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A study of an INDOEX period with aerosol transport to the eastern Mediterranean area

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[1] Forward trajectories of the air masses from the Arabian Sea area were computed for each day from February 1 to April 10, 1999. This allowed the determination of the episodes characterized by the air mass transport to Africa and the Mediterranean region. Numerical simulation of one of such episodes, also characterized by intense cyclone and dust plume development, was performed using the Eta weather and dust predicting system. The simulation allowed an evaluation of the vertical distribution of the pollutants in the cyclone. Backward trajectories, ending in the area of the cyclone development point to the origin of a part of its air masses over the Arabian Sea. Potential role of the eastern Mediterranean weather systems in the transport to Europe of the polluted air masses from the INDOEX area is discussed. *INDEX TERMS:* 1704 History of Geophysics: Atmospheric sciences; 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); *KEYWORDS:* Arabian Sea, Mediterranean, INDOEX, aerosol transport, cyclone, dust plume

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1. Introduction

[2] The Asian/African winter monsoon is characterized by persistent northeastern air mass transport from the Indian subcontinent region into those of the Arabian Sea and equatorial area of the Indian Ocean. The process has significant implications to atmospheric chemistry effects on the global scale. Intensity of the pollution increases with the rapid economic development of the region and becomes an important component of the global warming process. International Indian Ocean Experiment (INDOEX, http://www-indoex.ucsd.edu) with its Intensive Field Phase (IFP) during January–March 1999 has been performed with the aim of analysis of the role of aerosols, clouds and tropospheric chemistry processes in the regional and global atmospheric developments. The main target of the experiment was to investigate the processes associated with the interaction of pristine air masses from the southern Indian Ocean and polluted air from the Indian subcontinent during the Asian/African winter monsoon.

[3] Main interactions take place over the equatorial area of the Indian Ocean. Africa and the Mediterranean region, however, also experience the winter monsoon effects. Low-troposphere northeast flows over the Arabian Sea play a role in the development of typical Eastern Mediterranean (EM) systems such as the Red Sea Trough [e.g., *Ashbel*, 1938; *Itzikson*, 1995; *Krichak and Alpert*, 1998; *Krichak et al.*, 1997a, 1997b, 2000]. This opens a way for a direct transport of the polluted air masses from the Indian subcontinent to Europe.

[4] During the dry monsoon period the air masses flowing over the Arabian Sea contain black carbons, sulfates and other anthropogenic aerosols. On the average, advection of the pollutants to northern Africa is relatively low. Optical depth calculations in the sulfate transport study by *Pham et al.* [1995] demonstrated gradual south-west propagation of the zone with high level of pollution during the winter-spring period. In January, relatively small amounts of the black carbon and sulfate are transported from the Indian subcontinent to the Arabian Sea. By April, however, significant amounts of black carbon and sulfate are transported over the southern area of the Arabian Sea. A significant part of the aerosols reach equatorial Africa and in some cases the Mediterranean region. Climatological consequences of the process in the equatorial Indian Ocean have already been proven [*Podgorny et al.*, 2000, 2001; *Ramanathan et al.*, 2001a, 2001b]. The potential role of the transport of the pollutants to Africa, the Mediterranean area, and then to Europe has not yet been investigated accordingly.

[5] The aim of the current study was to analyze the atmospheric conditions, which characterize episodes with such effects based on the data of the INDOEX 1999 IFP period. Forward air mass trajectories from the Arabian Sea area were computed for each day from February 1 to April 10, 1999. This allowed the determination of the episodes with the air mass transport to Africa and the Mediterranean region. Numerical simulation of one of such episodes characterized by intense cyclone and dense mineral dust plume development was performed using the Eta weather and dust predicting system [*Kallos et al.*, 1997; *Mesinger et*

