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A HEMISPHERIC DUST STORM IN APRIL 1994 OBSERVATIONS, MODELLING AND ANALYSES

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INTRODUCTION

Atmospheric inputs of aerosol dust from deserts are important in the climate system, primarily because of their effects to modify the global (Charlson and Heintzenberg, 1995; Hansen *et al.*, 1993; Tegen *et al.*, 1996) and regional radiative heat budgets (*e.g.* semi-enclosed seas, Gilman and Garrett, 1994, Gilman and Outerbridge, 1994), or to influence the heterogeneous chemistry of the tropospheric and greenhouse gases (Dentener *et al.*, 1996), as well as the biogeochemical cycles in the marine environment (Duce *et al.*, 1991).

Mediterranean dust events are typically associated with the so-called 'Sharav' cyclones (Alpert and Ziv, 1989) created south of the Atlas Mountains (Reiter, 1979; Brody and Nestor, 1980). On the other hand, Sahara dust is transported into the Atlantic Ocean (Prospero, 1981) with the Equatorial Trade Winds. Large scale atmospheric / climatic controls are suggested by the simultaneous occurence and the similar interannual dependence of the Mediterranean and Atlantic transports (Moulin *et al.*, 1997), demonstrated through annual correlations with the North Atlantic Oscillation (NAO, Hurrell, 1995). The Saharan dust arriving at Barbados Islands appears well correlated with African drought conditions, but some winter events have been associated with the El Niño / Southern Oscillation (ENSO, Prospero and Nees, 1986). During exceptional cases, such as in early April 1994 (Li *et al.*, 1996; Andreae, 1996) also studied in the present paper, significant alterations are found in the radiative energy fluxes on a hemispheric scale.

The spectacular dust event in early April 1994 creating simultaneous transport into the Tropical Atlantic (Li *et al.*, 1996; Andreae, 1996) and the Eastern Mediterranean, and producing the 30 years' maximum concentrations on Barbados Island (Li *et al.*, 1996), and a marked decrease of visibility in the eastern Mediterranean, is analyzed with the aid of ground and satellite measurements and numerical modeling, for a case study establishing the roles of synoptic meteorology and large scale controls.

THE DATA AND THE METHODS

Aerosol measurements at Erdemli, Turkey (36°N, 34°E, height: 20 *m*, Kubilay, 1996) and published data from the tropical Atlantic (Barbados, 13°N, 59°W, Li *et al.*, 1996; Sal Island, 16.7°N, 23.0°W, height: 125 *m*, Chiapello *et al.*, 1995, 1997; Tenerife, 28.3°N, 16.5°W, height: 2500 *m*, Arimoto *et al.*, 1995) are used to describe the transport and verify the modelling results. Rawinsonde profiles of temperature and humidity acquired from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA), and visibility data obtained from the

