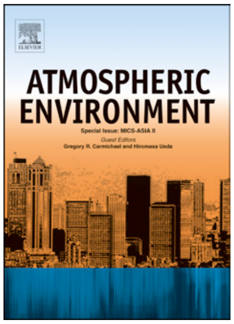


Title: Megacities as hot spots of air pollution in the East Mediterranean

Authors: Maria Kanakidou, Nikolaos Mihalopoulos, Tayfun Kindap, Ulas Im, Mihalis Vrekoussis, Evangelos Gerasopoulos, Eirini Dermitzaki, Alper Unal, Mustafa Koçak, Kostas Markakis, Dimitris Melas, Georgios Kouvarakis, Ahmed F. Youssef, Andreas Richter, Nikolaos Hatzianastassiou, Andreas Hilboll, Felix Ebojie, Folkard Wittrock, Christian von Savigny, John P. Burrows, Annette Ladstaetter-Weissenmayer, Hani Moubasher

PII: S1352-2310(10)01016-2

DOI: 10.1016/j.atmosenv.2010.11.048

Reference: AEA 10063

To appear in: *Atmospheric Environment*

Received Date: 4 July 2010

Revised Date: 17 November 2010

Accepted Date: 30 November 2010

Please cite this article as: Kanakidou, M., Mihalopoulos, N., Kindap, T., Im, U., Vrekoussis, M., Gerasopoulos, E., Dermitzaki, E., Unal, A., Koçak, M., Markakis, K., Melas, D., Kouvarakis, G., Youssef, A.F., Richter, A., Hatzianastassiou, N., Hilboll, A., Ebojie, F., Wittrock, F., von Savigny, C., Burrows, J.P., Ladstaetter-Weissenmayer, A., Moubasher, H. Megacities as hot spots of air pollution in the East Mediterranean, Atmospheric Environment (2010), doi: 10.1016/j.atmosenv.2010.11.048

Megacities as hot spots of air pollution in the East Mediterranean

Maria Kanakidou[a,*], Nikolaos Mihalopoulos[a], Tayfun Kindap[b], Ulas Im[a], Mihalis Vrekoussis[c, h], Evangelos Gerasopoulos[d], Eirini Dermitzaki[a], Alper Unal[b], Mustafa Koçak[a,e], Kostas Markakis[f], Dimitris Melas[f], Georgios Kouvarakis[a], Ahmed F. Youssef[g], Andreas Richter[h], Nikolaos Hatzianastassiou[i], Andreas Hilboll[h], Felix Ebojie[h], Folkard Wittrock[h], Christian von Savigny[h], John P. Burrows[h], Annette Ladstaetter-Weissenmayer[h] , Hani Moubasher[g]

[a] Environmental Chemical Processes Laboratory, Department of Chemistry, University of Crete, POBox 2208, 71003 Voutes, Heraklion, Greece

[b]Istanbul Technical University, Istanbul, Turkey

[c] Research Centre for Atmospheric Physics and Climatology, Academy of Athens, Athens, Greece

[d]National Observatory of Athens, Lofos Koufou, Penteli, Athens, Greece

[e] Middle East Technical University, Institute of Marine Sciences, Erdemli-Mersin, Turkey

[f] Aristotle University of Thessaloniki, Thessaloniki, Greece

[g] Cairo University, Center for Environmental Hazard Mitigation (CEHM), and Basel Convention Regional Centre for Training and Technology Transfer for the Arab States in Egypt, Giza, Egypt

[h] Institute for Environmental Physics, Bremen University, Bremen, Germany

[i] Department of Physics, University of Ioannina, Greece

[*] Corresponding author. Tel.: +30 2810 545033; Fax: +30 2810 545166. E-mail address: mariak@chemistry.uoc.gr (M. Kanakidou)

Abstract

This paper provides a comprehensive overview of the actual knowledge on the atmospheric pollution sources, transport, transformation and levels in the East Mediterranean. It focuses both on the background atmosphere and on the similarities and differences between the urban areas that exhibited important urbanization the past years: the two megacities Istanbul, Cairo and the Athens extended area. Ground based observations are combined with satellite data and atmospheric modeling. The overall evaluation pointed out that long and regional range transport of natural and anthropogenic pollution sources have about similar importance with local sources for the background air pollution levels in the area.