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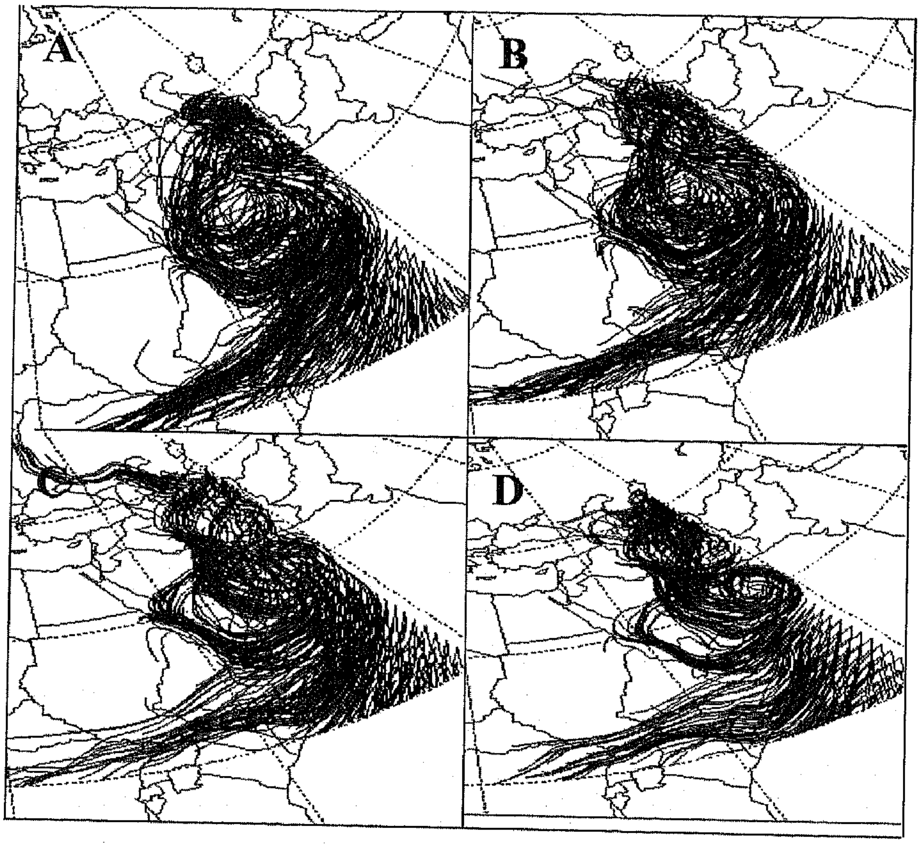

Figure 1. Forward 5-day trajectories originated in the 1000–700 hPa layer from an Arabian Sea area indicated in Figure 6 (0°–40°N; 50°E–60°E) at 0000 UTC: (a) 17, (b) 18, (c) 19, and (d) 20 of March 1999.

al., 1988; *Nickovic et al.*, 1997b; *Nickovic and Dobricic*, 1996]. The model-simulated mineral dust concentrations were considered as a 'tracer' for the determination of the cyclone associated air pollution. The model results were used for the determination of the area of the origin of the air masses that participated in the cyclone development. The area was specified with the help of the backward trajectories, ending in the area of the cyclone development.

2. Air Mass Trajectories From the Arabian Sea During February–April 1999

[6] An advanced package for the three-dimensional trajectory calculation [*Wernli and Davies*, 1997] was applied for tracing the propagation of the air masses from the Arabian Sea to Africa. The tool allows three-dimensional (x, y, p) determination of the forward and backward trajectories based on the gridded model-predicted or analysis data. The procedure for objective identification of the different air streams consists of two steps: First, tracks of all air parcels are computed and, second, the ensembles of the trajectories are identified employing selected threshold criteria. Examples of application of the tool for the analysis of the EM weather developments have been presented [e.g., *Tsidulko and Alpert*, 2002; *Krichak and Alpert*, 1998]. The National Center for Environmental Prediction (NCEP) objective analyses data available with 1.25 deg resolution at ten isobaric surfaces 1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa were adapted for the trajectory analysis.

[7] Forward 5-day trajectories of the air parcels from the area 0°N–40°N; 50°E–60°E (see box A in Figure 6) over the Arabian Sea in the layer from 1000 to 700 hPa were computed for each day from February 01 to April 10, 1999 (only partly presented below). The 5-day time period is significantly shorter than that necessary for complete deposition of the aerosols transported from the Arabian Sea.

[8] Large quantities of the air masses from the selected area over the Arabian Sea were mainly transported to the tropical part of northern Africa during February 1999. The transport was especially intensive during the periods from 01 to 06 and from 14 to 21 of the month. During the rest of the month, the airflow from the area was mainly directed to the southern African regions. Two periods with the trajectories entering northern Africa from the Arabian Sea were detected during March (from 14 to 23 and from 28 to 31). During the first decade of April 1999, two such periods with the trajectories entering northern Africa from the Arabian Sea were detected (from 02 to 03 and from 09 to 10).

