

## **AIR POLLUTION MODELING IN THE MEDITERRANEAN REGION: FROM ANALYSIS OF EPISODES TO FORECASTING**

**George Kallos, Marina Astitha and Petros Katsafados**

University of Athens, School of Physics, Division of Applied Physics,  
Atmospheric Modeling and Weather Forecasting Group,  
University Campus, Bldg. PHYS-V, Athens 15784, Greece  
kallos@mg.uoa.gr

### **ABSTRACT**

Air pollution modeling in the Mediterranean Region is at its third decade now. The first step beyond the Gaussian-type plume dispersion was the combined use of mesoscale atmospheric models with 3-D dispersion ones. During the last decade computer power became very cheap and sophisticated configurations of atmospheric and photochemical models were applied in regional studies. Advanced modeling techniques have opened a new horizon in air pollution studies, providing the capability of forecasting air pollution episodes along with the traditional analysis of air quality measurements for specific cases of severe atmospheric pollution episodes.

**Key Words:** Air Pollution, Modeling, Particulate Matter, Photochemistry, Dust

### **1. INTRODUCTION**

In the beginning of the 3D dispersion models the techniques used were either Eulerian or Lagrangian-type. Later, the first photochemical models were applied with Eulerian-type approach. The mesoscale models at the time were initialized on a rather simplistic way by considering horizontally uniform initialization fields. The domain sizes were at the order of 100 km. Such type of modeling was appropriate for either conceptual type of analysis or for thermally-driven local circulations. This type of modeling was applied for urban regions. The problems were considerable and several of these simulations led to wrong conclusions. A typical example is Athens where the proposed conceptual models of the 80-ties were reproduced by the models. In these early simulations the recirculation of the air pollutants over an area of a few tens of kilometers was demonstrated and was widely adopted. During 90-ties the new generation of atmospheric models was in use where the initialization was performed on a non-uniform way and multi-scale type of approach was adopted (Kallos et al, 1995, 1997, 1999). In such simulations the role of various-scale flow interactions was demonstrated and conceptual model of recirculation of air pollutants within a few tens of kilometers showed its limitations.

During the last decade computer power became very cheap and sophisticated configurations of atmospheric and photochemical models were applied in regional studies (Kotroni et al, 1999). Such simulations demonstrated the role of Long-Range Transport on air quality degradation in various places around the Mediterranean. Phenomena like recirculation over realistic scales, multiple layering of different ages of air pollutants horizontal transport within or above the marine boundary layer together with the thermal circulations over the mountainous regions were the key issues. Despite this progress the problem related to emission inventory was still a real one.

With the experience gained during all these years the first attempts of operational air quality forecasts are evident. Such forecasting activities were organized recently from the Atmospheric Modeling and Weather Forecasting Group of University of Athens during the Athens Olympics. The forecasting activities were based on the SKIRON weather and Saharan dust forecasting system RAMS weather forecasting system, together with the CAMx photochemical model. These models run on nesting mode in order to cover the multi-scale flow and air pollution processes. The chemical processes include gaseous and particulate pollutants. The sources of air pollutants included in the system are both anthropogenic and natural origin (e.g. Saharan dust). In this presentation, the above issues are summarized and the experience gained from these operations is discussed.

## **2. MODEL DESCRIPTION**

A short description of the modeling systems used for performing simulations is provided below.

*The SKIRON/ETA* is a modeling system developed at the University of Athens from the Atmospheric Modeling and Weather Forecasting Group (Kallos et al, 1997, Nickovic et al, 2001). It has enhanced capabilities with the unique one to simulate the dust cycle (uptake, transport, deposition).

*RAMS (Regional Atmospheric Modeling System)* is considered as one of the most advanced atmospheric models. Detailed information about RAMS model can be found in Cotton et al (2003).