Keywords: megacities, East Mediterranean, air pollution, transport, anthropogenic impact

1. Introduction

The increasing need of humans for facilities, security, health care and employment have been the driving forces for increasing urbanization that gave birth to the Megacities, urban agglomerations with more than 10 million of inhabitants (http://www.worldclimate.com). This increasing urbanization not only affected the neighboring landscape, air quality, regional climate and ecosystems in the megacities but also downwind of these regions. During the last decades, the Mediterranean, following the general trend, has experienced a rapid growth in urbanization, vehicle use and industrialization as being reflected in pollutant emissions to the atmosphere.

The Eastern basin of the Mediterranean and the surrounding regions, include two megacities: the Greater Cairo area (GCA) (>15 million, Egypt) at the south edge of the basin and the Greater Istanbul Area (GIA) (>12 million inhabitants, Turkey) at the North East edge, as well as several large urban centers like to its northern part the Greater Athens area (GAA) (>4 million) in Greece (Table 1, Figures 1 and 2a) that exhibited important urbanization the past years. The region covers rural (inland Greek and Anatolian peninsulas), maritime (Crete and Cyprus islands) and desert (Anatolian plateau, north Africa, Middle East) sites.

The Mediterranean located at the boundary between the tropical and mid-latitudes, is subject to large (about 50%) changes in the total O_3 column (Ladstaetter-

Weissenmayer *et al*., 2007), which have been attributed to changes in the location of the sub-tropical front (Hudson *et al*., 2003). It is also a crossroad of air masses coming from Europe, Asia and Africa, where anthropogenic emissions, mainly from Europe, Balkans and the Black Sea, meet with natural emissions from Saharan dust (e.g. Kallos *et al.,* 1993, Kanakidou *et al.,* 2007), vegetation (e.g. Liakakou *et al*., 2009) and the sea (e.g. Kouvarakis *et al*., 2002), as well as from biomass burning (e.g. Balis *et al.,* 2003), which present a strong seasonal pattern. The transport of anthropogenic pollutants from America also exerts a significant influence in the free troposphere (Lelieveld *et al.*, 2002).

The typical Mediterranean climate is characterized by hot, dry summers and mild, rainy winters. Evaporation is especially high in its eastern half basin, greatly exceeding precipitation and river runoff in this region. This causes the sea water level to decrease and salinity to increase eastward (Demirov and Pinardi, 2002). As a consequence of its unique location and emissions, the Mediterranean is a climatically sensitive region, often exposed to multiple stresses, such as a simultaneous water shortage and air pollution exposure (IPCC, 2007) that is favored by the Mediterranean climate and is likely to grow in the future due to the rapid urbanization.

Air pollution is one of the challenging environmental problems in the whole East Mediterranean basin since both ozone and aerosol air quality limits are often exceeded, in particular during summer. In contrast to Central and Northern Europe, photochemical episodes can also occur during winter since at these latitudes solar radiation is intensive year-around, driving photochemical reactions that favour air pollution. The contribution of natural emissions to these exceedences seems significant and remains to be determined. High ozone and aerosol concentrations are harmful for human health and ecosystems, and they also cause agricultural crop loss and climate change.

This paper summarizes the actual knowledge on the atmospheric pollution sources, transport, transformation and levels in the Eastern Mediterranean. It first outlines characteristics of the two megacities Istanbul and Cairo and the Athens extended area, air transport patterns and meteorology. Then it discusses the similarities and differences between these major pollution sources in the region and compares them to the background atmosphere. Areas where further research is needed to support mitigation strategy development are pointed out.

2. The Megacities characteristics

The studied urban areas are distributed over three continents: Europe, Asia and Africa and present some common features as well as significant differences (Table 1). Istanbul extends on two continents with the European part of the city being the oldest one. It is separated from the Asian part by Bosporus strait of 30-km length that connects the Marmara Sea at the south with the Black Sea at the north.

