Contribution of European Aviation on the Air Quality of the Mediterranean Region: A modeling study

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***Abstract*—Aviation is one of the anthropogenic activities with significant past and forecasted growth rate. The emissions from aviation alter the atmospheric composition and have many non neglectable impacts on regional air quality and climate. The study of such processes can be conducted with mathematical models which use an online approach of the meteorological and chemical processes that affect and/or are affected by aviation. The Integrated Community Limited Area Modeling System (ICLAMS) is a fully integrated atmospheric model developed at the Atmospheric Modeling and Weather Forecasting group of the University of Athens. It deals with atmospheric meteorology and chemistry and their interactions in an online coupled way and on the same spatial, temporal and projection platform.**

The model was tested for the month of July 2005 for Europe and the Mediterranean Region. Two simulations have been performed, one with emissions from all anthropogenic activities and the second excluding the emissions from aviation. The comparison of the model results, with and without the aviation emissions, gave the opportunity to assess the impact of airport operations on the air pollution levels of the region and downwind areas, under characteristic summer meteorological conditions. The area that is influenced by the emissions from European aviation operations is very large, and the most effected region is the Western and Eastern Mediterranean and several areas in North Africa. The prevailing west – northwest circulation over West and Central Europe favors the transport of pollutants towards East, South East Europe and North Africa leading to perturbations in the atmospheric composition especially up to 4 – 5 km above surface. The ozone field is altered by the aviation emissions with perturbations in its daytime values that reach 5 - 8 ppb. The atmospheric concentrations of other gas and aerosol pollutants are also effected.

Keywords-air quality, pollution models, Athens Airport, emission inventories, aviation emissions

I. INTRODUCTION

Transportation (land transport, shipping, aviation) is an important contributor to regional and global emissions of several greenhouse gases and aerosols which play a crucial role, directly and indirectly, on clouds, radiation and climate (IPCC 2001). Aviation is one of the transport sectors with a remarkable growth rate that is expected to continue growing. This growth raises concerns on the environmental impact associated with aviation, including air pollution and noise, stratospheric ozone, radiation and cloud impacts, from regional to global spatial scales and from seasonal to decadal timescales. The attention has shifted from stratospheric ozone depletion from supersonic aviation in the 1970s, to upper troposphere – lower stratosphere (UTLS) ozone enhancement from subsonic aviation emissions during the 1990s. Recent research focuses on cloud cover perturbations (aerosol activation as CCN and IN) and radiative forcing (absorption and scatter of solar radiation) of aviation emissions. On the other hand, environmental issues can constrain air transport through adverse meteorology and environmental performance regulations.

The meteorological and chemistry processes that take place in the atmosphere are usually treated mathematically in an offline approach with non-existing or inadequate representation of significant microphysical and radiation processes and the interaction between these processes and the pollutants fields. Under specific conditions, this variability and the feedback of the chemical component on the meteorological processes becomes a dominant factor in the evolvement of the air pollution field and leads to alterations of the cloudiness and radiation transfer budget. In this study a new approach for the treatment of the aviation emissions in a regional atmospheric model has been used.

The ICLAMS model is an online coupled fully integrated, meteorology – chemistry – aerosols – cloud radiation atmospheric modelling system (Kallos et al. 2009; Kushta et al., 2008). It comprises of four submodels: a pre-processing, two core meteorological and chemical and a post-processing submodel. The pre-processing unit prepares the emission fields for the domain of interest, from different emission inventories (local, regional, global) converting them to the spatial resolution and the projection of the meteorological and chemical unit (polar stereographic). The meteorological unit is based on the Regional Atmospheric Modeling System (RAMS) (Pielke et al., 1992; Cotton et al. 2003). Its explicit microphysics parameterization provides detailed information

on the cloud properties allowing a more accurate representation of the cloud-aerosol interaction processes. The chemical unit treats the photochemical reactions, the gas, aqueous and aerosol phase chemistry mechanism and the atmospheric cycle of the online emissions of natural aerosols (mineral dust, sea salt) and biogenic emissions (isoprene). The natural aerosols and the chemical aerosols of sulfates and nitrates have been coupled with the radiation budget scheme and the microphysics scheme, accounting for the radiative forcing and CCN activation of these aerosols.

