GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 5, PAGES 619-622, MARCH 1, 1998

On the long-range transport of air pollutants from Europe to Africa

G. Kallos, V. Kotroni, K. Lagouvardos, and A. Papadopoulos

Meteorology Lab., Department of Applied Physics, University of Athens, Athens, Greece

Abstract. The general climatic conditions and the physiographic characteristics of the area around the Mediterranean Sea, result in the formation of a flow pattern which is from North to South during all seasons and mainly during summer. This flow transports polluted air masses from southern Europe towards Africa. This transport is being investigated with the combined use of an atmospheric and a Lagrangian dispersion model. Air pollutants released from sources located in southern Europe were found in the entire tropospheric region over North Africa. The time scales for such a transport were found to be four to six days. This kind of transport can have several implications ranging from degradation of the air quality in North African cities to the water budget and regional climatic change.

1. Introduction

The Mediterranean is a closed sea, surrounded by high peninsulas and mountain barriers. The climatic conditions in the Eastern Mediterranean can be roughly divided into cold and warm periods. During the cold period, cyclogenesis is a common characteristic taking place in preferable locations. The anticyclonic circulation during this period is associated with a cold core anticyclone laying over Central Europe or the Balkans. The climatic conditions during the warm period are mainly defined by the two semi-stationary weather systems: the Azores anticyclone and the Anatolian and Iraqi Plateau low-pressure system. This results in the formation of a pressure gradient of a few tens of hPa between the West and East Mediterranean Coasts (e.g. Millan et al., 1997).

The land of North Africa is mainly desert with relatively small patches of agricultural areas, especially near the coast while the land of Southern Europe has a considerable amount of vegetation cover. The sea surface temperature in the Mediterranean ranges from 19° to 27° C during the warm and 10° to 18° C during the cold period of the year. The land of North Africa becomes warmer than this of South Europe during the day due to the latitudinal differences and the difference in landscape. This differential heating becomes more pronounced during the warm period of the year. The temperature difference between land and water and the existence of significant topographic variations favours the development of thermal circulations at various scales, which are stronger over the North African coast.

The balance of the two semi-stationary synoptic-scale systems mentioned previously, in association with the differential heating between the land of Africa and Europe, establishes a northerly flow pattern (Meteorological Office, 1962). Consequently, large-scale subsidence is always evident over the Mediterranean. In addition, compensatory flows are further enhancing such phenomena. The gaps between the major mountainous regions around the Mediterranean act as channels for the air mass transport towards the Mediterranean. A characteristic example is the N-NE winds across the Aegean during summer known as Etesians (Kallos et al., 1993 and the references therein) which are very strong during the day-hours and present considerably lower speeds during night.

Because of these complicated flow patterns, air pollutants emitted from various sources located in the surrounding areas can be transferred over long distances, in a complicated way (Kallos et al. 1996; Luria et al., 1996). Such transport phenomena are very important as they can affect the air quality of areas as far as the North African coast and the Middle East. Moreover, the lack of systematic information on the air quality in several Mediterranean areas, makes it very important to define characteristic spatial and temporal scales of such type of transport and transformation phenomena.

In this paper, an attempt has been made in order to provide some information about the characteristic transport and transformation scales in the Eastern Mediterranean during the warm period of the year. The regional-scale transport mechanisms are investigated by using the Regional Atmospheric Modeling System (RAMS) and the Hybrid Particle Concentration and Transport (HYPACT) model.

2. Model description and set-up

Atmospheric model

RAMS is a highly versatile numerical code developed at Colorado State University and ASTeR Division of Mission Research Inc (Pielke et al., 1992). Some RAMS features are the two-way interactive nesting with any number of fine nested grids, the terrain following coordinate system, the non-hydrostatic or hydrostatic time-split time differencing, the cloud microphysics, turbulence and radiative transfer (short and longwave) parameterizations, the various options for upper and lateral boundary conditions, the various levels of complexity for surface-layer parameterization (soil model, vegetation etc.)

