Mediterranean regions by *Israelevich et al.* [2002] for identifying distinct North African desert dust aerosol sources, the way in which dust was transported eastward and northward, and the way it varied on a daily basis over the eastern (25°E–35°E), central (12°E–22°E), and western (0°–10°E) basins of the Mediterranean Sea. Apart from this work, only a few studies have dealt with the satellite-based characterization of dust transport over the Mediterranean. *Moulin et al.* [1998] presented the seasonal climatology of North African dust transport over the Mediterranean basin using dust optical thickness data for June 1983 through December 1994, retrieved from the daily visible radiances measured by Meteosat. A similar seasonal dust optical thickness variation over the Mediterranean was also obtained from MODIS data for the year 2001 by *Barnaba and Gobbi* [2004]. Using visible radiances from AVHRR on the NOAA-9 and NOAA-11 satellites over a 1-year period (August 1988 to September 1999), *Dayan et al.* [1991] examined some specific dust intrusion events in the central and eastern Mediterranean, and identified preferentially high or low altitude transports from two distinct sources: the Sahara and the Middle East-Arabian Desert. *Kubilay and Saydam* [1995] and *Kubilay et al.* [2000, 2003] noted individual contributions of these sources, together with distinctly different chemical and physical properties, to mineral dust loading in the northeastern Mediterranean atmosphere.

[5] So far, *Chiapello et al.* [1999] provided the only long-term independent data sets used for validating the temporal record of the TOMS-AAI. They documented the mineral dust transport characteristics across the North Atlantic by measuring ground-based mineral dust concentrations at four sampling stations (Sal Island, Tenerife, Barbados, and Miami). These measurements indicated that TOMS was able to detect 99% of the events recorded by surface dust concentration measurements at Tenerife station located at an altitude of 2400 m, well above the boundary layer and in a region of the troposphere where Saharan dust is usually transported. In contrast, monthly variations of the TOMS-AAI and surface mineral dust concentrations were shown to differ significantly at Sal Island. In winter, when dust was transported at low altitudes in the trade wind layer, surface measurements indicated high dust concentrations in contrast to threshold TOMS-AAI values of around 0.5. In summer, when dust transport switched to high altitude mode, the TOMS-AAI values attained a maximum (around 2–3), whereas surface dust concentrations decreased to their lowest levels. Surface measurements carried out at Barbados and Miami showed some capability for the TOMS-AAI in detecting high altitude African mineral dust transport events over the North Atlantic Ocean. Good agreement between the TOMS-AAI and surface dust concentrations was found over Israel for a strong dust storm event during 14–17 March 1998 [*Alpert and Ganor*, 2001].

[6] Our long-term (1991–1992, 1996–2002) daily surface aerosol aluminum (Al) concentration measurements performed at the Erdemli sampling site constitute yet another valuable independent data set for assessing the performance of the TOMS-AAI in the northeastern Mediterranean, and for exploring regional dust transport characteristics (e.g., frequency, direction, thickness, intensity of high and low altitude transports). Highly dynamic intrusions from different nearby sources (the Sahara in the south-southwest, the Middle East-Arabian Desert in the east-southeast, and Anatolia and the Balkans in the north-northwest) with a complex vertical structure [*Dayan et al.*, 1991; *Hamonou et al.*, 1999; *Kubilay et al.*, 2000, 2003; *Alpert et al.*, 2004] makes the northeastern Mediterranean an ideal test site for assessing the performance of TOMS products. In the present study, we first make use of all available TOMS-AAI data over the northeastern Mediterranean to point out the frequency, intensity, and seasonal patterns of specific intrusion events. The assessment of the use of the TOMS-AAI for detecting mineral dust aerosol content exported from different sources around our analysis region is then provided by means of daily aerosol Al concentration measurements. Finally, the TOMS Aerosol Optical Thickness (AOT) data are compared with the AOT data derived from the ground-based Sun photometer measurements to assess the performance of the AOT retrieval directly from the TOMS for northeastern Mediterranean conditions.

2. Data Description

[7] The 21-year-long (1979–1992 and 1996–2002) record of Absorbing Aerosol Index (TOMS-AAI) data were obtained from observations by the TOMS/Nimbus-7 (1979–1992) and TOMS/Earth Probe (1996–2002) sensors. The TOMS AAI is a very useful qualitative parameter for the detection of the presence in the atmosphere of UV-absorbing aerosols, and for the identification and analysis of dust and smoke transport patterns. Because of its qualitative nature, the TOMS-AAI is sensitive to absorbing aerosols even when mixed with clouds. The AAI data is available on a daily basis, on a 1° (latitude) by 1.25° (longitude) resolution. Positive TOMS-AAI values around our sampling station at Erdemli (see Figure 1 for its location) were obtained as an average of nine pixels in the small box confined by 33.0°E–35.5°E and 35.5°N–37.5°N.

[8] Aerosol data from TOMS observations is also available as AOT, obtained from a retrieval algorithm [*Torres et al.*, 1998, 2002], that uses as input the measured radiances at two near UV wavelengths (331 and 360 nm for the EP-TOMS sensor). The derived quantities are optical depth and single scattering albedo (SSA). Unlike the AAI, which is mainly sensitive to UV-absorbing aerosols, the TOMS near UV retrieval algorithm are sensitive to all aerosol types regardless of their altitude and absorption properties. Validation analysis of both the AOT [*Torres et al.*, 2002, 2005] and single scattering albedo [*Torres et al.*, 2005] using AERONET measurements, show that in general, the TOMS AOT retrievals are within 30% of the AERONET observations for absorbing aerosols and 20% for non-absorbing aerosols. The TOMS retrieved AOT and SSA are affected by cloud contamination, and, therefore, their temporal and

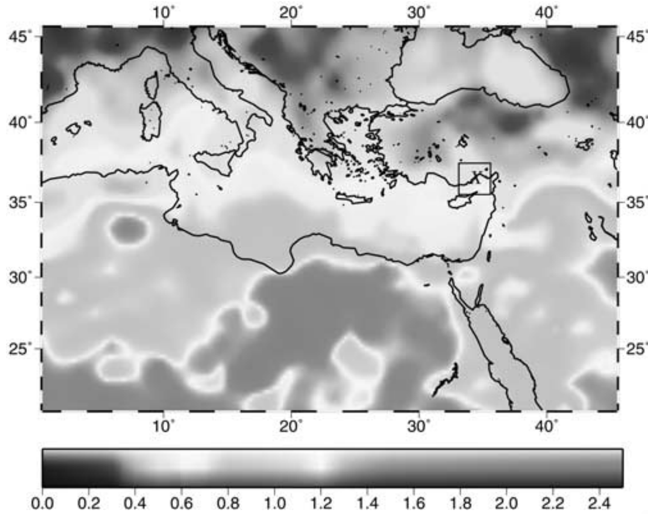

Figure 1. April-mean TOMS-AAI distribution obtained by averaging 21 years of daily data at each pixel of the analysis region. Three distinct regions with different TOMS-AAI properties are clearly indicated in the map. North Africa (red) identifies the major dust load (TOMS-AAI $\geq$ 1.0), whereas Southern Europe and Asia Minor (blue) (TOMS-AAI $\leq$ 0.4) represent a negligible dust load. The eastern Mediterranean is a transitional region with latitudinal TOMS-AAI variations between 1.0 in the south and 0.5 in the north. The Erdemli sampling station, as well as a small box around it, near the northeastern corner of the eastern Mediterranean is also shown in the figure. See color version of this figure at back of this issue.

spatial coverage are not as large as the coverage provided by the AAI.