The air circulation patterns at all three urban locations are affected by the existence of hills: seven hills in GIA, the Mogattam hill to the east and the southeast of GCA and the Parnes, Penteli and Hymettus mountains, all three over 1000 m, surrounding mainly the North- and East boundaries of GAA. In Istanbul northeasterly winds prevail during summer (Kindap, 2008) whereas southwesterly occur mainly during winter (Koçak *et al.*, 2010). Istanbul is vulnerable to trans-boundary transport of air pollutants from Europe, because of its location on the eastern end of the continent in the zone of westerly synoptic air flow (Kindap *et al.*, 2006). Cairo experiences two dominant wind sectors: the North sector and the South–West sector. Although prevailing all year long, the north sector presents maximum occurrence frequency in summer. The winter and spring seasons are significantly impacted by south-western winds (Favez *et al.*, 2008a,b). Finally, in Athens, the prevailing wind axis is north-east/ south-west and the ventilation takes place at northeasterly directions (Melas *et al.*, 1995).

GIA and GAA are both subject to sea and land breeze local circulation phenomena, favored during the weakening of the synoptic wind. During summer, the southern part of GIA close to the Marmara Sea experiences such circulation patterns that influence pollutants transport and accumulation in the boundary layer (Im *et al.*, 2006). The northern part of GIA is affected by the colder northern air masses and the cooler Black Sea. In Athens sea/land breezes appear along the axis of the basin (NE to SW) and anabatic/catabatic flows from the surrounding mountains. Under these circumstances the ventilation of the basin is poor; the boundary layer is shallow and the air pollution potential increases (Melas *et al.*, 1995 and references therein). The sea breeze system from the Saronic Gulf, located to the south of GAA, sweeps primary pollution from the city center, combined with O_3 titration, and favors pollutant accumulation to the northern suburbs where significant episodes are encountered. Air pollution episodes may occur in Athens during all seasons of the year but most of these episodes are associated with the development of sea-breeze (Kallos *et al.*, 1993).

2.1.Istanbul

The city of Istanbul (Table 1) is hosting almost 17% of Turkey’s population. Since the southern part of the GIA is the most urbanized, further growth will intensify pressure on industrial and residential uses in the northern part of the metropolitan region, where the natural protection areas and the watersheds are located (OECD, 2008). Average wind speed is highest in winter and lowest in summer with annual average of about 2.7m/s. The humidity is high during all seasons (Ezber *et al.*, 2007).

The heating effect due to urbanization was found to produce two-cell structure during summer, one on the European and one on the Asian side of the city. The cells extend to about 600–800 m height in the atmosphere over the city and combine aloft (Ezber *et al.,* 2007).

2.2.*Cairo*

Cairo (Al-Qāhirah), Egypt's capital (Table 1) situated south of the delta in the Nile basin, is the largest rapidly expanding city in Egypt facing many environmental problems. GCA's main populated area of about 200 km^2 is 4 km wide stretching 50 km along the banks of the Nile River. Outside GCA desert areas extend in the west and east directions. Dust and sand storms frequently occur in spring and autumn (Zakey and Omran, 1997). Hot desert cyclones known as the "Khamasin" depressions pass over the desert during spring, always associated with strong hot and dry winds often carrying dust and sand that increase particulate matter (PM) levels. During winter the climate is generally cold, humid and rainy; while during the summer season the predominant weather is hot and dry (Zakey *et al.,* 2008). The mean wintertime wind is weaker than during summer, implying a lower ventilation of the area during winter that could favor pollutant accumulation in the vicinity of the sources (Abu-Allaban *et al.,* 2009). Robaa (2003) showed that rural and suburban parts of the city have higher ventilation due to higher wind speeds than urban parts, which may lead to higher pollutant levels in the urban regions of GCA. Cairo has a very poor dispersion factor because of the advection patterns, its layout of tall buildings and narrow streets and the lack of rain (Table 1). This results in a permanent haze over the city with PM in the air reaching over three times the background levels.