Dispersion model

For the dispersion calculations, the HYPACT model has been used. This model is a combination of a Lagrangian particle model and an Eulerian concentration transport (Tremback et al., 1994). It utilizes the velocity and turbulence fields simulated by RAMS. Almost any type of sources can be specified anywhere in the domain and the emissions can be instantaneous, intermittent, or continuous.

Paper number 97GL03317.
0094-8534/98/97GL-03317$05.00

Model set-up - Data used

For the performed simulations, the ECMWF (0.5 x 0.5 degree lat-lon) analysis fields at standard pressure levels were used for intialization and for nudging the boundaries of the model domain every 6 hours. Moreover, the climatological 1x1 degree lat-lon sea-surface temperature (SST) fields, and a 30 arc sec topography, 10 arc min land-use and 2 arc min soil textural class data set, have been used.

Several simulations have been performed during the summers of 1994 and 1995. The model domain included the area from the Atlantic Ocean to the Caspian Sea and from the Equator to Scandinavia. The defined grid has a mesh of 140x140x28 points and a 40 km horizontal grid increment. The top of the domain is at 17 km. The grid increment used is sufficient to resolve the important regional scale circulations which exhibit a diurnal cycle (Etesians). All the performed simulations had a duration of at least 6 days.

The Lagrangian mode of HYPACT was used and particle releases were performed continuously during the entire simulation. The releases were made at geographic locations where large urban conglomerates or significant industrial activities exist in South Europe, within a box of 10x10x0.2 km^3 representing the main sources of each conglomerate.

3. Model simulations

All the performed model simulations, reproduced the general trend of the flow over the Mediterranean which is from North to South. A representative simulation lasting from 0000 UTC 1 July 1994 to 0000 UTC 8 July 1994 is discussed in the following. Figure 1 shows the near surface flow at 1600 UTC 6 July 1994. The Etesians are evident across the Aegean Sea during this day and a relatively strong northerly flow is directed towards Africa and penetrates deeply over Egypt and Libya. This northerly flow is maintained during the day and night-hours. The location of the Intertropical Convergence Zone (ITCZ) is clearly shown in the area south of 20° N. During the day, the flow-field is slightly distorted by the local thermal circulations (sea-breezes, upslopes). This is more pronounced over the eastern part of Egypt where a veering towards east is due to the strong upslopes (not shown).

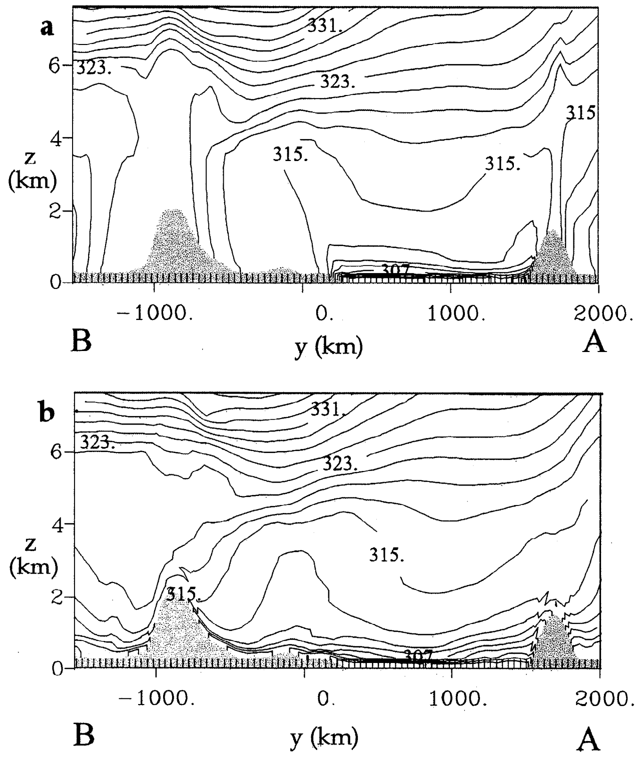

Figure 2. Potential temperature vertical cross section (at 2 K interval) at (a) 1600 UTC 6 July 1994, (b) 0000 UTC 7 July 1994. The cross section location is defined by the points AB (on line CD) in Fig.1.