This paper is organized as follows: A description of the model characteristics is given in section II. In section III an evaluation of the new modeling system is performed. Section IV analyzes the case study regarding the contribution of the European aviation emissions on the air pollution field of Europe and Mediterranean. Section V summarizes the main findings.

II. MODEL CHARACTERISTICS

For the development of the new modeling system the Regional Atmospheric Modeling System – RAMS (version 6.0) is used as the base meteorological model, providing the dynamic cores for the advection, diffusion, radiation, clouds and surface processes. The nesting capabilities of RAMS allow the model to solve large domains of low resolution together with high and very high resolution nested ones. The explicit cloud microphysics scheme provides detailed information on the cloud properties adding to the accuracy of the wet deposition process, and aerosol – cloud interaction.

The first part of the new development includes the implementation of the natural and anthropogenic emissions. The atmospheric cycle of natural emissions includes the mobilization, transport and removal processes for desert dust and sea salt. These two categories of natural particles are important to aviation for many reasons. They can affect aviation in a direct way through reduced visibility or in an indirect way through dust ingestion by the jet engines. Another category of natural emissions are the VOC emissions from vegetation. Isoprene is the main chemical species emitted by vegetation and its emission is described with the method proposed by Guenther et al. 1993.

The anthropogenic emissions database is provided by the Joint Research Project (Ispra, Italy) and includes the gas pollutants, such as NO, NO_2, SO_2, CO, NH_3, VOCs and aerosol pollutants OC and BC at a resolution 0.1x0.1 latitude longitude. The aviation emissions include the same pollutants and are given in 4 operation altitudes: Land – Take off cycle 0 – 1 km, Climbing and descend 1 – 9 km ,Cruise 9 – 13 km, Supersonic > 13 km.

The chemical component of the model constitutes of the gas and aqueous chemistry module, the gas-particle interaction module, the transport and removal modules. The gas chemistry module is based on the chemistry mechanism SAPRC99 (Carter et al. 1988, 1990). The photochemical scheme uses the basic formulations proposed by Madronich et al. (1987). They are calculated directly on the detailed 3D temperature and pressure fields from RAMS model at a user defined frequency of 600 seconds. The aqueous chemistry module deals with the removal of the pollutants through scavenging and wet deposition, and with the chemical processes that take place inside a cloud. For the gas-aerosol processes the ISORROPIA mechanism is incorporated into the model. The mechanism used in this development includes ammonium, sodium, chloride, nitrate, sulfate and water, which are partitioned between gas, liquid and solid phases (Nenes et al. 1998).

III. TEST CASE JULY 2005

A test case for July 2005 has been performed, in order to study the ability of the coupled modeling system ICLAMS to capture the temporal and spatial variability of important air pollutants in the Mediterranean – Europe region and the contribution of aviation emissions on their atmospheric distribution. During this period there is high photochemical activity over the region of interest, low cloud cover and high irradiances. The domain of study has been set to have the characteristics given in Table 1. Ozone is the main gas pollutant used in this study because of its importance in defining the air quality index of an area. Sulfate aerosols are also analyzed due to their impact on the cloud properties (by acting as CCN) and the radiation budget of the Earth.

The initial conditions used as the starting point for the model calculation of the concentrations of air pollutants are taken from a lookup table with the value for background ozone being 35ppbv. A spin off time of 48 hours is given to the model with the analysis period being from 03 till 30 July. An initial statistical performance study has been performed with mean hour surface ozone observations from more than 60 EMEP station around Europe. These are stations with different characteristics, such as different altitudes, geographic location (shore, mountain, valley etc) and background classification (rural, background rural, semi urban etc). The mean hour surface ozone concentrations are compared in all stations. The statistics used for the analysis of the results include the mean bias which states the systematic error for a continuous variable and is defined as:

$$bias = \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i) = \overline{F} - \overline{O}$$

and the correlation coefficient – R which describes the correlation level between the model and observation values and

is defined as the covariance of the values to the product of their standard deviations:

$$r_{F,O} = \frac{\mathrm{cov}(F,O)}{s_F \cdot s_O}$$

The mean bias (units ppbv) factor quantifies the analogy between the mean modeled value and the mean observed value and can take negative or positive values. If bias < 0 then the model underestimates the set of values of the variable while bias > 0 means that the model has an overestimation over the observed mean value. The correlation coefficient can vary from -1 to + 1. The best correlation of the observed versus modeled values of the variable is achieved when the correlation coefficient reaches the value +1.