[9] Ground-based aerosol sampling and analysis at the Erdemli coastal station were carried out during the periods of August 1991 through December 1992, January 1996 through May 1997, February 1998 through May 2000, and January 2001 through December 2002. Apart from some seasonal gaps in the data during the study period, measurements have sampling interruptions of a few days to a week every month due to the malfunctioning of sampling instrument. The sampling and analytical procedures together with some findings from these measurements were reported by *Kubilay and Saydam* [1995], *Kubilay et al.* [2000], and *Koçak et al.* [2004].

[10] As a part of the ground based Aerosol Robotic Network (AERONET) Program, the columnar integrated aerosol optical properties (e.g., aerosol optical thickness, single scattering albedo, Ångström coefficient, and refractive index) were retrieved daily at the Erdemli coastal station during the 1.5-year period from January 2000 through June 2001 as a product of direct sun radiance measurements by the CIMEL Sun photometer/sky radiometer [*Kubilay et al.*, 2003].

[11] Transport routes of air masses ending at our sampling site at 1000-, 850-, 700-, and 500-hPa pressure levels were determined by the three-dimensional, 3-day air mass back trajectory analysis using wind fields provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).

[12] Daily TOMS-AAI values corresponded to instantaneous satellite measurements made during the overpass once a day at about 1130 local time, whereas the daily aerosol Al concentrations were obtained by continuous sampling over a nominal 24-hour period. Similarly, the values of aerosol optical properties were based on the daily averaging of the measurements repeated every 15 min. Considering the fact that the dust concentrations may have a strong daily cycle [*Alpert and Ganor*, 2001] and satellite overpass time does not necessarily coincide with the time of typical dust loading, TOMS-AAI values thus may not truly represent the daily mean conditions as compared to the other two data sets. Reliability of once-a-day TOMS-AAI measurements is further hampered by cloudiness. The ground-based measurements include contribution of all aerosols, whereas the TOMS-AAI specifically represents the contribution by absorbing aerosols. These differences may introduce some difficulties and uncertainties in their comparisons.

3. Mineral Dust Over the Northeastern Mediterranean

3.1. Spatial Distribution of the TOMS-AAI

[13] The long-term mean April TOMS-AAI distributions computed by averaging 21 years of the daily data for UV-absorbing aerosols at each pixel of the region surrounded by 20.5°N and 45.5°N latitudes and 0.0° and 45.5°E longitudes is shown in Figure 1. April was specifically chosen since dust transports are particularly intensified over the eastern Mediterranean (hereinafter also referred to as EMed) atmosphere during this period (Figure 2) [see also *Ganor*, 1994; *Moulin et al.*, 1998; *Israelevich et al.*, 2002]. In general, the TOMS-AAI distribution reveals considerable latitudinal variations from the most intense dust load in the south to a negligible load over the continental landmass in the north. North Africa is characterized by highest dust accumulation with TOMS-AAI > 1.0. The red spot with TOMS-AAI$\sim$2.0 over the Eastern Sahara has been identified as "source region D" (centered at $\sim$25°N, 18°E) by *Israelevich et al.* [2002], and forms the northward extension of the Sahel to the south of 20°N. The red spot on the eastern end of the region represents either a local dust source over the Saudi Arabian Desert or eastward transport from the Sahara.

[14] The EMed atmosphere yields latitudinal TOMS-AAI variations between 1.0 and 0.6. This long-term mean dust distribution is, however, known to be modified by episodic dust intrusions, specific examples of which were provided earlier by *Kubilay and Saydam* [1995], *Özsoy et al.* [2001], *Alpert and Ganor* [2001], *Israelevich et al.* [2002], *Kubilay et al.* [2000; 2003], and *Koçak et al.* [2004]. The western Mediterranean atmosphere is, on the other hand, less affected by dust transports during this period. As reported by *Moulin et al.* [1998], *Israelevich et al.* [2002], and *Barnaba and Gobbi* [2004], the western basin receives the maximum dust transport in summer months. When long-term mean monthly data are taken into account, as shown in Figure 1, both North African and Middle East dust sources,

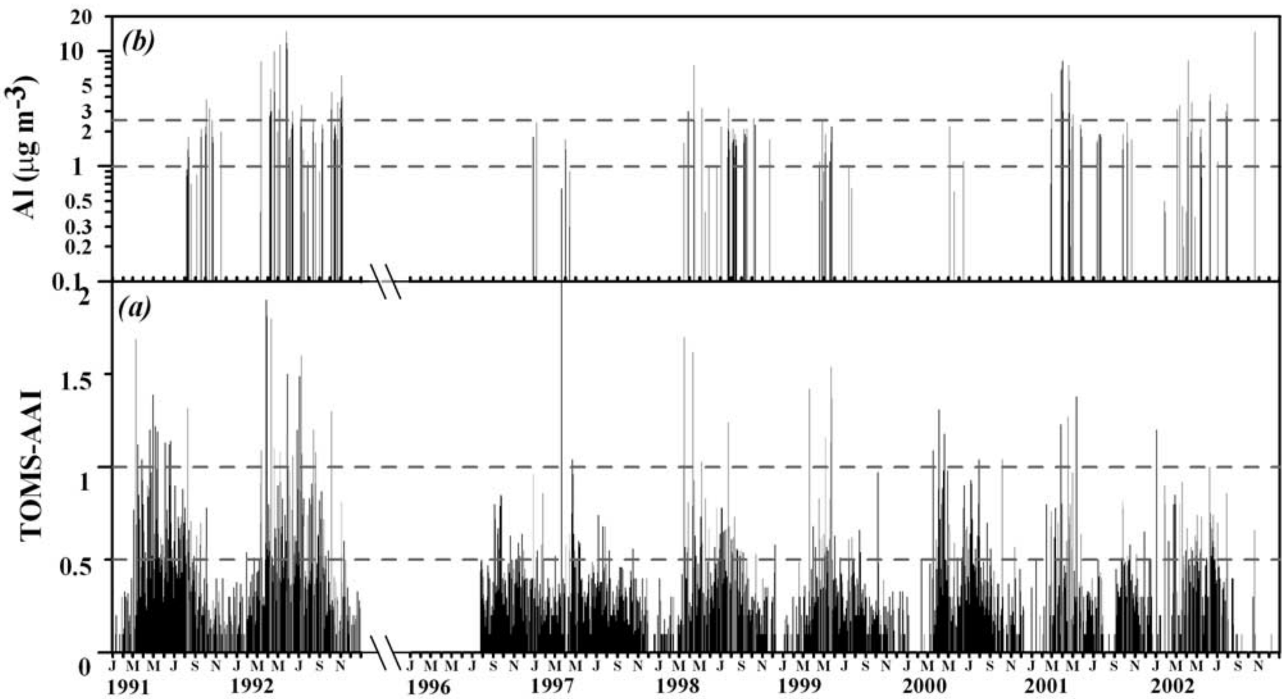

Figure 2. (a) Daily TOMS-AAI distribution around Erdemli during 9-year period from 1 January 1991 to 31 December 1992 and 26 July 1996 to 31 December 2002 (black bars). Superimposed on this data, red bars indicate dust events either with TOMS-AAI > 0.5 or aerosol Al > 1.0 or both, for common days with TOMS-AAI and aerosol Al data. Two broken horizontal lines represent the threshold AAI values for moderate and intense dust events classified on the basis of TOMS retrievals. (b) Daily aerosol Al (μg m^{-3}) measurements performed during the study period. The data represent a subset of all the available measurements corresponding to the events shown by red bars in Figure 2a. Two broken horizontal lines indicate the threshold values for moderate and intense dust events classified according to the ground-based measurements. See color version of this figure at back of this issue.

however, have limited intrusions over Anatolia and Southern Europe. TOMS-AAI values less than 0.5 for these regions are therefore considered to represent the background state with negligible spring dust transport.