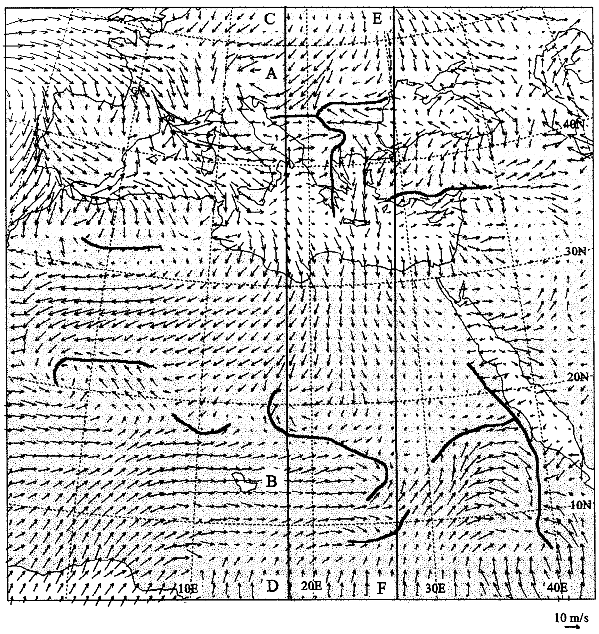

Figure 1. Wind field at z= 210 m AGL, predicted by RAMS model at 1600 UTC, 6 July 1994. Bold lines denote convergence lines. Line AB denotes the position of the vertical cross sections presented in Fig. 2. Lines CD and EF denote the positions of the vertical cross sections presented in Fig. 3. Wind arrows are plotted every third grid point.

The polluted air masses leaving the urban conglomerates located near the coast are mainly transported in long distances following two paths:

- through the marine boundary layer, and
- through the upslopes to the free troposphere.

The first path dominates during the night with the aid of the land-breezes and drainage flows. It can also occur during the day when the synoptic/regional flow is relatively strong from land to the sea and dominates over the local thermal circulations. This is due to the fact that urban air pollutants are mainly emitted near the ground. As the urban plume enters into the stable marine boundary layer, it is advected horizontally over long distances without changing its main characteristics. The second path dominates during the day. The plumes are injected into the free troposphere at heights ranging from a few hundred meters to a few kilometers. The depth of the afternoon mixing layer over most of the south European regions is ranging from 1500 to 2000 m (Kassomenos et al., 1995; Millan et al., 1997). This kind of transport is relatively efficient, especially when local thermal circulations are not precluded from large-scale flow and