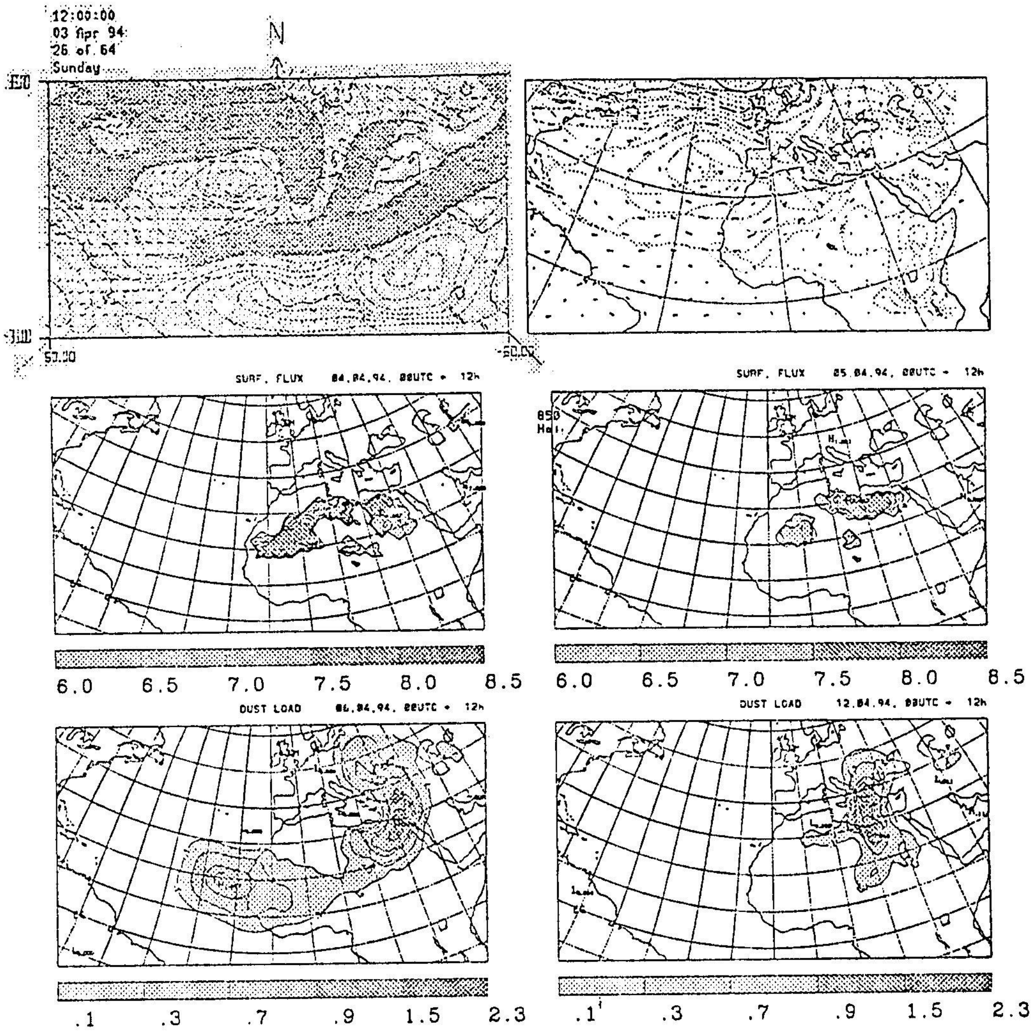

Figure 1. (a) The upper air streamfunction at 8.35 km and wind vectors at 0.5 km elevations, plotted together with the projected polar and subtropical jet streams (shaded areas where upper air speeds are in excess of 30 m/s), April 3, 1994, 12:00 UTC, and (b) geopotential height, temperature and wind vectors on the $850 Hpa$ isosurface, (c) dust flux from the surface on April 4, 12:00 UTC, and (d) on April 5, 12:00 UTC, (e) dust load, on April 6, 1994, 12:00 UTC and (f) on April 12, 1994, 12:00 UTC. The dust flux contours in (c) and (d) are for $\log_1 0(S \times 10^6)$ where S is the surface flux in $\mu g m^{-2} s^{-1}$ (*e.g.* the contour value for for 1 $\mu g m^{-2} s^{-1}$ is 6).

African Center of Meteorological Applications for Development (ACMAD) have also been used in the analyses.

Three dimensional, 3-day back trajectories terminating at 900, 850, 700 and 500 hPa final levels in Erdemli obtained from the European Center for Medium-Range Weather Forecasts (ECMWF), and isentropic, 10-day back trajectories terminating at Barbados, Sal and Tenerife Islands obtained from the Climate Monitoring and Diagnostic Laboratory (CMDL) of NOAA, have been utilized to trace dust transport and identify possible source regions.

The 'ETA' regional atmospheric model, based on a generalized terrain following coordinate system, originally developed by the University of Belgrade and the Federal Hydrometeorological Institute of Yugoslavia, and further enhanced by the National Center for Environmental Prediction (NCEP), USA (Mesinger, *et al.*, 1988; Janjic, 1984, 1990, 1994; Janjic and Mesinger, 1989), is used for simulation. In addition to the sophisticated numerical techniques and physical parameterizations, the model also supports complex formulations for turbulent mixing, viscous sub-layer and convection (Mellor and Yamada, 1982; Betts and Miller, 1986; Janjic, 1994).