3.2. Interannual Variations of the TOMS-AAI

[15] Figure 2a shows daily TOMS-AAI values within the box around our sampling station at Erdemli. Only the periods of 1991–1992 and 1996–2002, which are common with surface aerosol Al measurements, are given in this plot; other years possess similar features except for some year-to-year variations in terms of intensity and timing of events. Within the study period under consideration here, a total of 1070 common daily data pairs of the TOMS-AAI and surface aerosol Al concentrations were available at Erdemli. Only 225 of the events corresponded to dusty days, which are defined either by aerosol Al concentrations greater than 1.0 μg m^{-3} (Figure 2b) or by AAI values greater than 0.5 (shown in Figure 2a by red color), or both. These dust events with transports from the Sahara or the Middle East were further supported by the air mass back trajectory analysis. The rest, with values below the thresholds, represent the no-dust and/or negligible dust transport cases.

[16] Following *Herman et al.* [1997] and *Chiapello et al.* [1999], TOMS-AAI = 0.5 is chosen here as the threshold for TOMS detection of absorbing aerosols, even though any choice between 0.3 and 0.6 seems to be acceptable. Looking at the data in Figure 2a, this value may be considered a rather conservative choice for monitoring dust. In order to simplify the analysis, the dust transports inferred from the TOMS were classified as either "moderate intensity" for AAI values between 0.5 and 1.0 or "high intensity" for AAI $\geq$ 1.0. The latter threshold value was chosen somewhat arbitrarily on the basis of the data given in Figure 2a. Similar distinction was also adopted for identifying transports by the aerosol Al data. Following *Kubilay et al.* [2000], the moderate intensity events were classified by concentrations between 1.0 μg m^{-3} and 2.5 μg m^{-3}, and high intensity events by Al $\geq$ 2.5 μg m^{-3}. These boundaries were shown in Figures 2a and 2b by broken lines. There was, however, no particular reason for the choices of these thresholds except an overall assessment of the whole data set, and different values may in fact be assigned for other regions depending on local dust transport characteristics.

[17] The data shown in Figure 2a indicate a regular pattern of seasonal variations characterized by a lack of appreciable dust intrusions during the late autumn-winter months from November to the middle of March, and episodic enhanced dust outbreaks during the rest of the year. The most intensive events take place in the second half

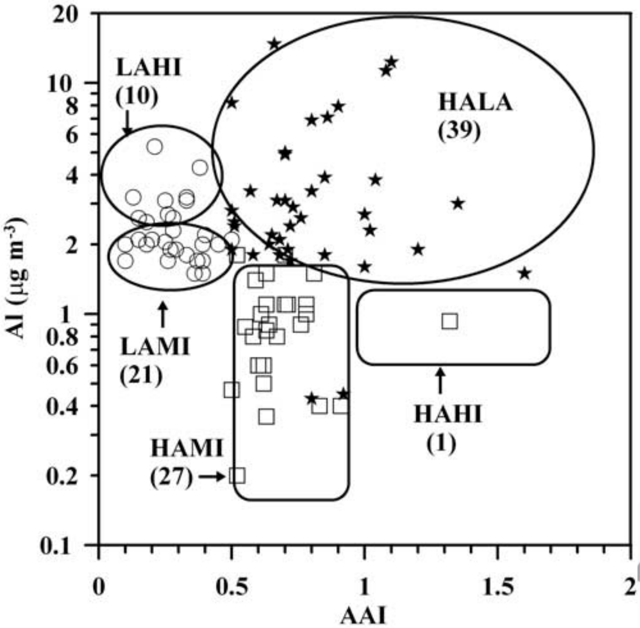

Figure 3. Scatterplot of aerosol Al concentrations and the corresponding TOMS-AAI values for the total of 98 events presented in Figure 2. HAMI and HAHI refer to "High Altitude Moderate Intensity" and "High Altitude High Intensity" modes, respectively, of dust transport. Similarly, LAMI and LAHI refer to "Low Altitude Moderate Intensity" and "Low Altitude High Intensity" modes, respectively. HALA mode denotes the dust events transported at both "High Altitude and Low Altitude". The numbers in parentheses show the number of total dust events for each particular mode.

of March, April, and May as also suggested previously by the dust optical thickness data [*Moulin et al.*, 1998; *Barnaba and Gobbi*, 2004], the TOMS-AAI data [*Israelevich et al.*, 2002], and the Sun photometer data [*Kubilay et al.*, 2003], as well as the ground-based aerosol measurements [*Kubilay et al.*, 2000]. Relatively strong dust intrusion events are also observed occasionally during the autumn until early November. The year 2002 was exceptional in terms of major dust transport period, which shifted earlier to January–March. These intrusions are characterized in our analysis region by 0.5 < TOMS-AAI < 1.0, indicating moderately intense dust loads. Their frequency is approximately 18% of the entire data set. More intense dust loads (TOMS-AAI > 1.0) are also noticeable in the data set. They constitute 3% of the entire data set, corresponding to six to eight events per year during the early 1990s, and decrease to one to three events per year toward the end of the 1990s and the early 2000s. The years 1996 and 1997 were particularly poor in terms of dust loading into the northeastern Mediterranean, even for moderate intensities. The decreased dust transport activity inside the Mediterranean basin during these years has been related to the North Atlantic Oscillation by *Moulin et al.* [1997]. The rest of the data set with TOMS-AAI $\leq$ 0.5 implies background conditions, without any dust transport signature. The entire late autumn-winter period as well as a part of summer season generally falls into this category, with a few exceptions.

3.3. Assessment of the TOMS-AAI

[18] Two-hundred-twenty-five days of the common data set of the dusty days shown in Figure 2 characterize 98 specific dust events with periods varying from 1 day to 1 week, but most commonly 2–3 days. If events lasted longer than 1 day, representative values of the TOMS-AAI and aerosol Al concentrations for each event were obtained by averaging their values over the duration of the event. The events are characterized by a wide range of aerosol Al concentrations and TOMS-AAI values: up to 15 μg m^{-3} for the former, and 1.6 for the latter. The "low altitude" transport to the analysis region is traced by the air mass back trajectories arriving at 1000- and 850-hPa pressure levels, and quantified by surface aerosol Al concentrations. The "high altitude" transport traced by air mass back trajectories arriving at the 700- and 500-hPa pressure levels, and intensity is quantified by the TOMS-AAI values. As mentioned in the preceding section, both high and low level transports were classified as either "moderate intensity" or "high intensity" according to pre-assigned threshold values of the aerosol Al concentration and TOMS-AAI. These modes of dust events over the northeastern Mediterranean are shown in Figure 3 by the scatterplot of the TOMS-AAI values versus aerosol Al concentrations.