[9] The March 17–20 1999 episode was selected for a detailed analysis. To March 17, 1999, the southern convergence zone in the Indian Ocean started was displacing to the South. The tropical Indian Ocean was characterized by strong westerly monsoonal flow between 0°S and 5°S [*Verver et al.*, 2001]. The process could have contributed

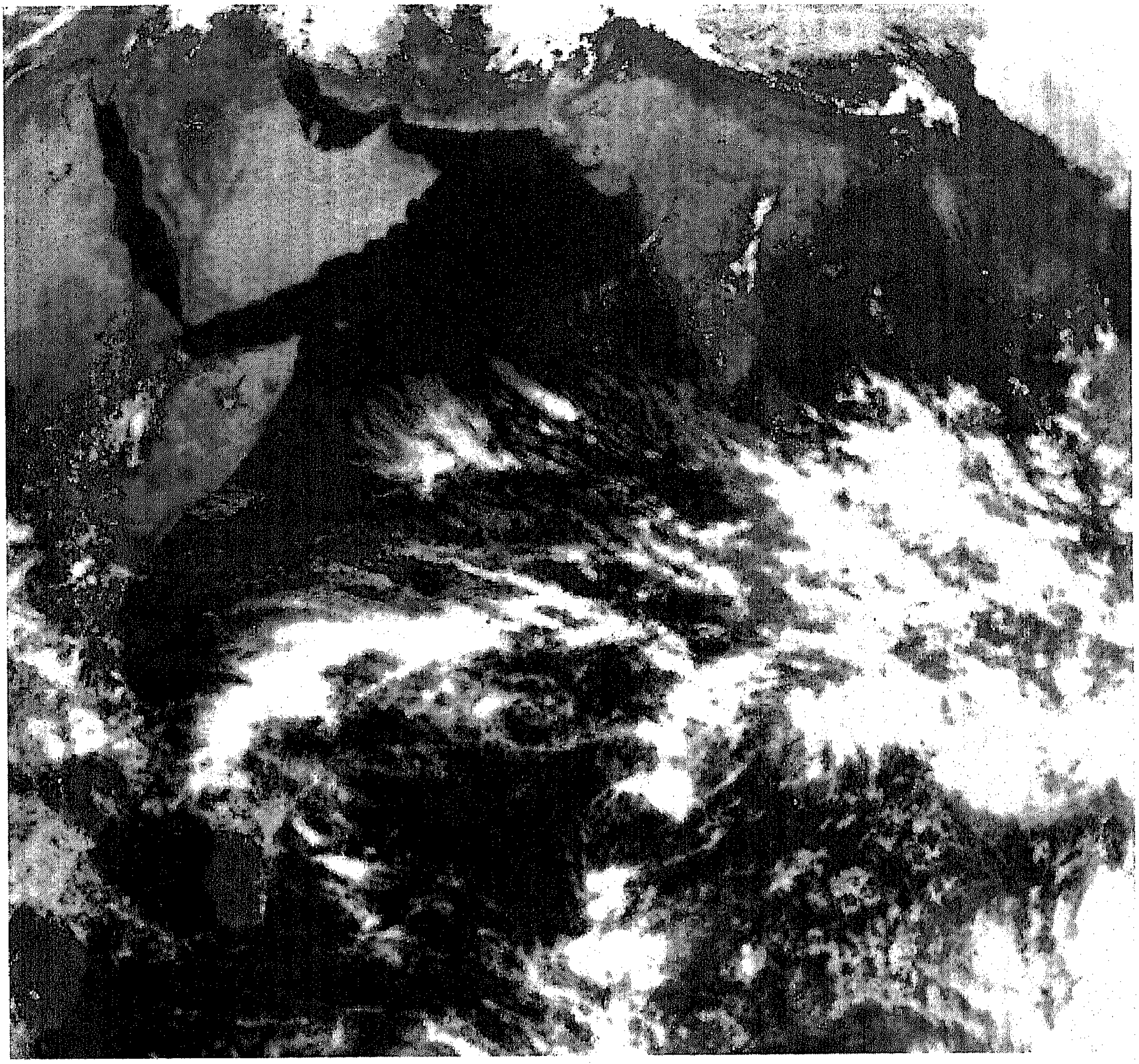

Figure 2. Meteosat-5 satellite pattern made in visible channel on March 19, 1999.

to the atmospheric developments over the Arabian Sea. Trajectories computed for the March 17–20 period are presented in Figures 1a–1d. Most of the initiated at 0000 UTC March 17 and 18 trajectories (Figures 1a and 1b) were directed to southern Africa. During the following 2 days the situation has changed. Many more trajectories were already directed to the tropical and northern Africa. Trajectories initiated at 0000 UTC March 19 and 20 (Figures 1c and 1d) demonstrated an intrusion of the air mass into Europe. According to the data from the ground-based observations of the columnar aerosol optical thickness (AOT) and of surface black carbon (BC) concentrations at Goa (15°45′N, 73°8′E) amount of the aerosols was increasing during the IFP. To the end of February the BC concentration reached 5 μgm^{-3}. It drooped to the middle of March to an also quite high value of 3 μgm^{-3}.