2.3.Athens agglomeration

The GAA gathers about 40% of Greece’s total population in a basin on the west coast of the Attica peninsula. During the warmer part of the year, the mean wind pattern in the atmospheric boundary layer is a persistent northeasterly flow of relatively high constancy. GAA is also exposed to the summer monsoon circulation of the Eastern Mediterranean. Etesians, a system of semi persistent summer northerly winds, favor good ventilation of the basin prohibiting pollution episodes.

2.4. Outflow of pollution

Trajectories at approximately 700m height have been used to define air pollution transport patterns from Istanbul, Cairo and Athens, in a regional scale. They are based on 30-year (1961-1990) reanalysis data (NCEP/NCAR), available for every six hours at a 2.5^o resolution (Kindap *et al*., 2009). The computed probability depends on the grid size and increases with the trajectories length, with very small changes for trajectories longer than 8 days (Kindap *et al*., 2009). Figure 1 depicts the probability of air masses originating from GIA, GCA and GAA to reach various locations in the East Mediterranean, demonstrating the regional importance of air pollution from these megacities. Istanbul pollution is exported mainly in the North East- South West direction (Koçak *et al*., 2010) whereas Cairo outflow is mainly affecting the south-southwest locations and the Arabian Peninsula. Similarly, Athens plume is transported mainly towards South East over the East Mediterranean Sea. These results are in good agreement with the global modeling study by Lawrence *et al.* (2007).

3. Emission sources of air pollutants

All three cities experience heavy pollution from the transportation sector with more than 2 million of cars in Athens and Istanbul and more than 1 million in Cairo, of variable age and technical characteristics with the older ones in Cairo. A large fraction of their country's industrial activities is also located in their vicinity.

The emissions inventories available for the entire East Mediterranean have relatively coarse resolution (e.g. EMEP in 50 km resolution, Vestreng *et al.*, 2006, and global inventories down to $1^o x 1^o$ Granier et al., 2005). The new EDGAR v4 inventory now becoming available, is making significant improvement increasing the resolution to $0.1^o x 0.1^o$ (http://edgar.jrc.ec.europa.eu/). However for large urban agglomerations such as GIA, GAA and GCA higher resolution detailed emission inventories would greatly improve our understanding of air pollution levels in the area. Such inventories of anthropogenic sources have been developed by Markakis et al. (2009; 2001a,b), in high spatial (2x2 km^2) and temporal resolutions for the GIA (reference year 2007) and for the GAA (reference year 2003), but appropriate information is still missing for Cairo (Table 2). Weekend emissions are lower than week days and diurnal profile fits with the rush hours due to the highest contribution of traffic emissions (Markakis *et al*., 2009). Application of the Markakis *et al.* (2009) inventory has significantly improved the simulations of PM_{10} levels (Im *et al*., 2010) in GIA.

Table 2 shows the annual sectoral distribution of pollutants. Industrial activities are important sources of PM and responsible for almost 30 % of the SO_2 emissions. On-road traffic is the major contributor to CO, NO_x and non methane volatile organic compounds (NMVOCs) in Istanbul and Athens. Residential combustion and cargo shipping are significant pollution contributors in GIA and GAA. Similar conclusions are reached for Istanbul by Koçak *et al.* (2010), based on Positive Matrix Factorization (PMF) analysis of aerosol chemical characterization observations (Theodosi *et al.*, 2010) from an urban background site in Istanbul. Almost 20% of PM emissions in GAA originate from non-exhaust sources, including tire, break wear and road abrasion. The central heating operations do not account for more than a few percent in the annual totals (with the exception of SO_2 ~ 15% contribution), but in the winter months they make a significant contribution.

Cairo shows different emissions fingerprint: Residential Combustion and Industries being the major emitters of CO and NOx whereas NMVOC emissions are mostly from solvents use seconded by road transport. A significant portion of NO_x (~50%) and SO_2 (~71%) originates from industrial activities. On-road traffic is also an important source for CO (35%), NMVOC (37%) and $PM_{2.5}$ (36%). Anthropogenic $PM_{2.5}$ in GCA originates mainly (54%) from residential combustion and open burnings. Open fire burnings is a common practice and a major contributor to air pollution in Egypt, as also seen on aerosol optical depth (AOD) seasonality derived from satellite data with peaks in fall (Hatzianastassiou *et al*., 2009).