[19] All together, 67 events involved high level transport (i.e., TOMS-AAI > 0.5). Their air mass back trajectories and the corresponding vertical motions during the last 3 days of their excursion (Figures 4a and 4b) suggest that an overwhelming proportion of the transport originated from the Sahara and at different altitudes. While most of the transports cross the EMed at preferentially high altitudes, some of them first start their excursion at lower levels and then rise toward higher levels on their way to the analysis region. In fact, 28 of these events attain no additional low level transport (since Al < 1.0 μg m^{-3}) and are considered to be confined to the levels above the 850-hPa pressure level. These are shown in Figure 3 by the high altitude–moderate intensity (HAMI), and the high altitude–high intensity (HAHI) modes. Thirty-nine of them are also accompanied with low level transport (since Al $\geq$ 1.0 μg m^{-3}) and therefore represent a vertically thicker and homogenous dust column (denoted by High Altitude Low Altitude, HALA mode in Figure 3).

[20] As documented in Table 1, 64 of the high level transports are directed from the south-southwest (S-SW), originating from the central and eastern Sahara, two from the north-northwest (N-NW) over western Anatolia and Balkans, and only one case from the southeast, Arabian Desert. Thus 96% of the events involve the long-range excursion of dust from the Sahara above 850 hPa. Moreover, 57 of these high altitude transports are classified as moderate intensity events with a mean AAI value of 0.68. The remaining 10 characterize high intensity events generally taking place in the spring months, with a mean AAI value of 1.17 (Table 1). As demonstrated by *Kubilay et al.* [2000] for selected events from 1992, and also described by *Moulin et al.* [1998] and *Israelevich et al.* [2002], these high

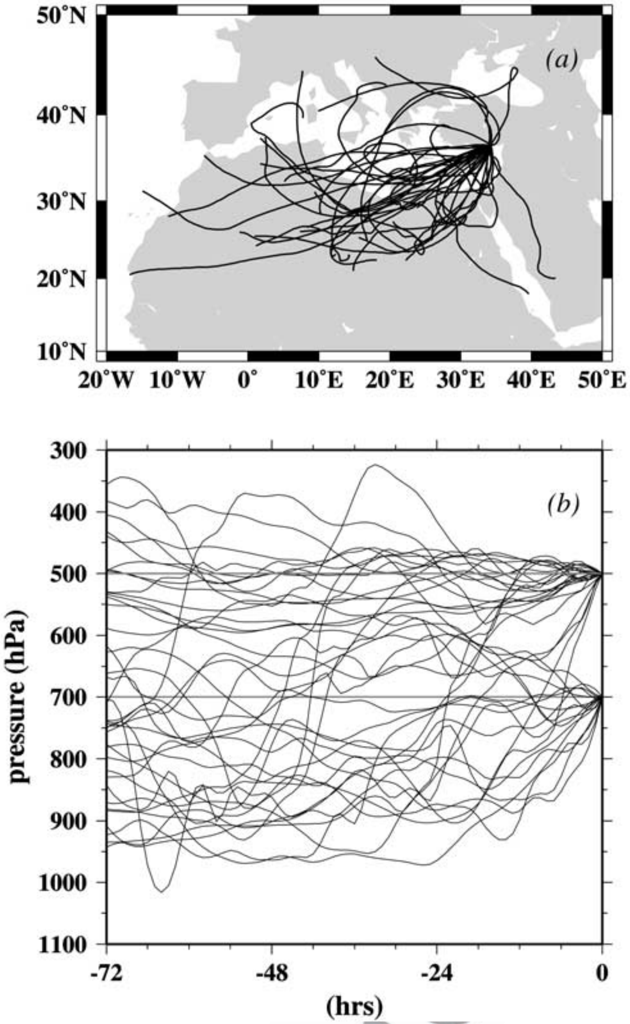

Figure 4. (a) Three-day back trajectories for high altitude transport events arriving at 700- and 500-hPa pressure levels to Erdemli, and (b) their vertical motions along the trajectories. They represent some selected events out of a total 67 during 1991–1992 and 1996–2002. See color version of this figure at back of this issue.

intensity spring events are generally products of dust storms associated with developing cyclones over the Sahara. As they form, these intense cyclones uplift substantial amounts of dust from the surface, ascend to higher altitudes by strong upward motion, and subsequently export dust to the north-eastern Mediterranean as they travel toward the east-north-east (see *Alpert and Ganor* [2001] for a specific case study). The remaining moderate intensity high level transports are suggested to be generally driven by mobilization of a dust load already accumulated at high altitudes of the atmosphere above North Africa in the spring-summer months by appropriate synoptic systems. As shown quantitatively by *Israelevich et al.* [2002], the flux of dust from sources in North Africa exceeds sinks due to the low settling and transport in spring and summer. As a result, the atmosphere over Northern Africa is almost permanently loaded with significant amounts of mineral desert dust. The major portion is exported over the North Atlantic [e.g., *Hsu et al.*, 1999; *Chiapello et al.*, 1999; *Chiapello and Moulin*, 2002; *Moulin and Chiapello*, 2004], but some moves northward over the eastern Mediterranean.

[21] The remaining 31 events are confined to the boundary layer (below 850 hPa) without any high altitude contribution when they arrive in the northeastern Mediterranean (Figure 5a). They correspond to low altitude–moderate intensity (LAMI) and low altitude–high intensity (LAHI) modes in Figure 3. They constitute ~30% of the total 98 events not captured by TOMS, as evident by the TOMS-AAI values of around 0.3 in our analysis region. A closer inspection of these low level only transport events suggests that 24 of them come from sources in close proximity of our analysis region, 16 from Anatolia (N-NW) with moderate aerosol Al concentrations of 1–2 $\mu g\ m^{-3}$ implying no appreciable dust input into the region, and eight from the Middle East (E-SE) with aerosol Al concentrations greater than 3 $\mu g\ m^{-3}$ (Table 2). These sources are very close to our analysis region for the establishment of the long-range, high altitude transports, and thus TOMS is unable to capture them. The remaining seven "low level" dust events represent high intensity long-range transport from the Sahara (S-SW) (see Figure 5b) with Al concentrations about 2–5 $\mu g\ m^{-3}$. Consequently, as far as long-range dust transport originated from North Africa is concerned, TOMS is unable to capture only seven events out of a total of 98. The use of TOMS-AAI data for monitoring Saharan dust transport characteristics in the northeastern Mediterranean is therefore justified, given its highly complex dynamic structure.

3.4. Comparison of TOMS and AERONET Optical Depth

[22] The quantitative use of the AAI as an indicator of aerosol amount is hampered by the multiple dependencies of the AAI on aerosol optical depth, elevation of the aerosol layer above the ground, absorption properties, and particle size distribution as documented in the literature [*Torres et al.*, 1998; *Herman et al.*, 1997]. Thus a more quantitative evaluation of the TOMS aerosol measurements can be carried out using the AOT product described in section 2.