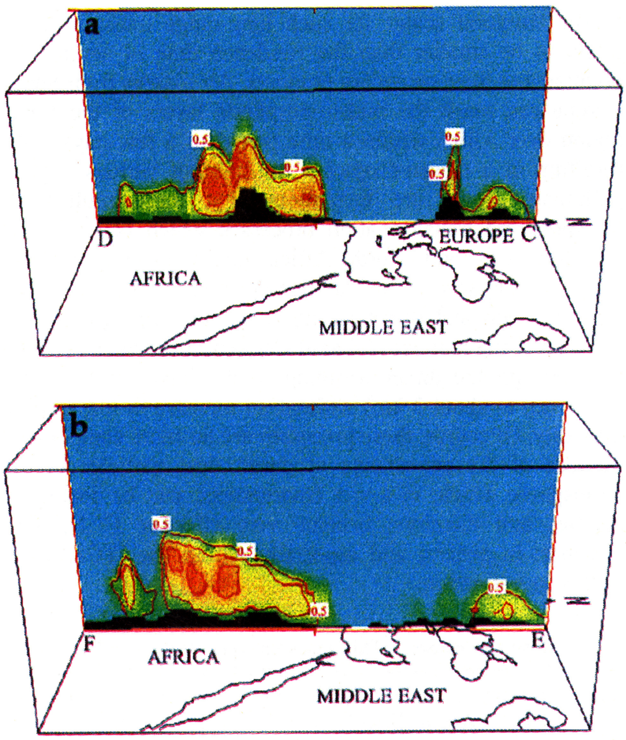

Figure 3. Turbulent kinetic energy vertical cross section (a) along line CD shown in Fig. 1, (b) along line EF shown in Fig.1, at 1600 UTC, 7 July 1994. Contour interval is at 0.5 m^2s^{-2}. The vertical domain extends from surface up to 13 km.

organized convergence zones are evident (Kotroni et al., 1997). In such cases, the long-range transport occurs within the lower troposphere, with the aid of the large-scale flow above the boundary layer.

In both cases, the general flow pattern is from North to South (or Southeast) across the Mediterranean. Therefore, the urban or industrial plumes from southern Europe are transported towards North Africa. When these plumes reach the coastal areas of North Africa and Middle East, they enter into a different dispersion environment. More specifically, the marine boundary layer is relatively shallow and stable while it becomes very deep and unstable over the land of North Africa, during the day. This situation is illustrated in Fig. 2a where a north-south vertical cross-section of the potential temperature field during the afternoon-hours over the Mediterranean waters and North African land is shown. The abrupt change in stability conditions has several implications as this will be discussed later. During the night, these differences over the water and land bodies are reduced (see Fig 2b) and therefore, the dispersion conditions are different.

The dispersion conditions are defined by the 3-D wind and turbulence fields. Over the Mediterranean and North Africa the spatial and temporal variations in both fields are very large. In order to have an insight on the spatial variations of the turbulence fields, two vertical cross-sections of Turbulent Kinetic Energy (TKE) are shown in Fig. 3. The TKE fields over southern Europe are distorted by the relatively strong updrafts at the mountainous regions during the day-hours. During the night some turbulence still exists due to the slow dissipation but in general, the TKE has very small values everywhere (except in areas with storm activities) as the only mixing mechanism is the mechanical mixing which is very small (not shown). Over the sea, the mixing layer is relatively shallow (300-400 m) and not varying significantly between day and night. The mixing layer is bounded underneath the areas where a sharp decrease of TKE with height is evident. Over Africa and especially over the desert, the mixing layer becomes very deep (4-5 km or even higher) during the day and very shallow at night. The deep mixing layer observed over Africa is enhanced by the strong updrafts regularly observed over the bald mountainous regions.

The HYPACT model has been used in order to make continuous particle releases for several days and from various sources located near the North Mediterranean coast line. Figure 4 illustrates the vertical projection of the particle positions after 160 hours of release from three locations representative of the urban and industrial conglomerates of Messina in Italy, Athens in Greece and Istanbul in Turkey. Note that there parts of these plumes are well dispersed (evident as widespread "clouds") near the sources while others are not (narrow strips). The well dispersed parts correspond to day-time releases while the others to night-time releases. Indeed, during the day-hours the dispersion conditions near the sources are good due to the development of thermal circulations and to the vertical mixing. These parts of the plumes are dispersed within the lowest 2 km of the troposphere and a part of them is advected above the mixing layer. During the night, when the flow is directed from land to the sea (both regional and local components) and stable conditions prevail, the plumes enter into the marine boundary layer and continue to travel within it during the day-hours. A similar situation can be observed during the day-hours when the regional-scale flow is relatively strong and directed from land to the sea. Such a case is shown in Fig. 4 for the releases from Messina in southern Italy (a narrow plume which changes its direction only due to wind shear). In both ways,