All the statistical results are summarized in Figure 1 and refer to the time period 03-30 July 2005. The correlation coefficients show good agreement between modelled and observed mean hour surface ozone for the majority of the EMEP stations. The mean biases for the test period are mainly negative for most of the stations. This is an indication of a slight underestimation of the mean hour ozone values that are predicted by the model in this area. There are several factors that can contribute to this outcome. One factor may be the initialization of the model from lookup tables with one value for the whole domain. Another significant factor may be the accuracy of the emission inventories and especially the temporal (daily and hourly) factors that are applied in order to convert the monthly emissions to daily and hourly values.

An additional parameter to better statistical results is usually the spatial and temporal resolution of the model configuration. The large resolution does not help in capturing maximum ozone levels as well as abrupt changes in ozone concentrations which depend on very local geophysical characteristics and localized traffic emissions. Long range transport of pollution from distant areas, which are outside of the model domain, can lead to underestimation of the pollutants field under specific meteorological conditions. Despite all these uncertainties, the comparison shows that the model captures in a satisfactory way the variation of the mean hour concentrations in European stations.

IV. CONTRIBUTION OF EUROPEAN AVIATION ON MEDITERRANEAN POLLUTION FIELD

In order to identify the contribution of the airport emissions on the ozone levels of Europe and Mediterranean another configuration has been set. Using the same domain characteristics and chemical and physical mechanisms as before, the air pollution field of the area has been simulated zeroing out the aviation emissions of BC, CO, NOx, OC and SO2 in the aviation emissions inventory from JRC. With this configuration the air pollution field of the area of interest has been modified.

The meteorological conditions during the test period present a complex wind field over Europe with an anti-cyclonic circulation over West Europe, during the first days of the test period, and a prevailing westerly flow during the rest of the days (Figure 2). The westerly flow is also present over Mediterranean especially during the second half of the test period. The surface flow pattern favors the transport of anthropogenic pollution produced over Europe and West Mediterranean towards East Mediterranean and North Africa, preventing at the same time the transport of natural aerosol pollutants like mineral dust towards higher latitudes

The alteration in the ozone field over Europe during day time and Mediterranean comes as a result of two mechanisms. Firstly, by excluding aviation emissions from the emission inventory of the region, less ozone precursors are emitted since NOx, CO and VOCs from airports are neglected. This leads to less ozone formation in and around airports in this case. Secondly, by not including aviation emissions, less ozone precursors are transported downwind leading to decreased amounts of ozone formed in distant areas due to less availability of its precursors. During night time the ozone field remains higher when the aviation emissions are included for two reasons: due to the preservation of the daytime difference and due to less reaction between ozone and NO.

Since the ozone formation reactions are fast reactions, the ozone transport is the main factor of the modification of the air pollution field in these downwind areas both during day (Figure 3a) and night (Figure 3b). This explains the linear and one sign alteration (positive = increase of ozone concentrations when the aviation emissions are included in the inventory) of the ozone air pollution field in these distant areas. The ozone difference patterns are dictated by the circulation patterns. For example when the westerlies are enhanced over West Europe the pollution is transported towards East Europe and further down towards Eastern Mediterranean due to the seasonal north winds (trade winds) over Aegean giving higher ozone concentrations over East Mediterranean and North-East Africa. The change of the wind field into an anticyclonic pattern over Central Europe and Italy leads to an enhanced transport of pollution towards Central Mediterranean and North coast of Africa and even inland Africa, before turning back to the Iberian peninsula leading to increases in ozone concentration over Spain and Italy of up to 5 – 6 ppbv. Respectively, the differences in the sulfate aerosols concentrations can reach 0.3 ug/m3 at noon time, in the case where the aviation emissions are included because of the elevated SO2 emissions. Due to limited cloud cover the main mechanism for the production of sulfate aerosols is the oxidation of the emitted SO2 rather than in cloud sulfate formation and heterogeneous mechanisms. Hence the surplus of SO2 emissions from aviation leads to an

increase in sulfate aerosols especially downwind from the airports areas. These results are illustrated in Figure 4 where the time series for mean hour ozone and sulfate aerosols for four main European cities in the vicinity of major airports are shown. In these cities, both ozone and sulfate aerosols in the case when the airport emissions are included in the simulation are higher than the respective concentration when the emissions from airports are not included. The differences in ozone concentrations vary from 5 ug/m3 for Madrid, Athens and Rome, to 10 ug/m3 for Paris Metropolitan area while sulfate aerosol increase reaches 10 – 15 % of the background value. Paris is located southwest of its main airport (Charles de Gaulle) and during this time period the main wind direction is north – northeast maximizing the impact of the inclusion of the airport emissions on the city air pollution burden.