To limit air pollution, measures were taken in all three urban centres around 1990-1995 with different level of implementation success.

3.1.Istanbul

Between 1980 and 1990 the consumption ratio of coal to fuel-oil increased from 0.68 (in 1980) to 3.09 (in 1990; Tayanc, 2000). There has been the use of higher quality coal and a shift from coal to natural gas for domestic heating purposes starting from early 90s, leading to a decrease in the concentrations of primary pollutants such as sulfur oxides (SO_x) and an increase in secondary pollutants such as secondary aerosols and ozone (Tayanç, 2000). From the beginning of 1998 liquefied petroleum gas (LPG) has been widely used in traffic. Low quality solid and liquid fuels with high sulfur content, natural gas and LPG are the most commonly used fuel types in the industrial activities that comprise 37% textile, 30% metal, 21% chemical, 5% food and 7% other industries (Istanbul Chamber of Industry reports cited by Im *et al*., 2006). Under these dense and various industrial activities, the region experiences very complex air quality conditions.

3.2.Cairo

About 52% of the industries and 40% of the electricity production in Egypt are located in the GCA (Nasralla, 2001). Cairo has many unregistered lead and copper smelters which heavily pollute the city. GCA accommodates 50% of Egypt's road transport fleet, 60% of which is over 10 years old, lacking modern emission cutting features like catalytic converters (Mowafi and Atalla, 2005). The information regarding the amounts of pollutants released in the atmosphere of Cairo is very limited (El Mowafi and Atalla, 2005; Gurjar *et al.*, 2008; Table 2). Source apportionment analysis based on simultaneous observations of several non methane hydrocarbons (NMHC), including aromatics, and of aerosol components, including metals, (Abu-Allaban *et al*., 2002, 2007, 2009), pointed to mobile and industrial emissions (lead smelting and LPG, considering that industrial processes may be fueled by LPG) as the major source of NMHC during both summer and winter.

In 1995, the first environmental acts were introduced and the situation has seen some improvement, with 36 air monitoring stations and emissions control on cars. 20,000 buses have also been commissioned to the city to improve congestion levels. In 2003, Egypt initiated an enforced vehicle emission-testing program in Greater Cairo. The limits of CO, hydrocarbons and opacity for the vehicles have been significantly reduced in 1995. However, the publicized information indicated an overall failure rate of about 10% (El Mowafi and Atalla, 2005).

3.3. Athens

The massive number of registered vehicles in circulation, growing at a rate of 7% yearly, is allegedly the major cause of air pollution related problems in the area, taking into account the large proportion of non-catalytic (0.8 million) or powered by old technology diesel engines vehicles (0.2 million). Athens experiences very severe congestion phenomena with the average speed not exceeding 12 km/h during rush hours. Although the use of natural gas for domestic heating purposes has increased lately, combustion of fuel oil is still primarily used for central heating. The large industrial complexes are located in the Thriassion plain, several kilometres to the west of the GAA. They are separated from the Athens basin by mount Aigaleo (up to 450 m) that acts as a physical barrier preventing most of the exchange of air pollutants between the industrialized area and the city (Melas *et al.*, 1998).