[23] Using the TOMS-AOT orbital data averaged over a $2° \times 2°$ box centered at our site Erdemli (converted to 440 nm), the TOMS retrievals of aerosol optical thickness were compared to the ground-based AERONET observa-

Table 1. Summary Statistics of Total High Level Dust Transport Events With or Without the Accompanying Low Level Transports[a]

	Number of Events	Duration	AAI	Al, $\mu g\ m^{-3}$
		Intensity		
Moderate	57	130	0.68	2.33
High	10	22	1.17	1.13
		Direction		
S-SW	64	148	0.75	2.63
E-SE	1	2	0.70	4.9
N-NW	2	2	0.85	0.75

[a]Events are expressed in terms of intensity and direction, total duration, and mean values of the TOMS-AAI and aerosol Al concentrations.

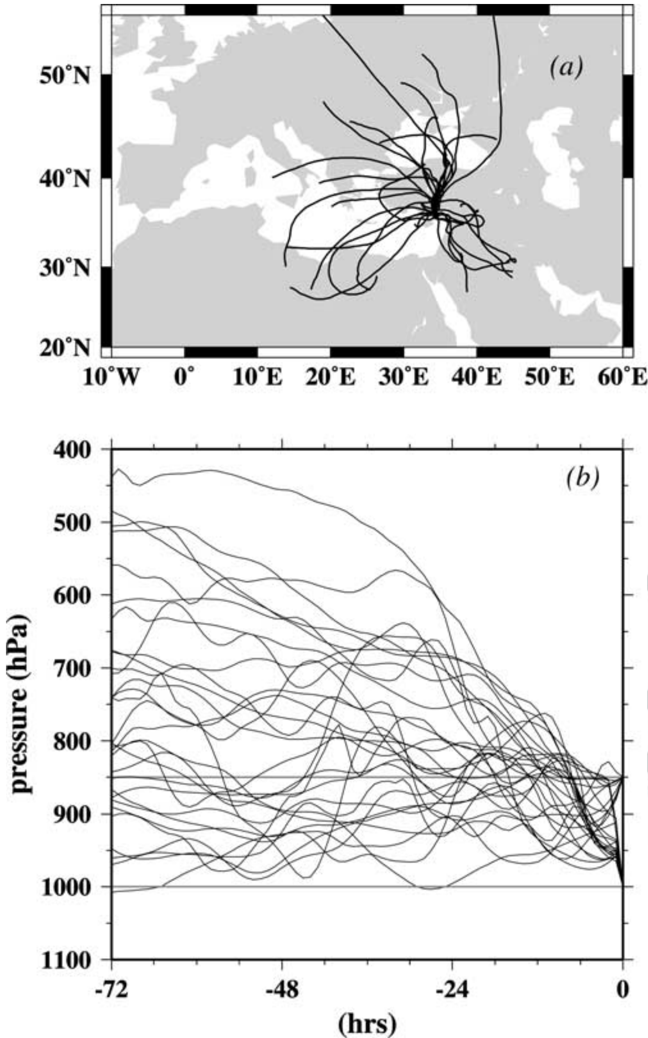

Figure 5. (a) Three-day back trajectories for low altitude transport events arriving at 1000- and 850-hPa pressure levels to Erdemli, and (b) their vertical motions along the trajectories. They represent some selected events out of a total 31 during 1991–1992 and 1996–2002. See color version of this figure at back of this issue.

tions for the period of January 2000 to June 2001. When all the AERONET data (a total of 116 measurements) were included, the scatterplot in Figure 6 depicts a linear fit (given by the thick continuous line) with the correlation coefficient 0.87 (significant at $p < 0.001$). The TOMS retrievals are found to account for 79% of the ground-based measurements. This level of agreement lies within the 30% range of theoretically predicted uncertainty [*Torres et al.*, 2002].

[24] As shown by *Kubilay et al.* [2003], a sharp drop in the Ångström coefficient to values near zero is among the most prominent features of dust episodes observed in the northeastern Mediterranean. Thus, when a subset of the AERONET data (41 measurements) was used representing specifically dust aerosols with the Ångström coefficient values less than 1.0, the agreement between the TOMS and AERONET measurements of AOT increases to 86% with the correlation 0.91 (see broken line in Figure 6). The difference between the AOT values of the TOMS and AERONET data sets is thus smaller, indicating a rather successful estimation of the AOT from TOMS for the northeastern Mediterranean. The difference can be explained by a combination of various factors such as sensitivity of the TOMS algorithm to the altitude of the mineral dust layer and sub-pixel cloud contamination, aerosol composition and size distribution, and sampling

Table 2. Summary Statistics of Low Level Transport Events Only, Without the Accompanying High Level Transports[a]

	Number of Events	Duration	AAI	Al, $\mu g\ m^{-3}$
		Intensity		
Moderate	21	57	0.31	1.9
High	10	17	0.29	3.3
		Direction		
S-SW	7	19	0.23	2.9
E-SE	8	14	0.29	2.8
N-NW	16	41	0.34	1.9

[a]Events expressed in terms of intensity and direction, total duration, and mean values of the TOMS-AAI and aerosol Al concentrations.

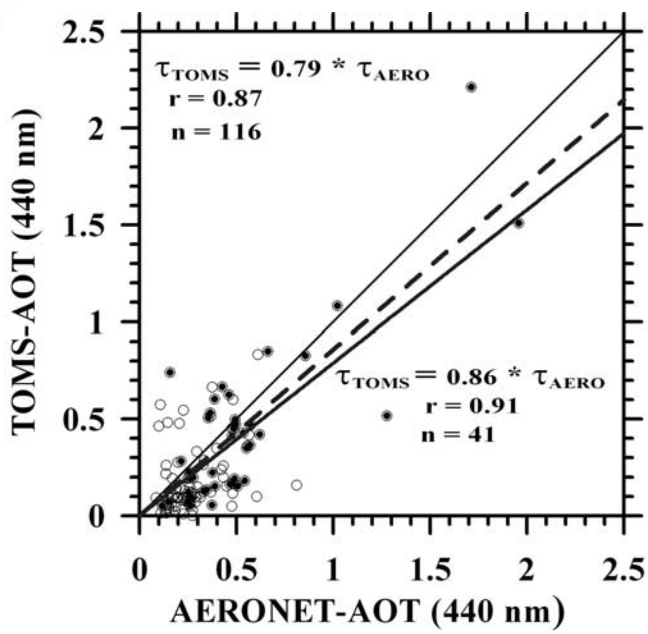

Figure 6. Scatterplot of TOMS-AOT versus AERONET-AOT at 440 nm for the northeastern Mediterranean during January 2000 to June 2001. The thin continuous line represents one-to-one line. The thick continuous line depicts the linear regression when all the available AERONET measurements (n = 116, open circles) are included. In this case, the data sets are related to each other linearly by $\tau_{TOMS} = 0.79\ \tau_{AERONET}$. The dashed line denotes the linear regression when a subset of the AERONET data (n = 41, solid circles) representing only the mineral dust cases with Ångström coefficient less than 1.0. Then, the data sets covary with the relation $\tau_{TOMS} = 0.86\ \tau_{AERONET}$.

frequency (daily for the sunphotometer versus instantaneous for TOMS).