*The Comprehensive Air Quality Model with Extensions (CAMx)* (Environ, 2003) is an Eulerian photochemical model that allows for integrated assessment of air-pollution over many scales ranging from urban to super-regional (<http://www.camx.com>). CAMx has also model structures for modeling aerosols, processes that are linked to the CB4 gas phase chemical mechanism, science modules for aqueous chemistry (RADM-AQ) inorganic aerosol thermodynamics/partitioning (ISORROPIA) and secondary organic aerosol formation/partitioning (SOAP).

## **3. AIR POLLUTION MODELING: ANALYSIS OF EPISODES**

The paths and scales of transport and transformation of air pollutants in the Mediterranean Region have been identified in previous work carried out at the framework of various EU projects (Kallos et al, 1997, 1999). The results showed that

the synoptic/regional circulation during summer, favors long-range transport of air pollutants released from Southern and Eastern Europe and Central Mediterranean towards the Eastern Mediterranean, North Africa and Middle East (Figure 1).

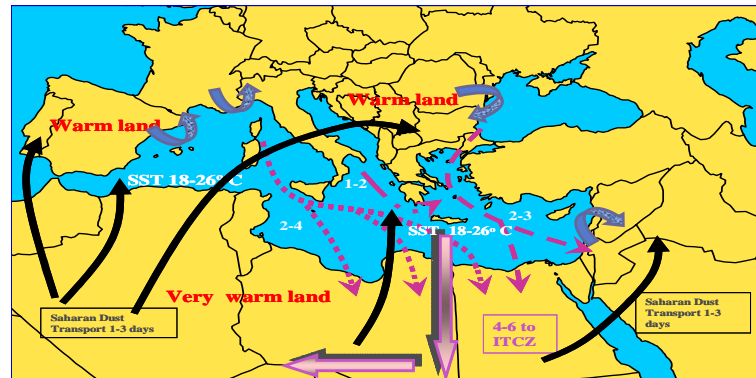


Figure 1. Characteristic paths and scales of transport of air masses in the Mediterranean Region.

Anthropogenic gases and particulate matter as well as natural aerosol like desert dust are the subject of modeling studies in conjunction with measurements of pollutants. Ozone is a well known secondary pollutant, which has been the primary target of several studies during the last 20 years. Ozone formation, destruction, transport and deposition patterns have been identified in various projects in the past. During the last years, a great number of studies focus on the important role of aerosols in the air quality of a specific area, due to the potential impact on human health and ecosystems (di Sarra et al, 2001, Rodriguez et al, 2001). Today the scientific interest focuses on the patterns that characterize aerosols in the atmosphere as well as the interaction between gases and particulate matter mainly of small sizes.

Concerning the anthropogenic aerosols, particulate sulfate production and transport is part of an on-going research using advanced modeling systems. In order to identify the paths and transformation of  $\text{SO}_2$  to particulate sulfate, the sulfate ratio was calculated within the code of CAMx model. Sulfate ratio has been used in previous studies (Luria et al, 1996) to define the chemical age of air masses, based on measurements of sulfur dioxide and particulate sulfate. Sulfate ratio is characterized as the ratio of sulfate concentration to total sulfur concentration (meaning both  $\text{SO}_2$  and particulate sulfate), leading to a dimensionless value from zero to unity. According to Luria (1996), the higher values for sulfate ratio (greater than 0.1) correspond to aged air masses, and the closer the ratio is to unity, the older the air mass and the longer its travel distance. CAMx model code was modified in order to calculate an average sulfate ratio for each hour of the simulation, using meteorological fields either from RAMS or from SKIRON/Eta model. Figure 2 shows one example of the analysis of episodes based on the comparison of modeling results with observations of particulate sulfate in Southern Greece (station located in Finokalia at northeastern Crete).