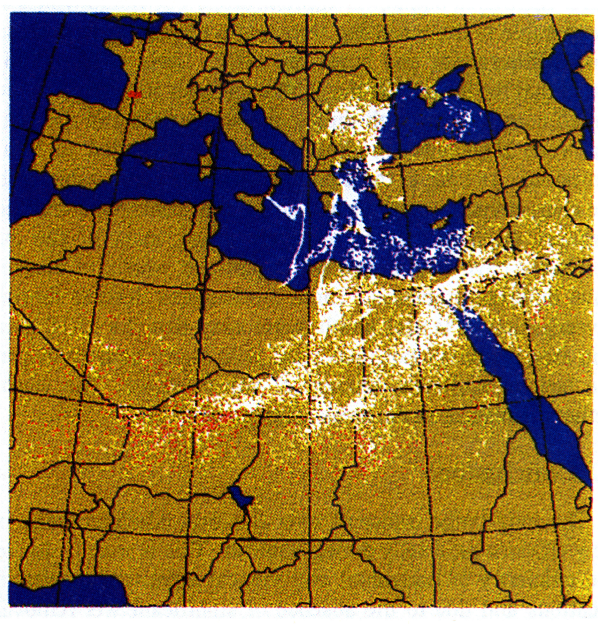

Figure 4. Particle projection from HYPACT dispersion model at 1600 UTC, 7 July 1994 (after 160 hours of particle release). Particles coloured in white are located below 5 km height while in red are located above 5 km.

the plumes are transported towards the North African coast. Due to the abrupt changes in dispersion conditions during the passage from the sea to the land the plumes start to disperse over Africa and cover a wide area. If the passage occurs during the night, the parts of the plumes which were not well dispersed near their sources may continue to keep their characteristics over the land until the day-hours.

During the day, due to the strong vertical mixing, the pollutants are transported to higher atmospheric layers. This vertical transport is also supported by the very strong upslopes in areas with orographic variations. A significant amount of the particles (coloured red in Fig. 4) are located at heights above 5 km in the vicinity of the ITCZ. During summer the ITCZ region is located around the 20°N. In this zone, the particles are trapped into the strong updraft regions and transported into the higher tropospheric layers.

The traveling time for plumes released from sources in northern Mediterranean Coast to reach North Africa, has been estimated to be approximately two to three days while at an average time of five days they are reaching the middle and upper tropospheric layers within the ITCZ. These time scales have been estimated from various simulations performed with RAMS and HYPACT models. The model results were in good agreement with the airborne measurements discussed in Kallos et al. (1996). Additional model simulations performed for sources located at the northwestern Mediterranean coast showed that the transport occurs mainly towards the Southeast and lasts longer.

As it was mentioned previously, the warm period of the year is also a dry one for the Mediterranean Region. Therefore, the dominant removal mechanisms for the various air pollutants are the dry which are much slower than the wet ones. Consequently, the air pollutants emmitted from the European part of the Mediterranean travel towards North Africa for time periods comparable to some characteristic time scales related to gas to particle conversion and deposition. For example, the time scale for the conversion of sulfur dioxide to sulfates is approximately 100 hours which is comparable to the travelling time that a plume needs to cross the Mediterranean and reach the ITCZ. Luria et al. (1996) found that the amount of the sulfate particles monitored in the Israeli coast is very high during the warm period of the year and such high concentrations cannot be attributed to local emissions. As long as the traveling times are comparable with the characteristic scales for gas to particle conversion and the removal mechanisms are relatively weak, most of the air pollutants have been converted to particles which, of course, have different properties. These mechanisms deserve further investigation. It is also worth mentioning that the ITCZ over this area is always not associated with storm activity due to the lack of sufficient amount of water vapour. The storm activity is evident in the areas southern of 10° N.

4. Conclusions

The long-range transport over the East Mediterranean is very efficient especially during summer. This is mainly due to the efficiency of horizontal and vertical advection at certain locations and due to the absence of significant wet removal processes. The air quality over the North African Region can be significantly affected from the transport of air pollutants released in the southern part of Europe.