4. Conclusions

[25] In the present study, the 21-year-long (1979–1992 and 1996–2002) daily Total Ozone Mapping Spectrometer Absorbing Aerosol Index (TOMS-AAI) and the multiyear (1991–1992, 1996–2002) daily surface aerosol aluminum (Al) concentration measurements at Erdemli sampling station were used to assess the capability of the TOMS-AAI in detecting mineral dust over the northeastern Mediterranean, when they are exported from North Africa and/or the Middle East.

[26] When all available common daily surface aerosol Al and TOMS-AAI measurements were taken into consideration (1070 data pairs in all), 98 specific dust events were identified for the northeastern Mediterranean. Seventy percent (67 events) involved moderate-to-intense high altitude transport. They were further accompanied with varying contributions of low level transport characterized by a wide range of surface aerosol Al concentrations, and mostly originated from the Sahara. The remaining 30% (31 events), on the other hand, predominantly took place below 850-hPa level, and were not detected effectively by TOMS. Sixteen of these low altitude events represented short-range dust intrusions from Anatolia and the Balkans in the north-northwest. They were weak-to-moderate intensity events, and therefore unable to introduce appreciable dust loads into the northeastern Mediterranean. Eight of the remaining 15 events corresponded to short-range high intensity intrusions from nearby dust sources of the Middle East, while the other seven events were ascribed to long-range transport from North Africa, undetected by TOMS. Given the highly complex dynamics of the region, the use of TOMS-AAI data is therefore justified for monitoring Saharan dust transport characteristics in the northeastern Mediterranean. Within the entire 21-year-long data set, moderate intensity ($0.5 <$ TOMS-AAI < 1.0) and high intensity (TOMS-AAI $\geq$ 1.0) contributions of Saharan-based dust outbreaks constituted 18% and 3% of events, respectively. They predominantly took place from mid-March to the end of August with the most intensive events observed in April–May. The rest, with TOMS-AAI $\leq$ 0.5, generally corresponded to negligible dust loads observed during the entire autumn-winter period, as well as a few isolated low level transports undetected by TOMS.

[27] Comparison of TOMS-retrieved AOT with its ground-based measurements suggests that the AOT can be estimated by TOMS reasonably well by a factor of 0.86. This value lies within the range of estimates at different oceanic and land sites by *Torres et al.* [2002].

[28] Our findings, when complemented with those of *Kubilay et al.* [2000], indicate that dust transport and deposition constitute a large fraction of annual dust deposition into the eastern Mediterranean. *Rutten et al.* [2000] have already noted a positive correlation between dust and surface chlorophyll concentrations and sediment trap data from a 3-year-long time series at ~34°N, 20°E. Thus TOMS aerosol data can be used to estimate regional dust transport and deposition, as recently provided for the Atlantic Ocean by *Kaufman et al.* [2005] using the Terra-MODIS products. This approach allows quantification of seasonally and regionally varying inputs of dust associated biologically available iron and phosphate flux into the sea.

[29] **Acknowledgments.** The authors would like to thank Brent Holben (NASA-GSFC) for providing us with the Sun photometer within the framework of the AERONET program, the NASA/GSFC/TOMS group for the use of TOMS-AAI data, and Emin Özsoy for making available the ECMWF trajectory analysis through collaboration with the Turkish State Meteorological Office. Finally, we appreciate the constructive remarks by the reviewers. This research was partly supported by the Middle East Technical University Research Funding AFP-2001-07-01-01, and the NATO Linkage Grant EST.CLG.977811.

References

Alpert, P., and E. Ganor (2001), Sahara mineral dust measurements from TOMS: Comparison to surface observations over the Middle East for the extreme dust storm, March 14–17, 1998, *J. Geophys. Res.*, *106*, 18,275–18,286.
Alpert, P., P. Kishcha, A. Shtivelman, S. O. Krichak, and J. H. Joseph (2004), Vertical distribution of Saharan dust based on 2.5-year model predictions, *Atmos. Res.*, *70*, 109–130.
Barnaba, F., and G. P. Gobbi (2004), Aerosol seasonal variability over the Mediterranean region and relative impact of maritime, continental and Saharan dust particles over the basin from MODIS data in the year 2001, *Atmos. Chem. Phys. Discuss.*, *4*, 4285–4337.
Chiapello, I., and C. Moulin (2002), TOMS and METEOSAT satellite records of the variability of Saharan dust transport over the Atlantic during the last two decades (1979–1997), *Geophys. Res. Lett.*, *29*(8), 1176, doi:10.1029/2001GL013767.
Chiapello, I., J. M. Prospero, J. R. Herman, and N. C. Hsu (1999), Detection of mineral dust over the North Atlantic Ocean and Africa with Nimbus 7 TOMS, *J. Geophys. Res.*, *104*, 9277–9291.
Dayan, U., J. Heffter, J. Miller, and G. Gutman (1991), Dust intrusion events into the Mediterranean basin, *J. Appl. Meteorol.*, *30*, 1185–1199.
Ganor, E. (1994), The frequency of Saharan dust episodes over Tel Aviv, Israel, *Atmos. Environ.*, *28*, 2867–2871.
Guieu, C., Y. Bozec, S. Blain, C. Ridame, G. Sarthou, and N. Leblond (2002a), Impact of high Saharan dust inputs on the dissolved iron concentrations in the Mediterranean Sea, *Geophys. Res. Lett.*, *29*(19), 1911, doi:10.1029/2001GL014454.
Guieu, C., M.-D. Loÿe-Pilot, C. Ridame, and C. Thomas (2002b), Chemical characterization of the Saharan dust end-member: Some biogeochemical implications for the western Mediterranean Sea, *J. Geophys. Res.*, *107*(D15), 4258, doi:10.1029/2001JD000582.
Hamonou, E., P. Chazette, D. Balis, F. Dulac, X. Schneider, E. Galani, G. Ancellet, and A. Papayannis (1999), Characterization of the vertical structure of Saharan dust export to the Mediterranean basin, *J. Geophys. Res.*, *104*, 22,257–22,270.
Herman, J. R., P. K. Bhartia, O. Torres, C. Hsu, C. Seftor, and E. Celarier (1997), Global distribution of UV-absorbing aerosols from Nimbus 7/TOMS data, *J. Geophys. Res.*, *102*, 16,911–16,922.
Hsu, N. C., J. R. Herman, O. Torres, B. N. Holben, D. Tanré, T. F. Eck, A. Smirnov, B. Chatenet, and F. Lavenu (1999), Comparisons of the TOMS aerosol index with sun-photometer aerosol optical thickness: Results and applications, *J. Geophys. Res.*, *104*, 6269–6279.
Israelevich, P. L., Z. Levin, J. H. Joseph, and E. Ganor (2002), Desert aerosol transport in the Mediterranean regions as inferred from the TOMS aerosol index, *J. Geophys. Res.*, *107*(D21), 4572, doi:10.1029/2001JD002011.
Kaufman, Y. J., I. Koren, L. A. Remer, D. Tanré, P. Ginoux, and S. Fan (2005), Dust transport and deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean, *J. Geophys. Res.*, doi:10.1029/2003JD004436, in press.
Koçak, M., M. Nimmo, N. Kubilay, and B. Herut (2004), Spatio-temporal aerosol trace metal concentrations and sources in the Levantine basin of the eastern Mediterranean, *Atmos. Environ.*, *38*, 2133–2144.
Krom, M. D., B. Herut, and R. F. C. Mantoura (2004), Nutrient budget for the eastern Mediterranean: Implications for phosphorus limitation, *Limnol. Oceanogr.*, *49*(5), 1582–1592.
Kubilay, N., and C. Saydam (1995), Trace elements in atmospheric particulates over the eastern Mediterranean: Concentrations, sources and temporal variability, *Atmos. Environ.*, *29*, 2289–2300.