In addition to the anthropogenic produced aerosols, such as sulfates and/or nitrates, desert dust contributes significantly to the air quality degradation, due to the episodic

character of increased desert dust concentrations (Table 1). In general, air pollution episodes originated from anthropogenic activities occur together with desert dust transport episodes, because of the prevailing synoptic conditions favorable to dust transport (ahead of a trough or behind an anticyclone in the Mediterranean Region). Such synoptic conditions are most of the times associated with stable atmospheric conditions and stagnation (transport of warm air masses aloft that suppress vertical developments like updraft and convergence zones). The amount of Saharan dust deposited on the Mediterranean waters or over the European land exhibits significant seasonal and inter-annual variability (Papadopoulos et al, 2003), having a rather episodic character (Figure 3). The strength and the frequency of occurrence of the Saharan dust episodes define the annual deposition amounts and patterns of aerosols to a high degree, alternating the mean annual values. This leads to the fact that long-term modeling and measurement data are essential in understanding the synergetic effects of sulfates and desert dust in the atmosphere of the Mediterranean Region.

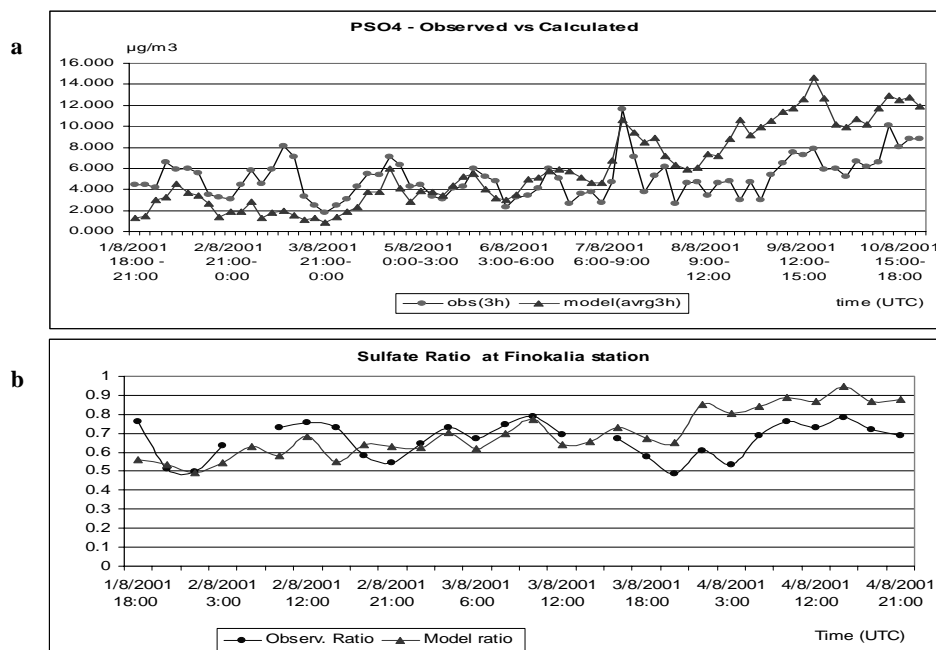


Figure 2. Intercomparison between measurements and model calculations of: a) particulate sulfate, and b) sulfate ratio, at Finokalia station, Crete, for August 2001.

Table 1. Desert dust episode for April, 2002, measured at Finokalia station, Crete.

Start date	End date	Saharan dust wet deposition (mg)
10/01/02	14/01/02	0
14/01/02	16/01/02	0
16/01/02	22/01/02	0
22/01/02	30/01/02	0.4
30/01/02	11/02/02	0.6
11/02/02	13/02/02	0
13/02/02	26/02/02	1.3
21/03/02	27/03/02	1.1
27/03/02	03/04/02	0
03/04/02	09/04/02	5.5
<b>09/04/02</b>	<b>16/04/02</b>	<b>179.6</b>
16/04/02	19/04/02	5.5
	26/05/02	0.4

#### 4. AIR POLLUTION MODELING: OZONE AND DUST FORECASTING

The knowledge gained from years of modeling atmospheric and photochemistry processes, provided the ability for forecasting weather phenomena and air pollutant concentration in the Mediterranean Region. Since January 2000, the SKIRON/ETA model runs operationally covering the Mediterranean Region, providing 3-day forecasts of dust load and deposition (<http://forecast.uoa.gr>), among other meteorological parameters. The ozone forecasting system applied for the Mediterranean Region runs operationally since July 2004, for the Athens Olympic Games (<http://forecast.uoa.gr>). The system is based on CAMx photochemical model and utilizes meteorological fields from SKIRON and RAMS in order to produce long-range transport fields of ozone and particulate for Europe and the Mediterranean Region.