The temporal scales for such long-range transport were found to be smaller than the residence time of several air pollutants or their secondary products. Air masses from South Europe can reach the mid-tropospheric layers of the ITCZ region over Africa within a time period of a few days (4-6) resulting in a massive upward transport of various "aged" pollutants. There are indications that these multi-scale transport and transformation processes which occur in the Mediterranean and North Africa might have significant climatic impacts. The aforementioned processes may influence rain and therefore the water balance, through the increase of the number of Cloud Condensation Nuclei (CCN) and through the direct warming of the lower tropospheric layers (up to about 3 km) without an increase in the specific humidity. Of course, these processes are far more complicated because of the appearance of desert dust particles in the atmosphere which, in a wet environment, can be coated by sulfates and therefore, become very effective CCN. This transport in general and especially within the ITCZ needs farther investigation.

Acknowledgements. This research was supported by the EU (DG-XII) project T-TRAPEM (Contract No: EV*-CT92-0005). Acknowledgement is also made to the National Center for Atmospheric Research (NCAR), for the data retrieved and the partial utilization of the computing facilities.

References

Kallos, G., P. Kassomenos, and R.A. Pielke, Synoptic and mesoscale weather conditions during air pollution episodes in Athens, Greece, *Boundary-Layer Meteorol.*, *62*, 163-184, 1993.

Kallos, G., Kotroni V., Lagouvardos K., and Varinou M., M. Luria, M. Peleg, G. Sharf, V. Matveev, D. Alper-SimanTov, A. Vanger, G Tuncel, S. Tuncel, N. Aras, G. Gullu, M. Idrees, F. Al-Momani, Transport and Transformation of Air Pollutants from Europe to the East Mediterranean, *Environmental Research Program AVICENNE, Final Report (DGXII of EU)*, 352 pp, 1996.

Kassomenos, P., V. Kotroni, and G. Kallos, Analysis of the climatological and air quality observations from the Greater Athens Area, *Atmos. Environment*, *29*, 3671-3688, 1995.

Kotroni V., Kallos G., and Lagouvardos K., Convergence zones over the Greek Peninsula and associated thunderstorm activity, *Q. J. Roy. Meteorol. Soc.*, *123*, 1961-1984, 1997.

Luria M., M. Peleg, G. Sharf, D. Siman Tov-Alper, N. Schpitz, Y. Ben Ami, Z. Gawi, B. Lifschitz, A. Yitzchaki, and I. Seter, Atmospheric Sulphur over the East Mediterranean region, *J. Geophys. Res.*, *101*, 25917-25930, 1996.

Meteorological Office, *Weather in the Mediterranean*, Vol. I, General Meteorology H.M. Stat. Office, London, 2nd Edition, 1962.

Millan, M., R. Salvador, E. Mantilla, and G. Kallos, Photooxidant dynamics in the Mediterranean Basin in summer: Results from European research projects, *J. Geophys. Res.*, *102*, D7, 8811-8823, 1997.

Pielke, R.A., W.R. Cotton, R.L. Walko, C.J. Tremback, W.A. Lyons, L.D. Grasso, M.E. Nicholls, M.D. Moran, D.A.Wesley,T.J. Lee, and J.H. Copeland, A comprehensive meteorological modelling system - RAMS, *Meteorol. Atmos. Phys.*, *49*, 69-91, 1992.

Tremback, C.J., W.A. Lyons, W.P. Thorson, and R.L. Walko, An emergency response and local weather forecasting software system, *Proc. of the 20th NATO/CCMS Int. Techn. Meeting on Air Pollution Modelling and Its Application*, X, 423-429, 1994.

G. Kallos, V. Kotroni, K. Lagouvardos, and A. Papadopoulos, Meteorology Lab., Dept. of Applied Physics, Panepistimioupolis, PHYS-5, 15784, Athens, Greece. (e-mail: kallos@ etesian.dap.uoa.gr)

(Received August 20, 1997; Accepted November 5 1997)