The model has been upgraded to include the suspension, transport and deposition of dust (Nickovic and Dobricic, 1996; Nickovic et al., 1997), such that the conservation equation for passive dust concentration is integrated on-line, using numerical schemes valid for other scalar variables, and the viscous sublayer model (Janjic, 1994) for production (suspension) of dust, exploiting the physical similarity between turbulent mixing over the sea and over deserts (Chamberlain, 1983; Segal, 1990). The

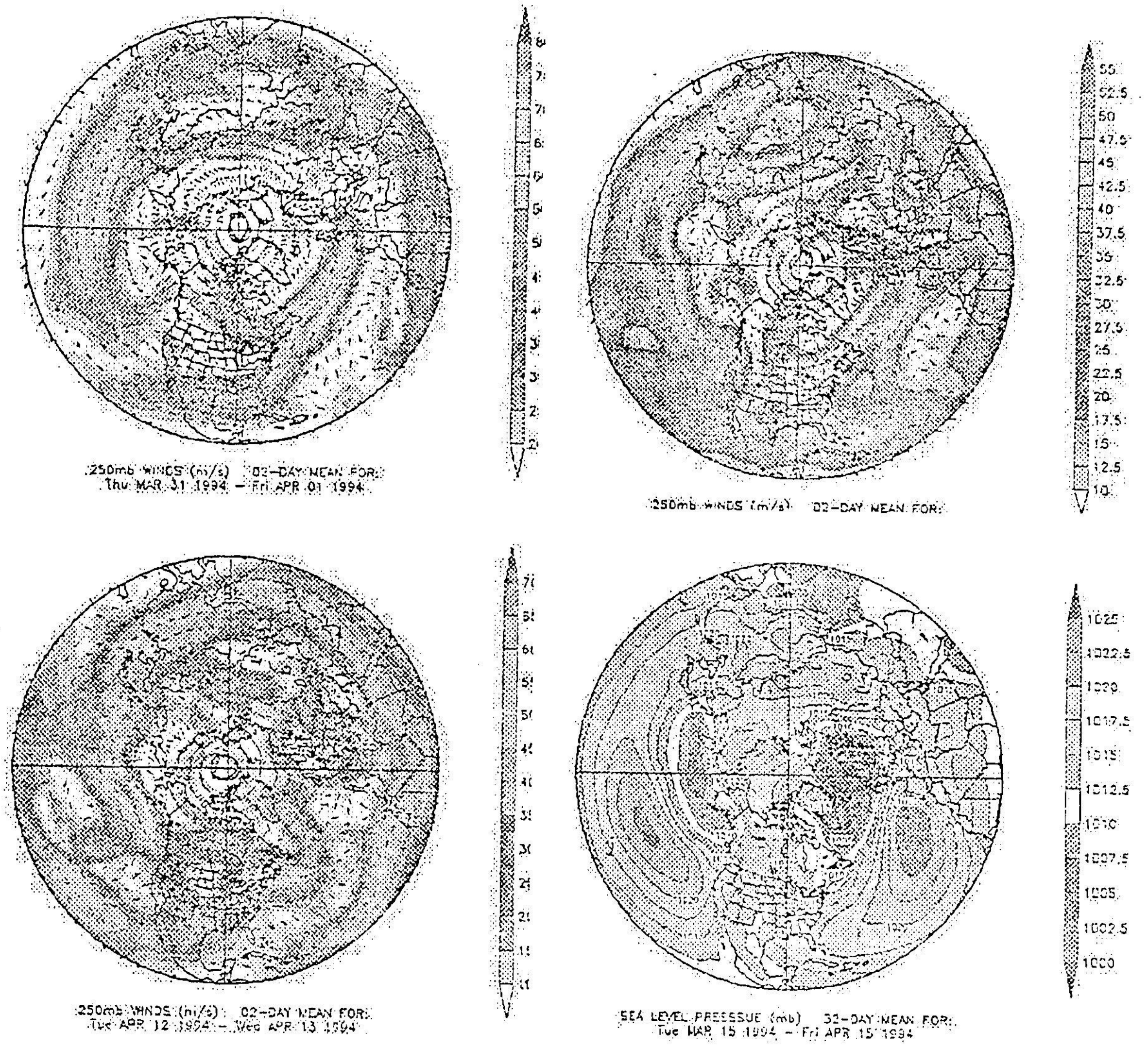

Figure 2. Northern hemisphere upper atmospheric circulation showing the evolution of the polar and subtropical jets. $250hPa$ wind speed (shading) and direction (vectors) based on two day averages for (a) March 31 - April 1, (c) April 4 - 5, 1994, (c) April 12 - 13, 1994 and (d) the monthly average sea level pressure for the priod March 15 - April 15, 1994. The source for the data is NOAA Climate Diagnostic Center (plotting page web adress http://www.cdc.noaa.gov/HistData/)

effects of ground wetness, wet/dry deposition are also accounted for. The surface dust source distribution is based on the Wilson and Henderson-Sellers (1984) vegetation data set, specifying desert areas as the source for dust.