V. SUMMARY AND CONCLUSIONS

A coupled online meteorological and chemical modeling system has been developed for a more accurate assessment of air quality patterns in a local and regional scale. This integrated modeling tool can be used either as operational (high resolution weather and air pollution forecasting), or as scenario and policy tool (environmental performance of aviation) or as a training asset. In this study, an effort has been dedicated to the identification of the emissions from European aviation on the air pollution field over Europe and Mediterranean.

Under characteristics summer conditions emissions from European aviation can influence not only Europe itself, but the Mediterranean Region and North Africa as well, and possible even far more distant areas. The aviation emissions as produced by JRC can increase the mean hour ozone concentrations during noon time by approximately 2 – 10 ug/m3 with the most affected areas being the Iberian Peninsula, Central and East Mediterranean. Other pollutants, such as sulfate aerosols show an increase due to SO2 emissions from the airports operations. Downwind areas are more vulnerable to such emissions, and especially when these areas are highly populated and/or industrialized. The perturbations in the concentrations of the ozone precursor such as VOCs, CO and NOx and particularly the ratio between VOCs and NOx determine the level of impact of the airport emissions over these areas. Large cities in the vicinity of major airports can show higher ozone differences, which can reach 10 ug/m3 under favorable meteorological conditions.

Due to the complex terrain and topographic characteristics of the area of study, the modeling of the air pollution patterns must be performed with high resolution configuration. This can be realized with the use of nested (smaller incorporated grids into the parent grid). A significant drawback to using high resolution configuration in air pollution models is the computational time required for the solution of the parameterization equations for each grid and the interaction processes between this grids. Despite this difficulty, the ICLAMS has been developed in order to perform high resolution modeling with parallel processing. In that case, the nested grids with higher resolutions can use other emission inventories which are expected to give a more accurate representation of the air pollution field of the area of interest. Aviation emission scenarios can also be applied in order to assess their impact on air quality in the short and long term.

Future work includes the performance of such assessment tests for winter and transition seasons (spring, autumn) and sensitivity tests for different scenarios on increase/decrease of all or particular gas pollutants emissions from aviation with feedbacks on clouds, precipitation and radiation budget.

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REFERENCES

[1] Carter W. P. L. (1988) Appendix C Documentation of the SAPRC Atmospheric Photochemical Mechanism Preparation and Emissions Processing Programs for Implementation in Airshed Models. Final Report for California Air Resources Board Contract No. A5-122-32

[2] Carter W. P. L. (1990) A detailed mechanism for the gas-phase atmospheric reactions of organic compounds. Atmos. Environ. 24A, 481-515

[3] Cotton, W. R. and Coauthors, 2003. RAMS 2001: Current status and future directions. Meteorol. Atmos. Phys., 82, 5-29

[4] Guenther, A., P. Zimmerman, P. Harley, R. Monson, and R. Fall, Isoprene and monoterpene emission rate variability: Model evaluation and sensitivity analysis, *J. Geophys. Res., 98*, 12609-12617, 1993.

[5] IPCC, 2001. Intergovernmental Panel on Climate Change's Synthesis Report. Climate Change 2001or web versions of 2001 IPCC reports.

[6] Kallos G., S. Solomos, J. Kushta 2009: Air Quality – Meteorology interaction processes in the ICLAMS modeling system. 30th International Technical Meeting Proceedings – Conference on Air Pollution Modeling and Applications, California, USA

[7] Kushta J., S. Solomos, C. Spyrou, M. Astitha, E. Mavromatidis, G. Kallos, 2008: A modeling system for describing mineral dust and sea salt cycles in the atmosphere. 12th ATRS World Conference, Athens, Greece

[8] Madronich S., 1987, Photodissociation in the atmosphere, 1, actinic flux and the effects of ground reflections and clouds. Journal of Geophysical Research, 92, 9740-9752

[9] Nenes, A., Pilinis, C., Pandis, S.N., 1998. ISORROPIA: A new thermodynamic model for inorganic multicomponent atmospheric aerosols. Aquatic Geochemistry, 4, 123Ð152.