The operational use of atmospheric and air quality models provides the opportunity to study the photochemical activity, particle formation and transport in various scales, from mesoscale to regional, as shown in Figures 3-5. The effort for producing reliable air quality predictions is a well-based and on-going task. Continuous research and sufficient measurements of air pollutants should aid this effort into the future of accurate predictions.

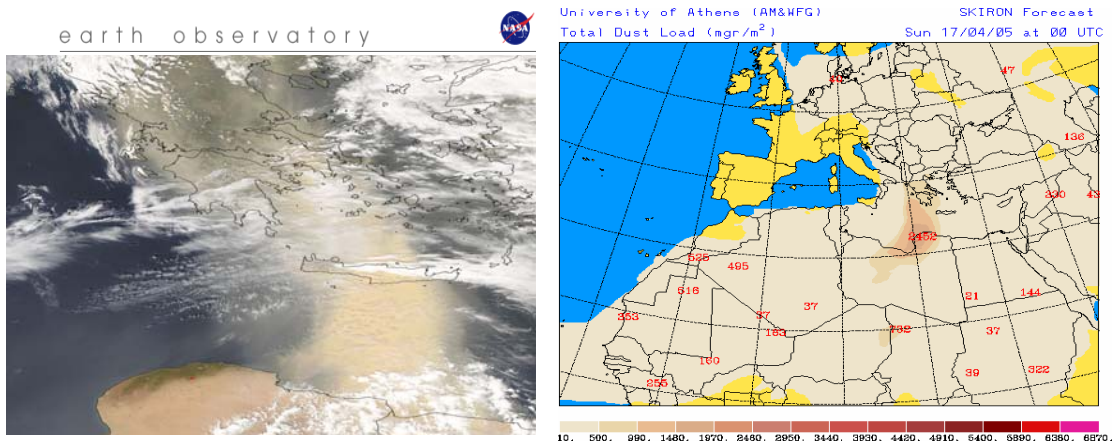


Figure 3. Saharan dust episode for April 17, 2005. Left: Dust over Greece, picture taken from NASA/GSFC satellite (2005/107 - 04/17 at 11:40 UTC). Right: Total dust load as simulated from SKIRON/Eta dust modeling system.