The model, with a coverage of the Sahara and Atlantic regions, with horizontal resolution of 0.75° and a vertical representation at 32 levels was run from March 28 until April 15, 1994, initialized every 24 hr with meteorological fields with the dust field updated from the previous day's results, and lateral boundary conditions updated every 6 hr, using forecast data obtained from the European Center for Medium-Range Forecasts (ECMWF).

JET INTERACTIONS AND STORM DEVELOPMENT

The prevailing synoptic situation in the beginning of April 1994 was characterized by the subtropical high pressure centered at 35 N, the subpolar (Icelandic) low pressure centered at 65 N in the Atlantic Ocean, and the equatorial low pressure extending across the Tropical Atlantic and the African continent, representing typical winter conditions (Tucker and Barry, 1984). Near the surface, the Trade Wind circulation dominated over the Atlantic Ocean. The Siberian high pressure dominated the Eurasian continent.

It appears that the active developments to follow were linked with a blocking circulation and the interactions of jet streams in the upper troposphere (Fig.s 1a and 2). An upper air modon structure

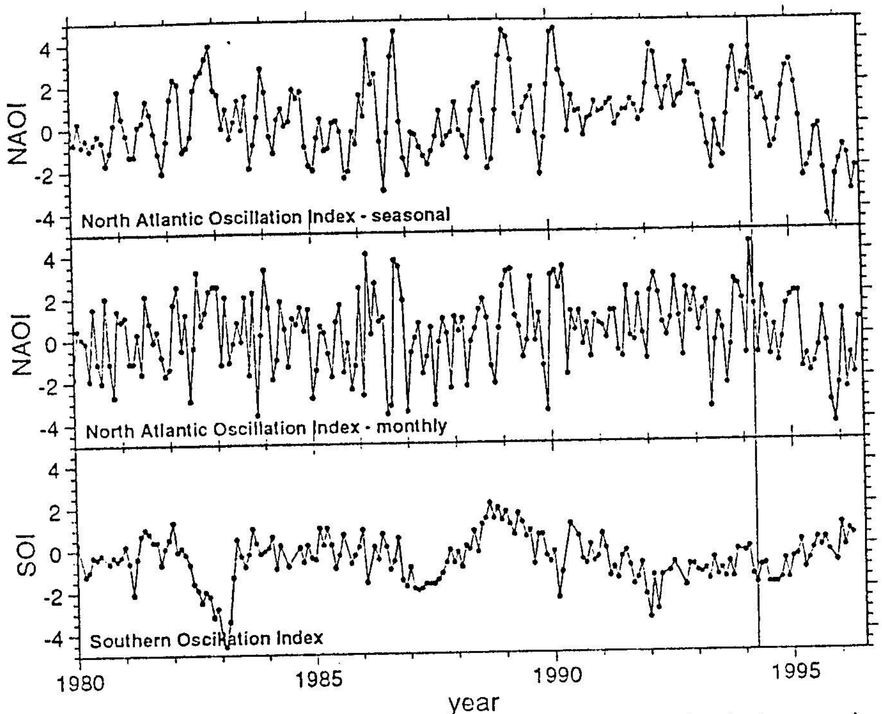

Figure 3. Time variation of (a) seasonal, (b) monthly NAO and (c) SO indices for the last two decades. The vertical line marks the April 1994 event.)