[10] Pielke, R. A., and Coauthors, 1992. A comprehensive meteorological modeling system – RAMS. Meteorol. Atmos. Phys., 49, 69-91

[11] Walko R., C. Tremback "RAMS Regional Atmospheric Modeling System: Introduction to RAMS 4.3/4.4". Colorado State University

FIGURES AND TABLES

Table 1. Model configuration

Number of X points	210
Number of Y points	160
Number of levels	29 (with vertical resolution starting from 100 m to 1000 m and model height up to 18 km)
Horizontal resolution	24 km
Temporal resolution	30 sec
Domain center	lat = 39^{o} lon 16 ^{o}
Chemistry options	Gas, aqueous and aerosol chemistry activated

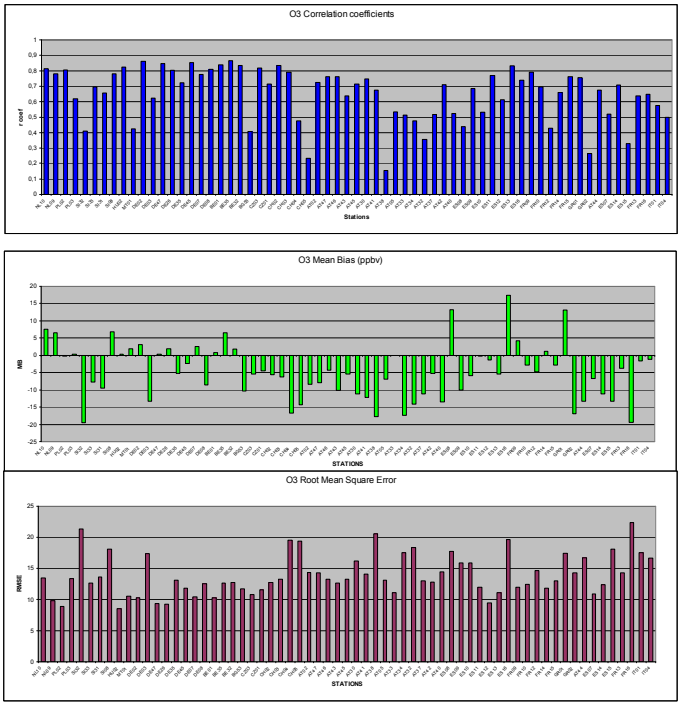

Figure 1. Correlation coefficients, Mean bias and Root Mean Square Error from the comparison of modeled values of mean hour surface ozone concentrations with observations from EMEP stations for the time period 03-30 July 2005.

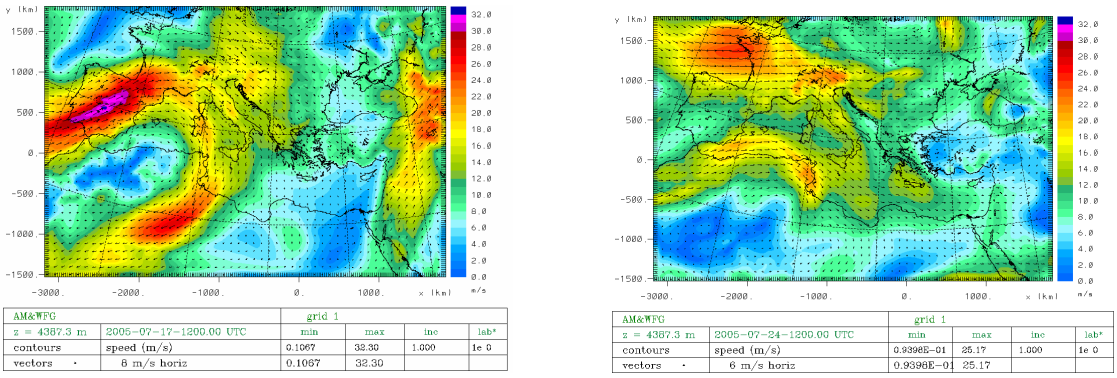

Figure 2. Wind speed and direction at 4500m over Europe and Mediterranean during the test period for 17 and 25 July 2005