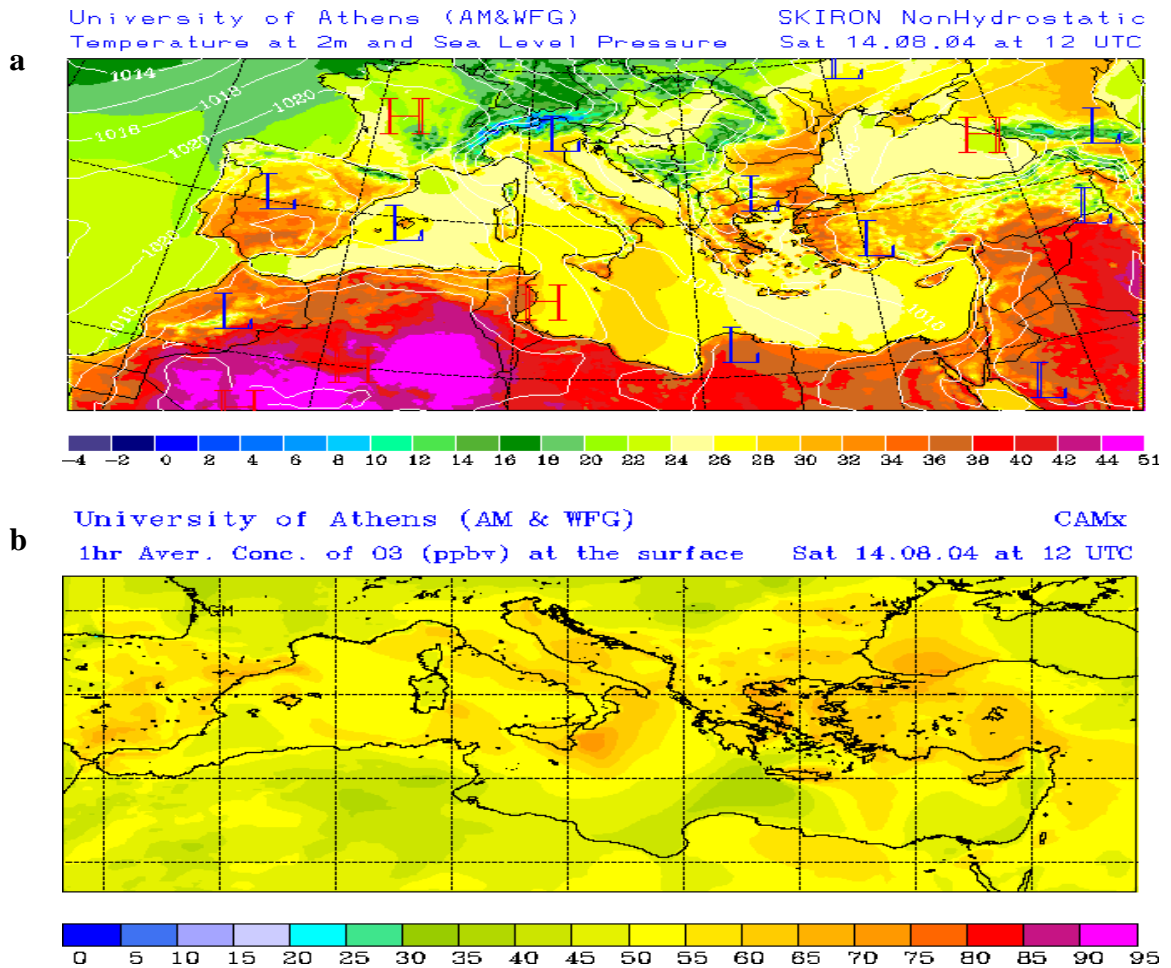


Figure 4. **a)** Regional weather forecasts from SKIRON/Eta and **b)** air quality forecasts from CAMx model (ozone) for the Mediterranean Region.