Kubilay, N., S. Nickovic, C. Moulin, and F. Dulac (2000), An illustration of the transport and deposition of mineral dust onto the eastern Mediterranean, *Atmos. Environ.*, *34*, 1293–1303.

Kubilay, N., T. Cokacar, and T. Oguz (2003), Optical properties of mineral dust outbreaks over the northeastern Mediterranean, *J. Geophys. Res.*, *108*(D21), 4666, doi:10.1029/2003JD003798.

Markaki, Z., K. Oikonomou, M. Kocak, G. Kouvarakis, A. Chaniotaki, N. Kubilay, and N. Mihalopoulos (2003), Atmospheric deposition of inorganic phosphorus in the Levantine Basin, eastern Mediterranean: Spatial and temporal variability and its role in seawater productivity, *Limnol. Oceanogr.*, *48*(4), 1557–1568.

Moulin, C., and I. Chiapello (2004), Evidence of the control of summer atmospheric transport of African dust over the Atlantic by Sahel sources from TOMS satellites (1979–2000), *Geophys. Res. Lett.*, *31*, L02107, doi:10.1029/2003GL018931.

Moulin, C., C. E. Lambert, F. Dulac, and U. Dayan (1997), Control of atmospheric export of dust from North Africa by the North Atlantic Oscillation, *Nature*, *387*, 691–694.

Moulin, C., et al. (1998), Satellite climatology of African dust transport in the Mediterranean atmosphere, *J. Geophys. Res.*, *103*, 13,137–13,144.

Özsoy, E., N. Kubilay, S. Nickovic, and C. Moulin (2001), A hemispheric dust storm affecting the Atlantic and Mediterranean in April 1994: Analyses, modeling, ground-based measurements and satellite observations, *J. Geophys. Res.*, *106*, 18,439–18,460.

Prospero, J. M., P. Ginoux, O. Torres, S. Nicholson, and T. Gill (2002), Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Rev. Geophys.*, *40*, 1–31.

Ridame, C., and C. Guieu (2002), Saharan input of phosphate to the oligotrophic water of the open western Mediterranean Sea, *Limnol. Oceanogr.*, *47*(3), 856–869.

Rutten, A., G. J. de Lange, P. Ziveri, J. Thomson, P. J. M. van Santvoort, S. Colley, and C. Corselli (2000), Recent terrestrial and carbonate fluxes in the pelagic eastern Mediterranean: A comparison between sediment trap and surface sediment, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *158*, 197–213.

Torres, O., P. K. Bhartia, J. R. Herman, Z. Ahmad, and J. Gleason (1998), Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation: Theoretical basis, *J. Geophys. Res.*, *103*, 17,099–17,110.

Torres, O., P. K. Bhartia, J. R. Herman, A. Sinyuk, P. Ginoux, and B. Holben (2002), A long-term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements, *J. Atmos. Sci.*, *59*, 398–413.

Torres, O., P. K. Bhartia, A. Sinyuk, E. J. Welton, and B. Holben (2005), Total Ozone Mapping Spectrometer measurements of aerosol absorption from space: Comparison to SAFARI 2000 ground-based observations, *J. Geophys. Res.*, doi:10.1029/2004JD004611, in press.

Washington, R., M. Todd, N. J. Middleton, and A. Goudie (2003), Dust-storm source areas determined by the total ozone monitoring spectrometer and surface observations, *Ann. Assoc. Am. Geogr.*, *93*(2), 297–313.

M. Koçak, N. Kubilay, and T. Oguz, Institute of Marine Sciences, Middle East Technical University, ODTU-DBE, P.K. 28 Erdemli 33731, Turkey. (mustafa@ims.metu.edu.tr; kubilay@ims.metu.edu.tr; oguz@ims.metu.edu.tr)

O. Torres, Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, MD, USA. (torres@qhearts.gsfc.nasa.gov)

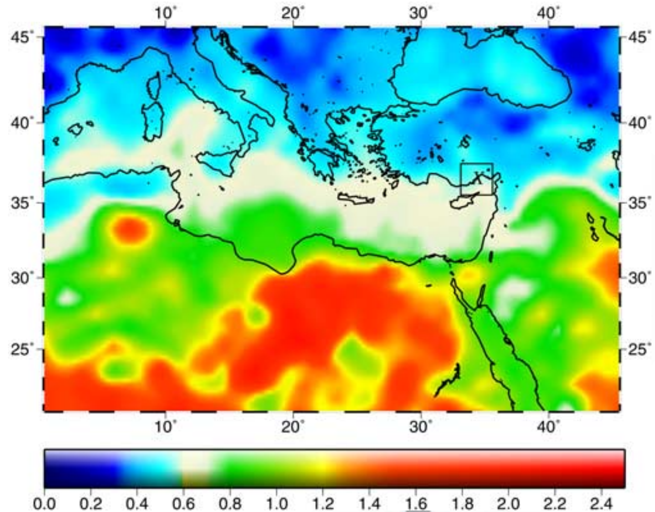

Figure 1. April-mean TOMS-AAI distribution obtained by averaging 21 years of daily data at each pixel of the analysis region. Three distinct regions with different TOMS-AAI properties are clearly indicated in the map. North Africa (red) identifies the major dust load (TOMS-AAI $\geq$ 1.0), whereas Southern Europe and Asia Minor (blue) (TOMS-AAI $\leq$ 0.4) represent a negligible dust load. The eastern Mediterranean is a transitional region with latitudinal TOMS-AAI variations between 1.0 in the south and 0.5 in the north. The Erdemli sampling station, as well as a small box around it, near the northeastern corner of the eastern Mediterranean is also shown in the figure.