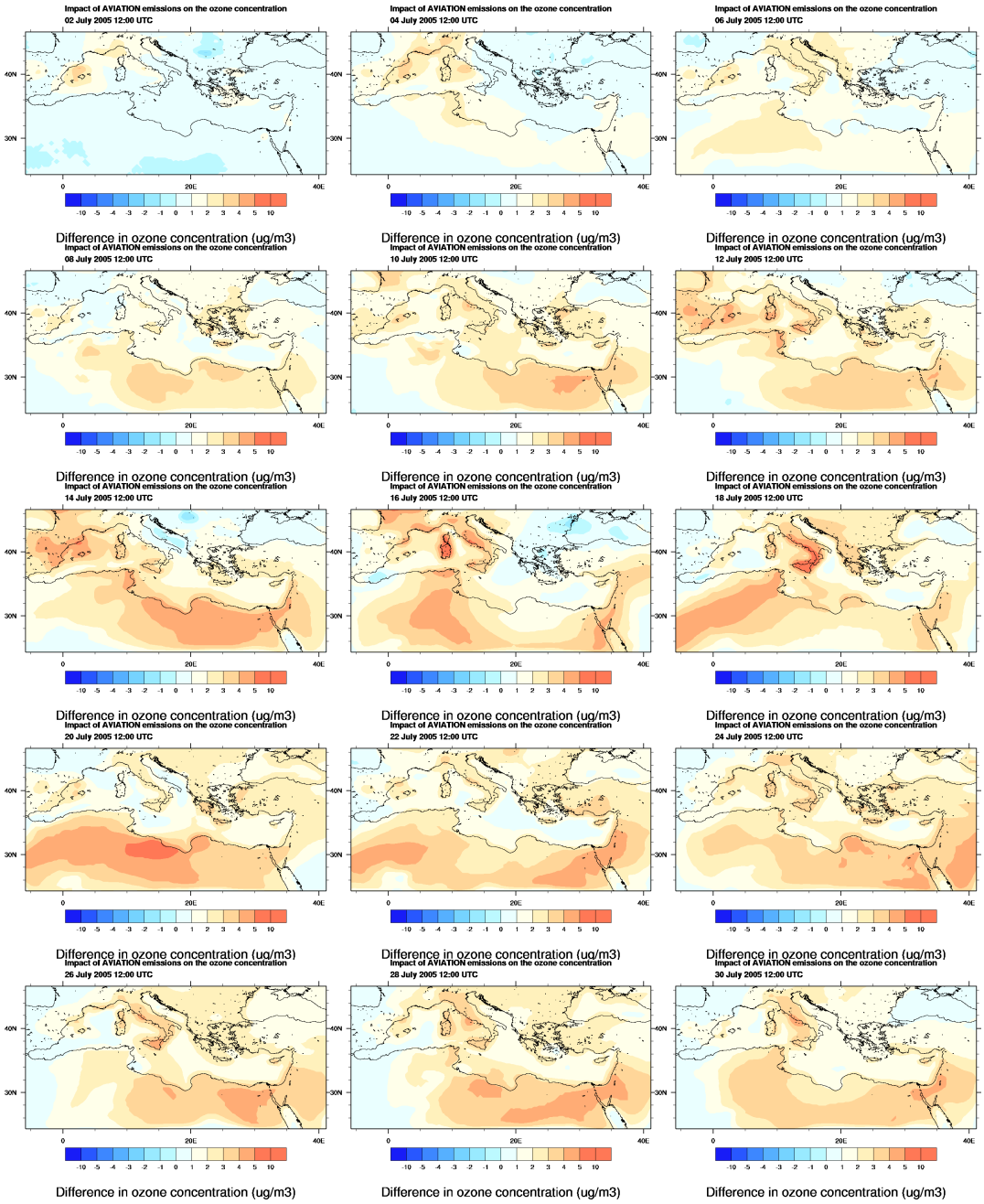

Figure 3a: Difference in the mean hour surface ozone concentration due to the utilization of the aviation emissions in the emission inventory for the even dates of July 2005, at 12:00 UTC. The difference is expressed as Concentration of ozone with aviation emissions minus Concentration of ozone without aviation emissions.