(a coherent dipole eddy with balanced weak nonlinearity and dispersion, often embedded in a zonal flow, *e.g.* McWilliams, 1980; Wallace and Blackmon, 1983) accompanied the surface anticyclone in the Atlantic Ocean, and its approach towards the Mediterranean first resulted in an intensification of Trade winds and a displacement of the polar jet stream to the south towards the subtropical jet stream. While the the two jet streams communicated through filaments earlier (March 29), the coming into contact of the two jet streams around 2-4 April (Fig. 1a) resulted in the development of strong meridional circulations over Europe and the Mediterranean area. An explosive cyclone development took place in the north central Sahara desert (Fig. 1b) in the lee of the Atlas Mountains, and was followed by its passage to the Balkans on April 6.

Initially, on March 31 - April 1, the when the two jet streams were separate, the upper air circulation pattern was defined mainly by the zonal jets (Fig. 2a). In the period following the Mediterranean activity and Sahara dust pulse initiated on around April 3-4, strong meridional circulation patterns developed over much of the northern hemisphere (Fig. 2b). The meandering hemispherical jet pattern continued for about 10 days, and on April 12-13, renewed cyclogenesis resulted from continuing jet interactions (Fig. 2c), consequently leading to a second instance of Saharan dust transport into the eastern Mediterranean, verified by observations and the model results.

The average sea level pressure during March 15-April 15 1994 (Fig. 2d) indicates a dipole of Icelandic low pressure and Azores high pressure typical of the North Atlantic Ocsillation (NAO). The NAO index had a high value of ~4 (seasonal index values of the same magnitude were reached only 8 times during the 1980-1997 period) as shown in Fig. 3, where a comparison is also made with the Southern Oscillation (SO) index. It is significant that a high NAO index circulation created the hemispheric disturbances leading to the anomalous dust event.

The interaction of the two jets, shown in the present case, has been suggested (e.g. Reiter, 1975) as a principal mechanism of Mediterranean cyclogenesis, although only limited cases have been demonstrated earlier (Karein, 1979). The Mediterranean / North African region is considered as one of the three global areas of potential jet interactions (Reiter, 1975; Özsoy, 1981), the other regions being in the lee of Rocky and Himalaya mountain ranges.

An 'Omega High' type of anticyclonic circulation often characterizes northwesterly Mistral winds in the western Mediterranean, in some cases leading to meridional flow that results in 'Genoa cyclogenesis' (Reiter, 1975; Brody and Nestor, 1980). The present case appears to be a rare extension of the strong Mistral winds and the associated subsidence (with subsequent surface divergence) reaching into the West African desert.