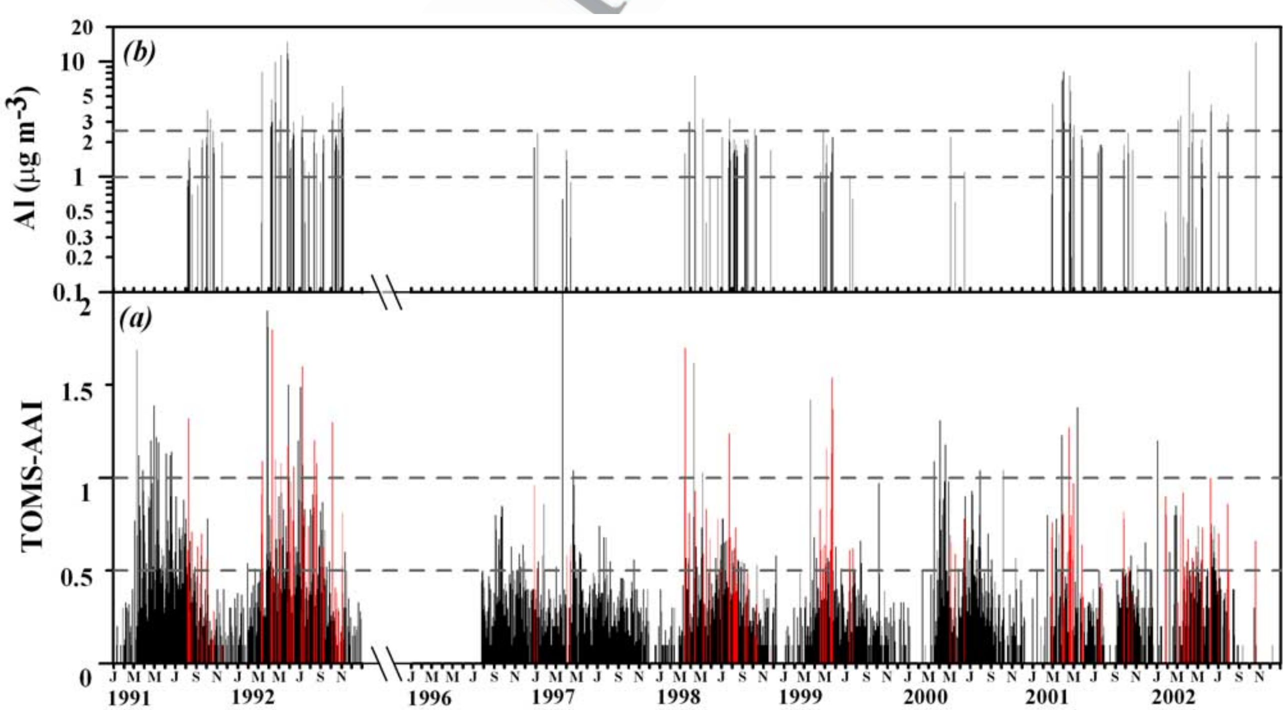

Figure 2. (a) Daily TOMS-AAI distribution around Erdemli during 9-year period from 1 January 1991 to 31 December 1992 and 26 July 1996 to 31 December 2002 (black bars). Superimposed on this data, red bars indicate dust events either with TOMS-AAI > 0.5 or aerosol Al > 1.0 or both, for common days with TOMS-AAI and aerosol Al data. Two broken horizontal lines represent the threshold AAI values for moderate and intense dust events classified on the basis of TOMS retrievals. (b) Daily aerosol Al (μg m^{-3}) measurements performed during the study period. The data represent a subset of all the available measurements corresponding to the events shown by red bars in Figure 2a. Two broken horizontal lines indicate the threshold values for moderate and intense dust events classified according to the ground-based measurements.

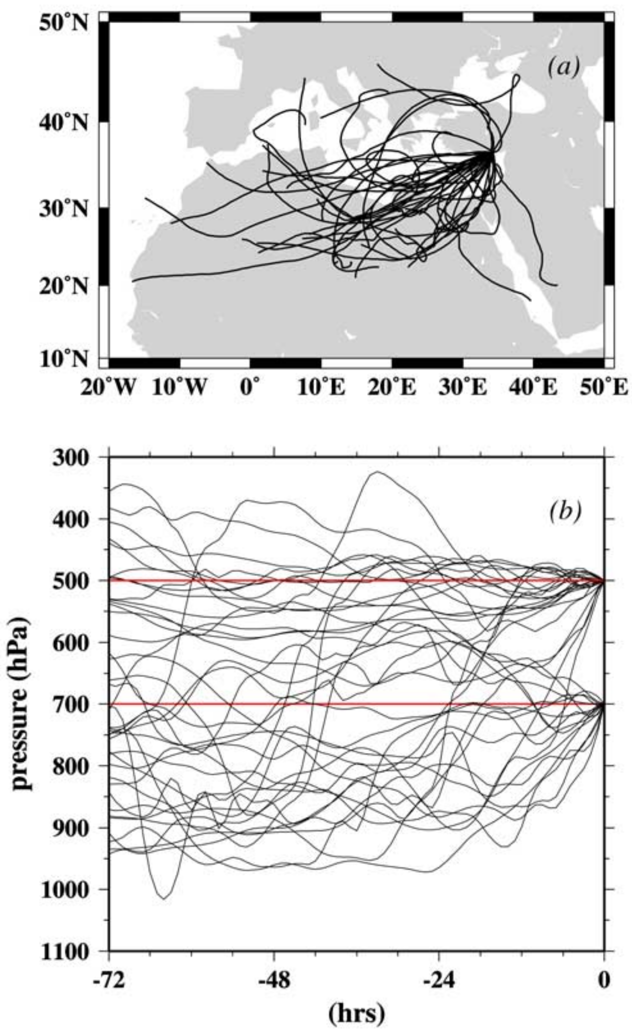

Figure 4. (a) Three-day back trajectories for high altitude transport events arriving at 700- and 500-hPa pressure levels to Erdemli, and (b) their vertical motions along the trajectories. They represent some selected events out of a total 67 during 1991–1992 and 1996–2002.

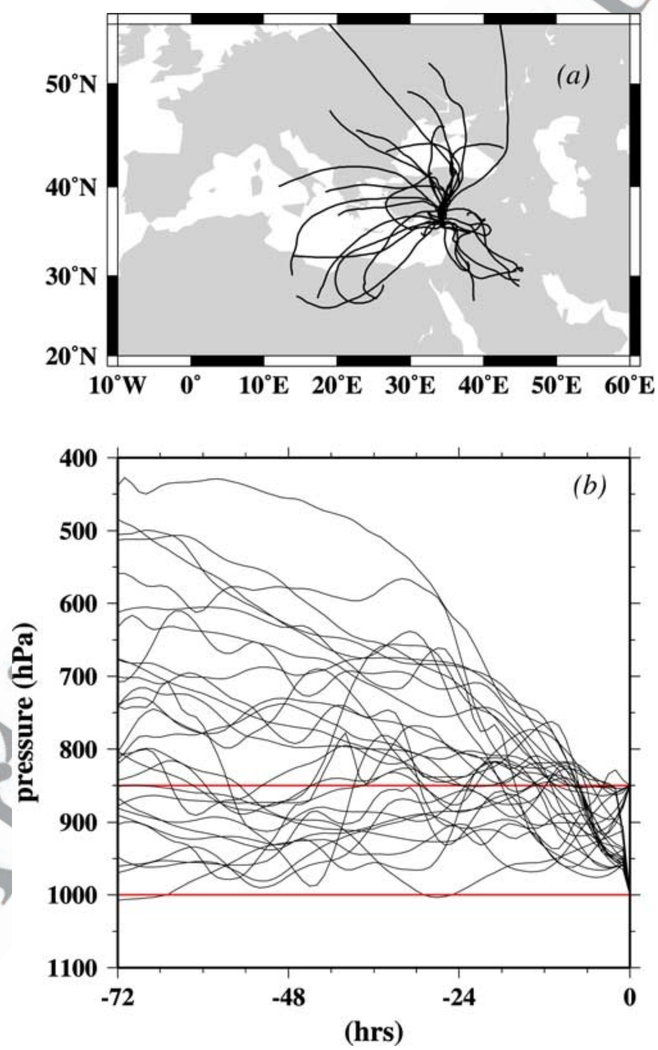

Figure 5. (a) Three-day back trajectories for low altitude transport events arriving at 1000- and 850-hPa pressure levels to Erdemli, and (b) their vertical motions along the trajectories. They represent some selected events out of a total 31 during 1991–1992 and 1996–2002.