[10] The AOT measurements at 550 *nm* demonstrated a significant increase of the AOT value (0.7) to March 15 [*Leon et al.*, 2001]. The data, complemented by the made March 19 in visible channel Meteosat-5 pattern (Figure 2) provide good reasons to assume a high concentration of anthropogenic aerosols in the air masses, which reached the eastern African coast from the Arabian Sea during the March 17–20 period.

3. The 17–20 March, 1999, African Cyclone

[11] The March 17–20, 1999, period was characterized by a rapid intensification of a "Sharaf" cyclone [*Alpert and Ziv*, 1989; *Egger et al.*, 1995] that has developed prior to the beginning of the episode over central Africa. The March 17–20 process is illustrated by the patterns with the geopotential heights and winds at 850 hPa at 1200 UTC of each day of the period (Figures 3a–3d). The patterns are from the NCEP/NCAR Reanalysis Project (NNRP) data archive. On March 17 1200 UTC the sea level pressure (SLP) in the

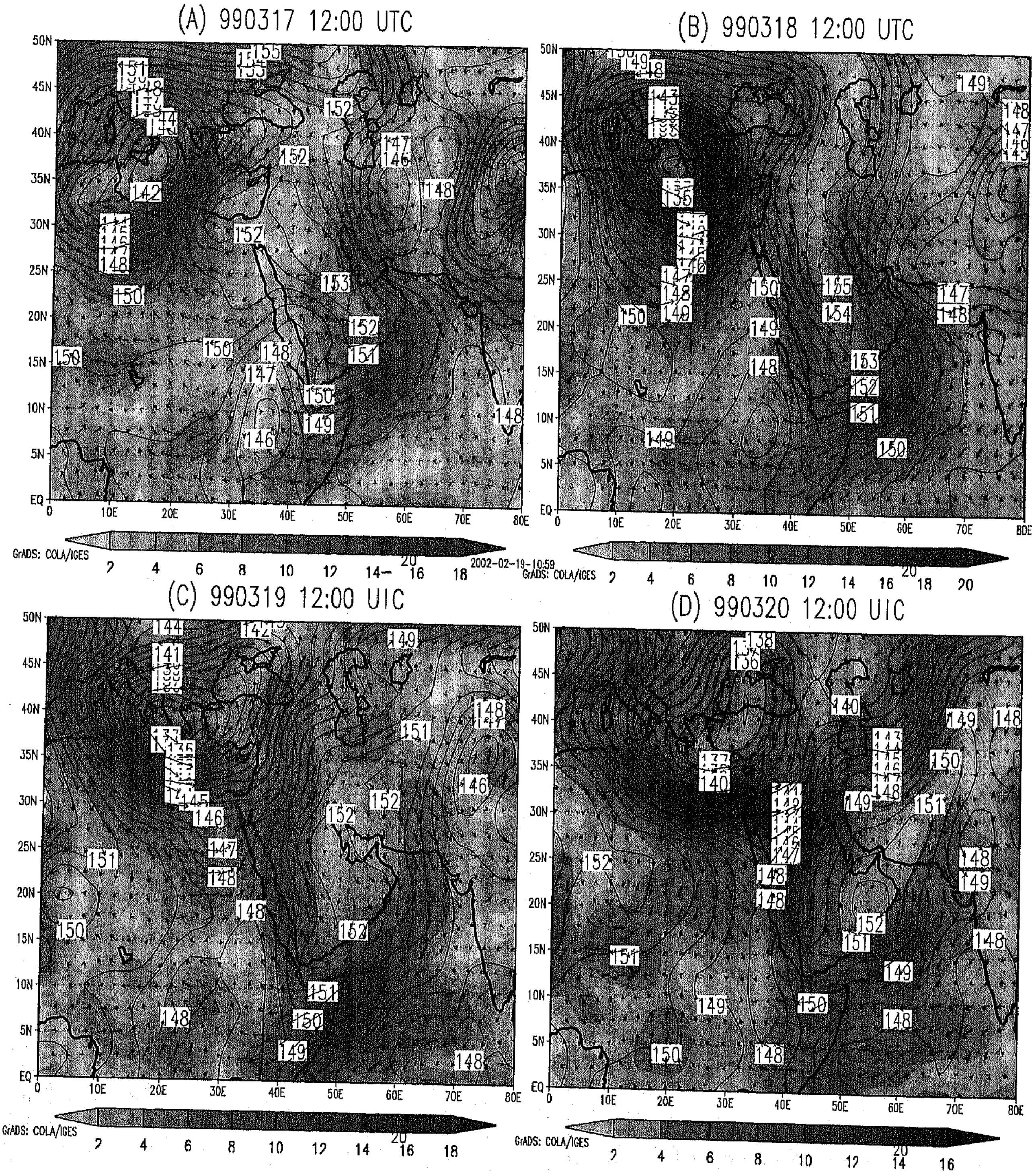

Figure 3. NNRP geopotential heights (contour interval 1 hPa) and winds at 850 hPa (grayscale gradations on the horizontal bar indicate the wind speeds) at 1200 UTC of (a) March 17, (b) March 18, (c) March 19, and (d) March 20, 1999.

center of the cyclone (not presented) was 1005 hPa. To 1200 UTC of March 18 SLP dropped to 998 hPa. The cyclone weakened already to March 19–20. The developments are represented in the patterns with the geopotential heights and winds at 850 hPa in Figures 3a–3d valid at 1200 UTC of March 17–20. According to the patterns the developed system was characterized by the northward winds over the EM allowing an air mass transport from the Arabian Sea region.

[12] During the March 17–20 period a dense dust plume developed over northern Africa. The area with the provided by the Laboratoire de Meteorologie Dynamique (LMD, Palaiseau, France) data of the Meteosat-5 European stationary satellite observations in the visible channel (Leon et