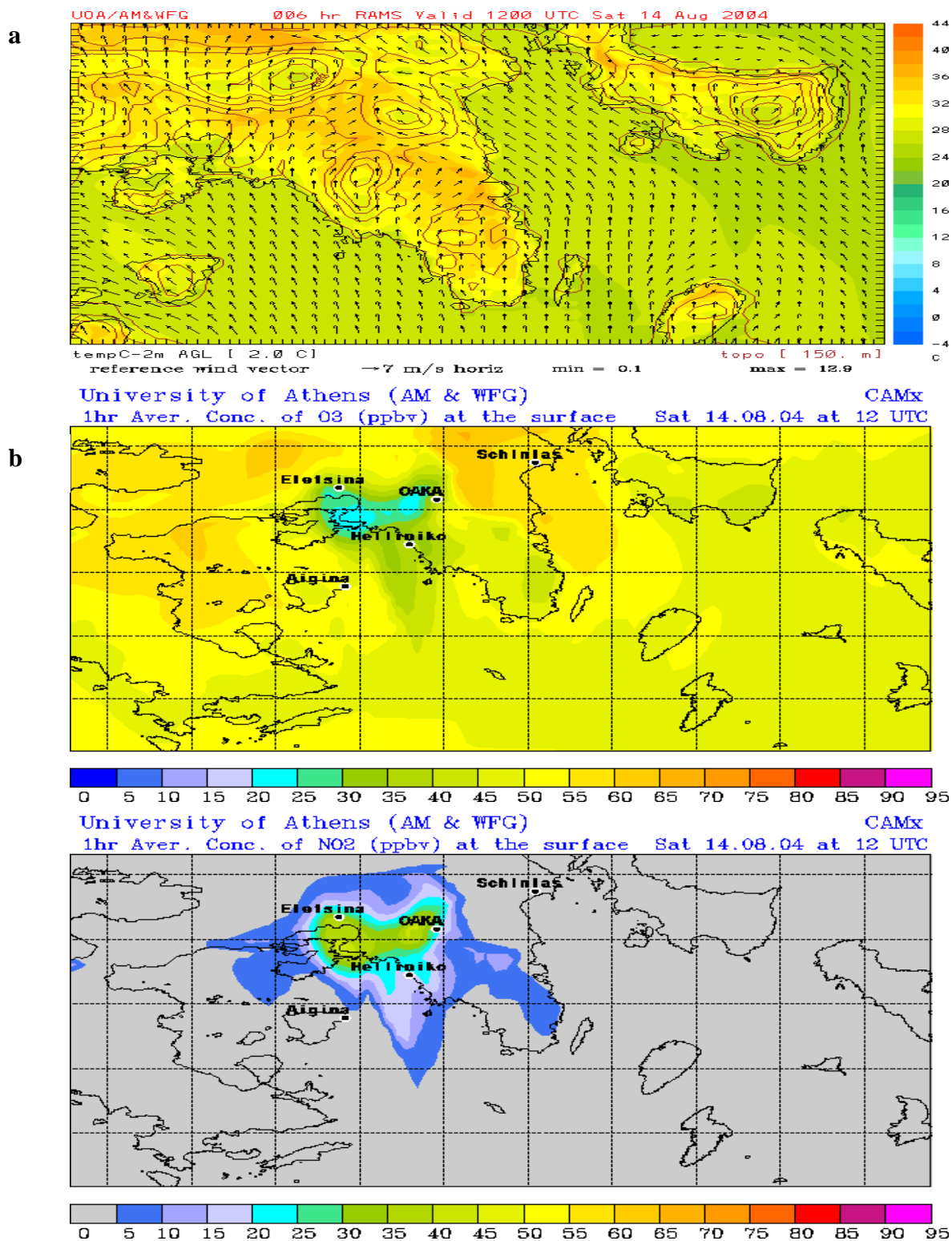


Figure 5. a) High resolution weather forecast from RAMS model and b) air quality forecasts (O<sub>3</sub>, NO<sub>2</sub>) from CAMx model for Athens Olympics (summer 2004).

## **5. CONCLUSIONS**

The present study summarizes the multi-year research modeling studies for identification of the characteristic spatial and temporal scales of photochemical activity along the previously defined main transport routes over the Mediterranean Region. Air quality degradation in the area is influenced by photochemical pollutants like ozone as well as aerosols such as particulate sulfate and desert dust. The photochemical activity, particle formation and transport are examined with the implication of model simulation in conjunction with measurements in several locations in the area. The remarks concluded from this work are summarized as follows:

The sulfate ratio sensitivity tests performed in this work showed results similar to those of Luria (1996), confirming the long range transport paths of sulfur towards the Middle East coast, during summer. Usually, high concentrations of sulfate, nitrate and other particles of anthropogenic origin, are associated with transport of desert dust due to the formation of stable atmospheric conditions. There are indications that the multi-scale transport and transformation processes might have significant climatic impacts. More specifically, there can be effects on rain and therefore the water balance in a region where the water budget is critical. This is possible 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 further more complicated because of the appearance of desert dust particles in the atmosphere which, in a wet environment, may be coated by sulfates and on that way they become very effective CCN.

The above conclusions are a result of the on-going research based on using modeling techniques for assessing the air quality over specific areas. Modeling tools are subject to continuous development in order to eliminate as many errors as possible. Thus, the on-going development has showed the way to producing real time forecasts of air pollution episodes in different scales: from urban to regional. The operational use of advanced atmospheric and air quality models has provided reliable predictions of several air quality episodes in the Mediterranean Region. Nevertheless continuous research and sufficient measurements of air pollutants should aid this effort into the future of accurate predictions.