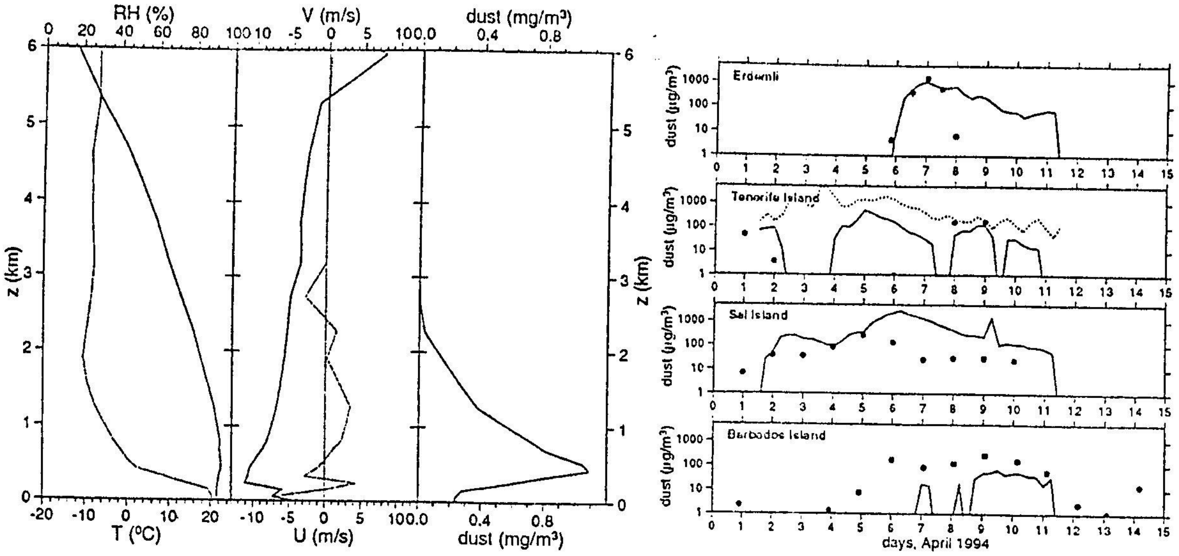

Figure 4. (a) The vertical structure of the trade wind system: Temperature, relative humidity (dotted line), east and north (dotted line) wind speed and dust concentration profiles at Sal Island on April 4 1994 12 GMT. (b) model predictions (solid line) and measurements (dots) of dust concentration at various locations in the Atlantic and the Mediterranean.

DUST SUSPENSION AND TRANSPORT

The synoptic situation in early April led to the generation and dispersal of desert dust in the atmosphere, confirmed by measurements and model simulations. Backward air mass trajectories (not shown) ending at Erdemli, Tenerife and Sal Island measurement stations on April 6 and Barbados Islands on April 9 indicated sources of air originating in the north Atlantic, passing over the Sahara desert and diverging towards the respective sites.

The model surface dust fluxes on April 4 and 5 are shown in Fig.s 1c and 1d, where the two main sources in the western and eastern Sahara can be identified. The dust source in the west was created on April 3 by the descending motions into western Sahara, and continued to be active during the next few days. Then on April 4 and 5, a second source was created in the eastern Sahara, as a result of the surface wind activity of the cyclone. An exceptional pattern of dust transport was then created, with one part of the cloud moving anticyclonically to the Atlantic, and the other part moving north towards the Eastern Mediterranean and Balkans with the cyclonic depression (Fig. 1e).

The column integrated dust load, a parameter directly correlated with the aerosol optical depth, in Fig. 1e shows the localization of dust into two separate clouds moving towards the Mediterranean and the Atlantic Ocean. A second dust pulse was created on 12-13 April (Fig. 1f), by a repeated cyclogenesis in the eastern Mediterranean by jet interactions shown in Figure 2b.

The subsidence south of the Atlas mountains on April 4 created a shallow suspension of dust flattened by divergence, transfering dust to the Atlantic Ocean with the intensified Trade Winds on later days, confined within the first few kilometers of the atmosphere. This structure of the Trade Winds, supplied by subsidence along the periphery of the North Atlantic anticyclone is well known (Tucker and Barry, 1984). On the other hand, the dust put into motion by the Sirte cyclone penetrated upwards along the warm front by convection and frontal uplifting. The model results also showed a large part of the domain affected by transport to be generally free of clouds, except in the east where frontal uplifting of the dust coincides with convective clouds of the cyclone.

In the subtropical Atlantic, the troposphere can generally be divided into a lower moist and an upper dry layer, the moist layer being capped by the Trade Wind inversion. The shallow Trade Inversion near the African coast (around 15° N) is strengthened by the effects of subsidence on the eastern side of the subtropical anticyclone, and cooling from below by the cold upwelled water along the African coast (Riehl, 1954). The inversion in the eastern subtropical Atlantic does not coincide with the top of the Trade Wind regime, but is usually much shallower, at about an elevation of 500 *m* near Africa. The thickness of the moist surface layer depends on the balance of convection and subsidence, and sharply rises to 2-3 *km* in the west, characterized with Trade Wind cumuli formed near the Caribbean (Byers, 1959). These features were also verified with model results (not shown). The dust maximum occurs immediately above the shallow Trade inversion.