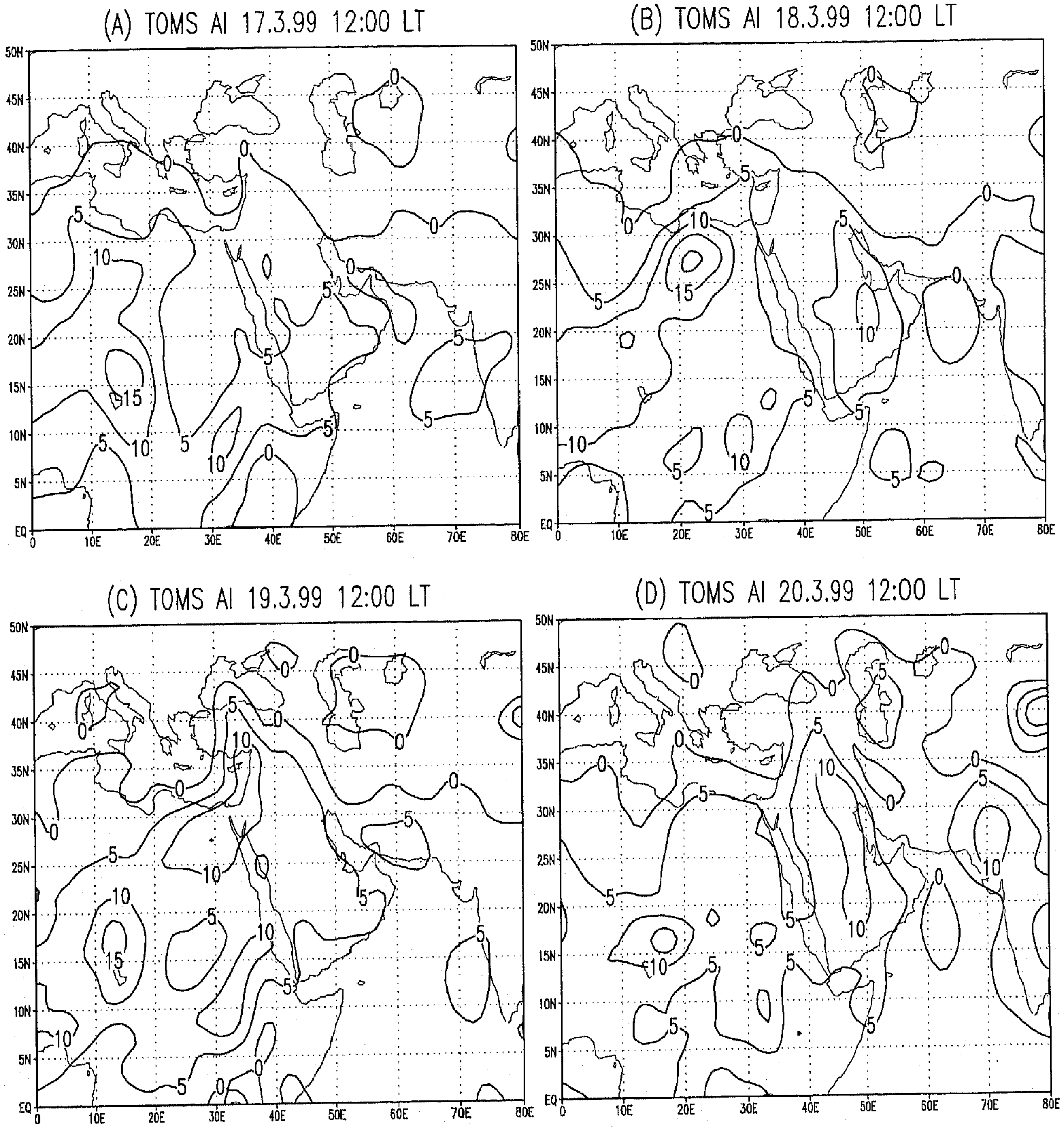

Figure 4. TOMS Aerosol Index values (× 10) at 1200 LT of (a) March 17, (b) March 18, (c) March 19, and (d) March 20, 1999, Contour interval is 0.3 (×10) AI units.

al 2001) did not include Africa and the Mediterranean region. The Total Ozone Measuring Spectrometer Aerosol Index (TOMS AI [*Hsu et al.*, 1999]) data on the vertically integrated content of the absorbing aerosols were used in the current study instead. The African dust plume is well presented in the TOMS AI patterns for 1200 LT from 17 to 20 March 1999 (Figures 4a–4d). To 1200 LT of March 17 the center of the dust plume (maximum AI index value of 1.5 units, 17°N, 15°E) was positioned over central Africa (Figure 4a). The area is typical for the dust updraft: Mineral dust plumes often originate from the area limited by 5°N–18°N; 0°–30°E [*Alpert and Ganor*, 2001; *Prospero et al.*, 2001]. A second dense dust plume may also be found over the Arabian Peninsula (Figure 4a). To March 18 the north-African plume (maximum value of 2.0 units) has been transported to the northeast and was positioned over the southern coast of the Mediterranean Sea (Figure 4b). Almost twice-lower TOMS AI values (1.2 units) were measured here at 1200 LT March 19. The decrease could be due to that in the dust concentration, the wet deposition processes and/or the effects of cloudiness in the TOMS observations [*Hsu et al.*, 1999]. On March 19 the plume was transported in the direction of Europe. A part of the second plume was also transported in the direction. To March 20 the already merged dust plume is found shifted to the east in the TOMS AI pattern (Figure 4d).

4. ETA Weather-Dust Prediction Model

[13] The two-dimensional TOMS AI data are globally available with 24-hour time interval only. No regular three-dimensional dust observations are presently performed. Additional information on the vertical profiles of the dust concentration may be obtained from atmospheric model simulation results. The March 17–20 development was simulated with a version of the Eta weather and dust prediction model adapted at Tel Aviv University with the help from University of Athens [*Krichak et al.