## **6. ACKNOWLEDGMENTS**

This work was supported by the following projects: ADIOS, EU/DG-XII: EVK3-CT-2000-00035, MERCYMS, EU/DG EVK3-2002-00070. Measurements of air pollutants from Finokalia station, Crete were provided by professor N. Mihalopoulos (Environmental Chemical Process Laboratory, Department of Chemistry, University of Crete, Greece).



## REFERENCES

- Cotton, W.R.; Pielke Sr., R.A.; Walko, R.L.; Liston, G.E.; Tremback, C.J.; Jiang, H.; McAnelly, R.L.; Harrington, J.Y.; Nicholls, M.E.; Carrio, G.G.; McFadden, J.P., 2003, "RAMS 2001: Current Status and Future Directions, Meteorology and Atmospheric Physics" (Volume 82 Issue 1-4).
- di Sarra, A., T. Di Iorio, M. Cacciani, G. Fiocco, and D. Fuà, 2001. Saharan dust profiles measured by lidar from Lampedusa. *J. Geophys. Res.*, 106, 10,335-10,347.
- Environ 2003: User's Guide to the Comprehensive Air Quality Model with Extensions (CAMx). Version 4.00. Prepared by ENVIRON International Corporation, Novato, CA.
- Kallos G., V. Kotroni, K. Lagouvardos, M. Varinou, A. Papadopoulos, 1995: "Possible mechanisms for long range transport in the eastern Mediterranean". 21st NATO/CCMS ITM on Air Poll. Model. and Its Applic., 6-10 Nov., Baltimore, USA. Plenum Press, N.York, Vol 21, pp.99-107.
- Kallos, G., V., Kotroni, K., Lagouvardos, M., Varinou, M., Uliasz, A., Papadopoulos 1997: Transport and Transformation of air pollutants from Europe to East Mediterranean Region (T-TRAPEM). Final Report. Athens, Greece, pp.298
- Kallos, G., 1997. The regional weather forecasting system SKIRON: an overview. Proceedings of the symposium on regional weather prediction on parallel computer environments, University of Athens, Greece, pp. 109-122.
- Kallos, G., V. Kotroni, K. Lagouvardos, and A. Papadopoulos, 1999: On the transport of air pollutants from Europe to North Africa. *Geophysical Research Letters*. 25, No 5, 619-622.
- Kotroni, V., G. Kallos, K. Lagouvardos, M. Varinou, and R. Walko, 1999: Numerical simulations of the meteorological and dispersion conditions during an air pollution episode over Athens, Greece. *J. Appl. Meteorol.*, **38**, pp.432-447.
- Luria M., M. Peleg, G. Sharf, D. Siman Tov-Alper, N. Schpitz, Y. Ben Ami, Z. Gawi, B. Lifschitz, A. Yitzchaki, and I. Seter, 1996: Atmospheric Sulphur over the East Mediterranean region. *JGR*, 101, (25917).
- Nickovic, S., G.Kallos, A. Papadopoulos and O. Kakaliagou, 2001: A model for prediction of desert dust cycle in the atmosphere. *J. Geophysical Res.*, Vol. 106, D16, 18113-18129.
- Papadopoulos A., P. Katsafados, G. Kallos and S. Nickovic, S. Rodriguez, X. Querol, 2003. Contribution of Desert Dust Transport to Air Quality Degradation of Urban Environments, Recent Model Developments. 26th NATO/CCMS ITM on Air Pollution Modeling and its Application, Istanbul, Turkey. Proceedings.
- Rodriguez S., Querol X., Alastuey A., Kallos G. and Kakaliagou O., 2001. Saharan dust inputs to suspended particles time series (PM10 and TSP) in Southern and Eastern Spain. *Atm. Env.* 35/14, 2433-2447.