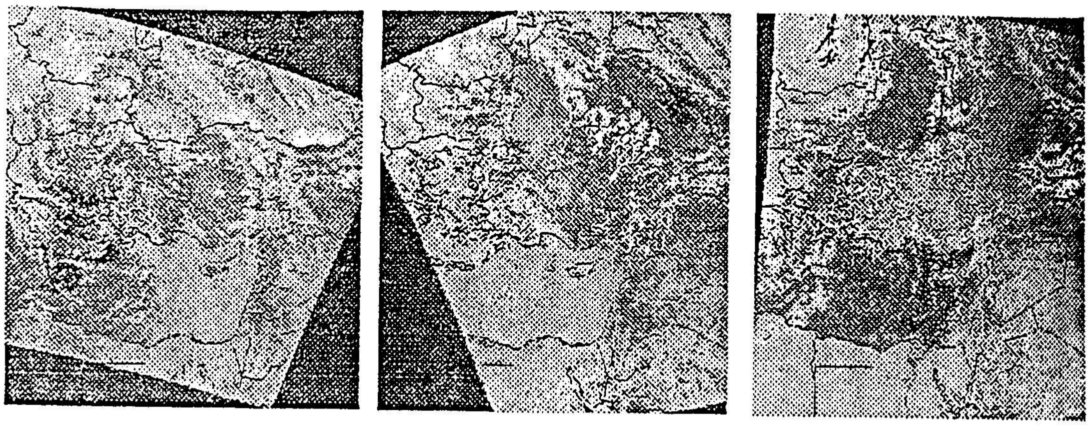

Figure 5. NOAA AVHRR satellite visible data on (a) April 6, 07:16 GMT, (b) April 6, 14:28 GMT and (c) Apı 7, 07:43 GMT, showing dust coming from Libya and Egypt and accumulated along the Levant coast,

The typical vertical structure of the Trade Wind system, and the dust concentration profiles Sal Island are shown in Fig. 4a. The dust maximum occurs immediately above the shallow Tra inversion, which is well below the Trade Wind boundary.

The model simulated instantaneous dust concentrations are compared with the available obs vations in Fig. 4b. At the Erdemli station, the observed peak concentration of 1.6 mg/m^3 on t evening of April 6 and its decrease on April 7 agrees well with the model calculated concentratic (Fig. 4b), and with the satellite observations of Fig. 5. At the sampling site on Tenerife Island, grou observations only existed on April 8 and 9 following a failure of the equipment for two days, reachi a level of 160 $\mu g/m^3$ April on 8 and 9 (R. Arimoto, personal communication). The model results 2.5 km elevation (solid lines, Fig. 4b, second panel from top), corresponding to the location of t measurement station indicate an order of magnitude agreement with model results. It is interesti to note that the measurement station at this height would have missed the much higher values at t lowest model level (dotted line, Fig. 4b), as a result of the shallow, boundary layer structure of t dust plume. At Sal Island, the available measurements indicated dust concentrations reaching a pe of about 260 $\mu g/m^3$ on April 5, which appeared approximately at the same time, but much smal than the model predicted maximum concentrations. Considering the shallow structure of dust clc to the source region and the relatively poor resolution of the present model in the lower layers, tl agreement is considered to be satisfactory. Throughout the monitoring study at Sal Island, conce trations in excess of 15 $\mu g/m^3$ were considered as dusty days. Peak dust concentrations of abc 300 $\mu g/m^3$ usually occurred in the winter period (December and January) at an altitude of 1.5 tc km as a result of dust transport by Trade Winds. In 1992 and 1993 the peak dust concentrations April were 45 $\mu g/m^3$, while exceptional levels were recorded in 1994 (Chiapello *et al.*, 1995; 1997). . Barbados Islands, the model predictions were considerably lower than the measurements, although t timing of the peak period was not dramatically inconsistent. The maximum measured concentratio of 280 $\mu g/m^3$ represented an all-time high in the observation period of 30 years (Li et al., 199' The seasonal cycle of dust measured at Barbados Islands reveals a maximum in the summer (Jun August), whereas the seasonal dust emission from the Saharan desert is estimated to have a maximu in the spring (March - May) in Africa (d'Almeida, 1986) indicating the importance of meteorologi conditions in the long-range transport of dust in comparison to the availability of dust at the sour region.