*, 1999]. For the current study the model domain was increased to cover a large part of the INDOEX region. The NCEP objective analysis and forecast data were used for determination of the initial and lateral boundary data. The data are available with the six-hour time interval and 1.25° resolution at ten isobaric surfaces 1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa. The model was already been discussed in details [*Mesinger*, 1996]. The dust package is described by *Nickovic et al.* [1997a, 1997b] and *Kallos et al.* [1997]. The following main characteristics of the system may be outlined for the reader's convenience.

[14] Hydrostatic Eta/NCEP sigma-eta vertical coordinate model [*Mesinger et al.*, 1988; *Janjic*, 1990] is used. The used model domain covers the area 15°E–45°E, 15°N–45°N with horizontal resolution of 0.5°. Arakawa E-grid in the horizontal plane and vertical eta coordinate, with the step-like silhouette topography is adapted. The model atmosphere contains 32 vertical levels. The model's finite difference approximation secures conservation of finite difference analogs of chosen integral constrains of the continuous atmosphere and minimization of spurious departures from the physical system, computational modes and false instabilities. Computation of the horizontal advection of passive substances (including dust concentration) is performed according to the conservative positive-definite scheme.

[15] The dust prediction module includes parameterization of mobilization, transport, and wet/dry deposition effects. The corresponding parameterization schemes are discussed by *Nickovic and Dobricic* [1996], *Nickovic et al.* [1997a, 1997b], and *Kallos et al.* [1997]. All of the dust (clay) particles in the model are assumed to be of the same size (effective radius of 2–2.5 microns). The dust is considered as a passive substance. Computation of the relative vertical velocity of the dust particles is performed according to the vertical air velocity and the gravitational settling velocity, derived from the Stokes formula. The dust mobilization scheme takes into account the values of the friction- and threshold friction velocity, soil wetness and the distribution of the dust source areas. Only the desert and semi-desert areas are assumed to contain the dust sources [*Nickovic et al.*, 1997a, 1997b].