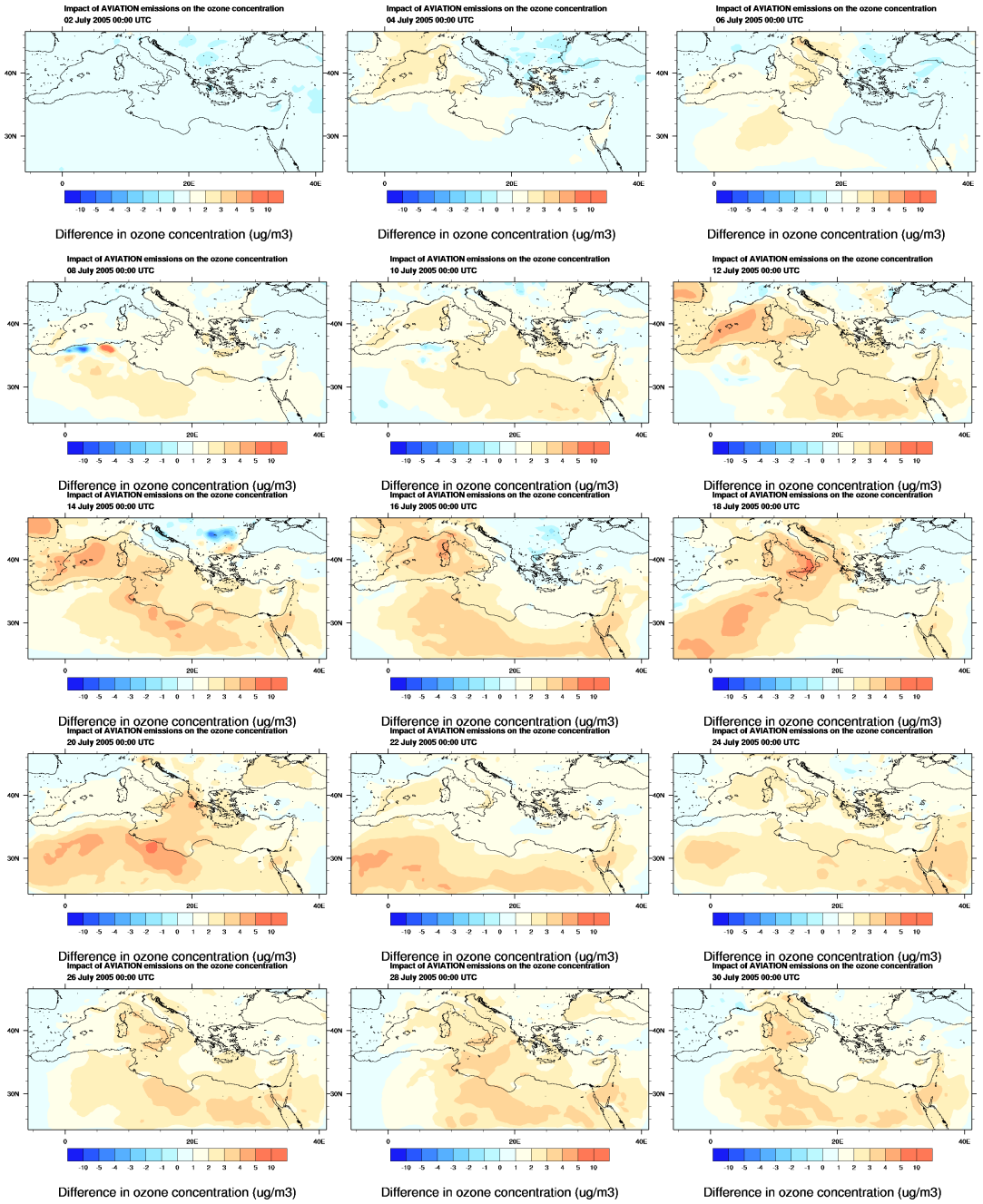

Figure 3b: Difference in the mean hour surface ozone concentration due to the utilization of the aviation emissions in the emission inventory for the even dates of July 2005, at 00:00 UTC. The difference is expressed as Concentration of ozone with aviation emissions minus Concentration of ozone without aviation emissions.