The high concentrations at the center of the dust plume moving towards the Atlantic decreas rapidly by settling in the marine region off the African coast. On the other hand, in the Easte Mediterranean, the massive dust incursion created by the cyclone resulted in high concentrations Egypt and along the Levant coast on April 6 (Fig.s 5a-c 3), which persisted on April 7 along the sar coast, and also moved across Anatolia to the Black Sea.

Limited comparisons were made with visibility data (not shown) at selected stations from Nigeri on the south side of the Sahara desert. Visibility lower than 10km is generally accepted as a sign atmospheric dust (Legrand *et al.*, 1989), although other variables such as humidity are interferi factors. The observations suggest heterogeneous behavior over a relatively small region, and possib signs of the dust storms during April 1-15 (Figures 10a-d) and 23-27, 1994.

CONCLUSIONS

The maximum concentration of dust measured in April 1994 at Barbados Island has been found to represent an extreme event, possibly carrying the signatures of a large amplitude climatic fluctuation. The limitless possibilities leading to the creation of an interdecadal climatic variation has not been tested in the present paper, leaving it open for further query. However, we emphasize the role of large scale atmospheric control in creating the dust event, and show that the sequence of events leading from a strong case of atmospheric blocking, to undulations of the polar jet, its interactions and exchange of mass and energy with the subtropical jet, cyclogenesis driven by barotropic / baroclinic instabilities, subsidence and strengthening of Trade Winds, *etc.*, make up the ingredients of the studied dust transport event. We also find that this kind of hemispherical weather is associated with a prominent example for the NAO transient, and hence strengthen the earlier attempts to correlate dust transport with characteristic teleconnection patterns; however we do that on an event basis, rather than on annual to seasonal time scales considered earlier.

Available ground measurements and satellite data confirm the modeling results and analyses. In particular, it is observed that the incursion of the jet circulation into Africa results in surface suspensions of dust propagating simultaneously but in two different directions into the Atlantic and Mediterranean regions. The two pulses are dissimilar in their characteristics representing different meteorological conditions, and mesoscale characteristics. The order of magnitude agreement between model results and observations is generally satisfactory. Dust reaching the Barbados Islands is underestimated, as a result of specific planetary boundary layer processes of the Trade Wind and the Trade inversion regimes not fully resolved in the model.

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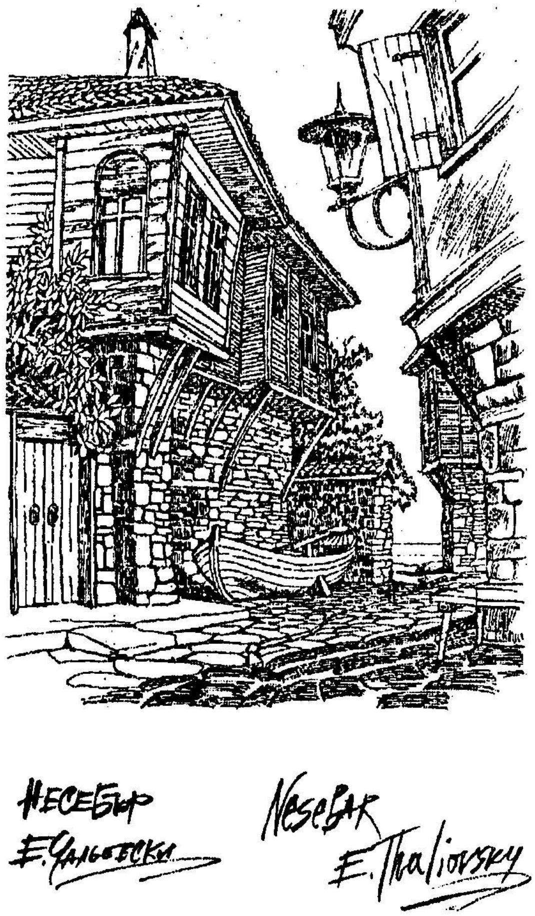

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