[16] The land-surface processes are parameterized in the model. The model employs the planetary boundary layer parameterization according to the Monin-Obukhov similarity theory with the use of the Mellor-Yamada Level 2 model. Cumulus parameterization is performed. Short- and longwave radiation processes (without the aerosol feedback effects) are parameterized. The fact that the dust effects are not included in the radiation transfer calculations may lead to an underestimation of the radiation heating inside (and a cooling below) a dense dust layer and the corresponding lapse rate changes [*Alpert et al.*, 1998; *Podgorny et al.*, 2000].

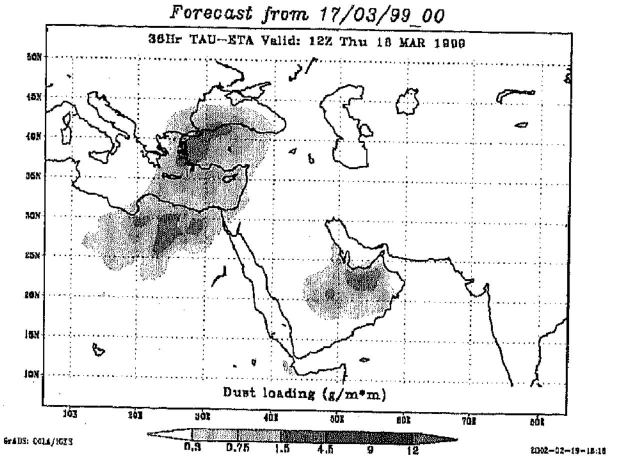

Figure 5. The 36-hour forecast of the dust loading to 1200 UTC March 18, 1999.

5. Modeling Results and the Backward Trajectories

[17] Results of the 36-hour prediction of the vertically integrated dust content to 1200 UTC March 18 are presented in Figure 5. The pattern may be compared with that of the TOMS AI (Figure 4b). The two main dust plumes of the period (over northern Africa and the Arabian Peninsula (Figure 4b) are found in Figure 5 at the correct locations. The absolute values of the observed (TOMS) and predicted vertically integrated dust contents are also in a reasonable agreement [*Alpert et al.*, 2002]. According to model results, mainly the dust particles of the north-African plume were transported to the EM (Figure 5). According to the forward trajectories (Figure 1), the meteorological patterns (Figure 3), and the TOMS data (Figure 4), however, the air masses from the Arabian Peninsula region were among those transported. The air arrived from the area of the Arabian Sea and contained significant amount of pollutants from the Indian peninsula, measured by TOMS on March 17 (Figure 4a).

[18] This was not the only one way for the air mass transport from the Arabian Sea to the EM. According to the model simulations the cyclone developed over the area with the coordinates 5°N–18°N; 0°E–30°E (box B in Figure 6). Results of 132-hour (5.5 days) backward computations in the 1000–700 hPa layer for the trajectories ending over the area to 1200 UTC March 20, 1999, are presented in Figure 6. The top/bottom layer pressures are in agreement with the model-simulated data on the vertical distribution of the aerosols as well as with those the INDOEX observations [*Leon et al.*, 2001] for the Arabian Sea region. According to Figure 6 the cyclone formation was associated with an interaction of the cold air from the north and northwest