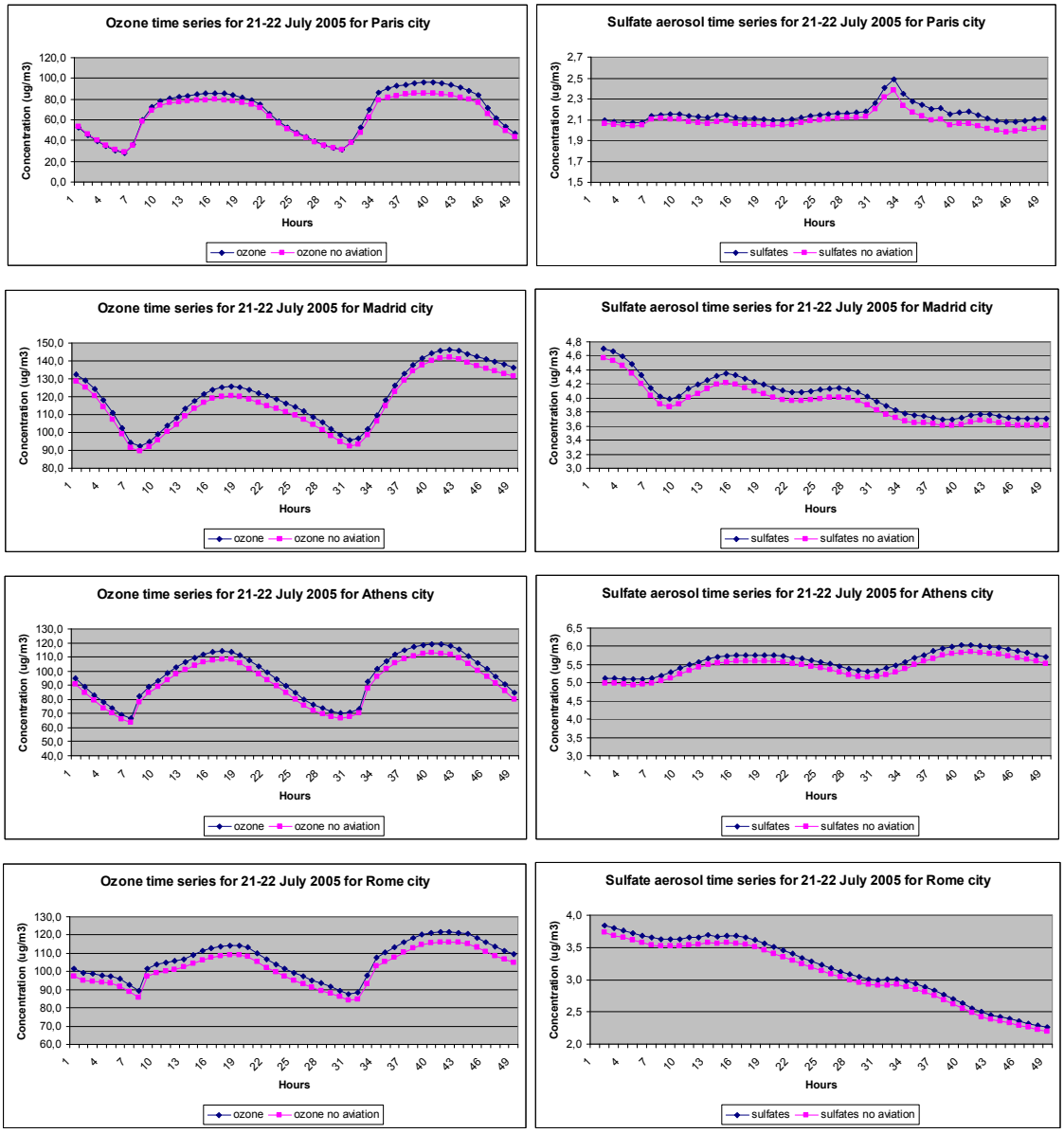

Figure 4. Ozone (left) and sulfate aerosols (right) time series during 21 and 22 July in four major European cities (Paris, Madrid, Athens, Rome) located near airports with significant emissions of gas and aerosol pollutants.