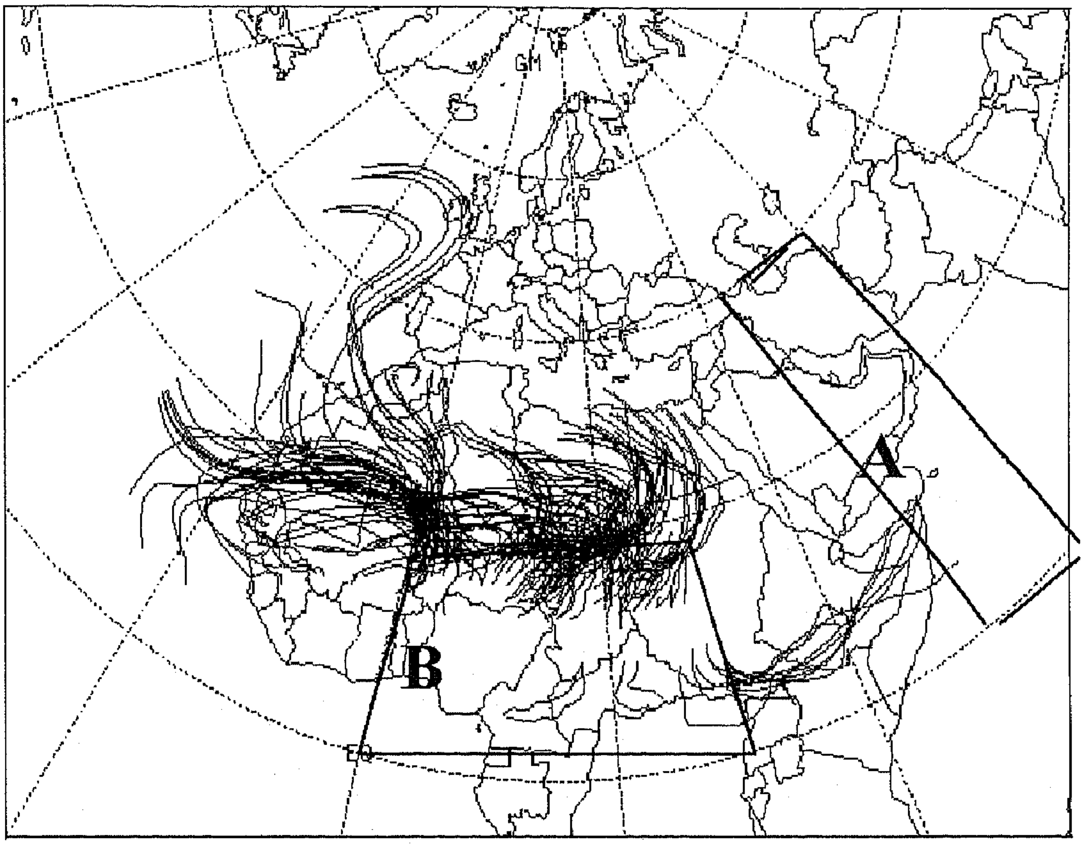

Figure 6. The 132-hour backward trajectories entering the area of the cyclone origin (5°N–18°N; 0°E–30°E). The area is approximately indicated by box B to 1200 UTC, March 20, 1999. Box A represents the area (0°–40°N; 50°E–60°E) for computation of the forward trajectories in Figure 1.

and (evidently polluted over the INDOEX area) warm air masses arriving from the east-African coastal regions of the Arabian Sea.

6. Discussion and Conclusion

[19] The air masses over the Arabian Sea contain significant amounts of anthropogenic pollutants during the dry monsoon period [*Ramanathan et al.*, 2001a; *Podgorny et al.*, 2000]. Synoptic scale developments over Africa may cause propagation of the polluted air to the EM area. According to the available data, such weather developments quite often take place over the region.

[20] The study presents an example of this type of the development. Analysis of a period characterized by origination and development of an intensive African cyclone is performed. Significant part of the participated in the cyclone development air masses was transported from the Arabian Sea area. During the Asian winter monsoon period low tropospheric circulation conditions are favorable for the transport of the polluted air masses from India to the Arabian Peninsula and equatorial Africa. According to INDOEX data the air masses reaching the Arabian Peninsula from the east contain large amount of the anthropogenic pollutants originated over the Indian subcontinent. The aerosols may contribute significantly to the atmospheric chemistry processes over the EM. The effect may explain the observed differences in the chemical composition of the mineral dist particles transported from northern Africa and the Arabian Desert as well as the sulfate enrichment of the aerosols in Israel [*Ganor et al.*, 1991].

[21] Possibility of a further increase of concentration of the aerosols from the Arabian Sea area over Africa and the Mediterranean region may not be excluded. Additional investigations are necessary for a more complete understanding of the possible consequences of the effects. Increase of the aerosol concentration in the air masses transported from the Indian subcontinent into the Arabian Sea area may contribute to additional significant climatic effects over Africa. Further analysis is required for the understanding the role of the aerosols from the Arabian Sea in the climate change processes over Africa and the Mediterranean region. The observed regional EM climate changes could be associated with increase in the number of the cloud condensation nuclea, a reduce in absorption of the solar energy by the sea and land surface, an increase of the solar heating in the lower atmosphere, etc. The effects may become more significant in the future. The regional precipitation and climate change processes over southern Europe and the Mediterranean may also be affected [*Krichak and Levin*, 2000; *Levin et al.*, 1996; *Ramanathan et al.*, 2001a, 2001b; *Rosenfeld*, 2000].

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