4. Air pollution in the East Mediterranean

Enhanced levels of pollution (Figure 2) and increasing trends over the last decade are seen by satellites over East Mediterranean and over the Middle East and Cairo (Lelieveld *et al.*, 2008; Vrekoussis *et al*., 2009). Background tropospheric O_3 levels in the area are high, particularly in spring and summer, depending on the meteorological conditions since they are controlled by large-scale, long-range transport and photochemical formation (Gerasopoulos *et al.*, 2005). Background PM levels are also high due to a significant contribution of Sahara dust aerosol (Querol *et al.*, 2009) but also transported pollution (Mihalopoulos *et al.*, 2007). In the urban atmosphere due to the high levels of primary pollutants, like PM and $NO_{x,}$ maintained by the anthropogenic emissions, O_3 titration by reaction with NO is leading to very low O_3 levels over city centers, whereas NO_x and PM remain high. Primary pollutants decrease downwind where O_3 and secondary aerosols build up photochemically. In the urban regions, the temporal variability of primary gaseous pollutants reflects the high emissions during winter time and the faster photochemical destruction during summer time. Figure 2b depicts the tropospheric NO_2 columns as observed by SCIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY) for the period 2005-2006 and highlights the local pollution sources all around the Mediterranean. SCIAMACHY observations of NO_2 tropospheric column over the region (Figure 2b) indicate high tropospheric columns of NO_2 over urban sites around the Mediterranean with those over both the GIA and the GCA increasing over the last years (Vrekoussis *et al.*, 2009). This distribution nicely contrasts to the O_3 distribution shown in Figure 2a, that presents the largest enhancement actually over the water, covering the whole East Mediterranean basin, which acts as receptor of the surrounding pollution. Total columns of CO over the region range between 1.5 and $3x10^{18}$ molecules.cm^{-2} maximizing in late winter/early spring (high emissions) and minimizing in late summer/early fall (high photochemical destruction) (MOPITT: Measurements of Pollution in The Troposphere; ftp://l4ftl01.larc.nasa.gov/MOPITT/ MOP03M.003/).

Mean satellite observations of short lived trace gases (NO_2, CHOCHO, HCHO and O_3) and AOD over the region during the recent years are summarized in Figure 3. High tropospheric columns of NO_2, HCHO, CHOCHO are observed over urban locations (GIA, GCA, GAA) and low levels over the background receptor site of Finokalia. The progressive reduction of tropospheric columns of NO_2 from Istanbul to Athens and then to Cairo can be noticed together with a similar trend in CHOCHO and HCHO, used as proxy for NMVOC levels. Remarkably, CHOCHO peaks over GCA pointing to a higher NMVOC/NOx ratio than over GIA and GAA. This indicates higher O_3 formation potential of NO_x in GCA due to high NMVOC loadings, in agreement with ground-based observations (Abu-Allaban *et al.*, 2009).

The HCHO/CHOCHO ratio appears different over GCA than over GIA and GAA, indicating a different NMVOC speciation in this region, most probably strongly marked by biomass burning emissions. Tropospheric O_3 columns indicate the elevated O_3 background towards the south that maximizes over the Finokalia receptor site. However, they minimize over GCA that is closer to tropics and thus affected by a much lower total O_3 column (~18 DU lower than over Finokalia, based on TOMS / OMI 2005-2008 data in 0.25°x0.25° grid; http://gdata2.sci.gsfc.nasa.gov).

4.1.Ozone and its precursors

Table 3 recapitulates the available measurements of ozone in the Eastern Mediterranean at urban and regional background locations. A clear North to South increasing gradient is evident. In particular, surface O_3 increases when moving from rural background sites of Istanbul to Athens and then to Cairo, indicating significant contribution from long-range transport sources in air masses that age in the region. Ozone measurements along the Aegean Sea (NE Mediterranean, Kourtidis *et al*., 2002; Kouvarakis *et al*., 2000) confirmed that transport from the European continent is the main mechanism controlling ozone levels in the region, especially in summer (or spring depending on the prevailing air transport patterns), when ozone presents a maximum of about 60±10 ppbv (Gerasopoulos *et al.*, 2005).

Kalabokas *et al.* (2007) analyzing aircraft data found that during summer in the middle troposphere of the eastern basin, O_3 was only 5–10% higher than over Central Europe and high tropospheric ozone values were mainly confined in the low troposphere. Gerasopoulos *et al.* (2006b) analyzing 7 years of surface O_3 observations at Finokalia, found that the entrainment of O_3 rich air masses from the free troposphere (4–6% of the observed ozone levels) maximizes during summer, when the chemical production of O_3 is also enhanced by photochemistry and long-range transport. This summertime high regional source term of O_3 is almost balanced by the enhanced O_3 destruction via deposition and chemistry. Below a brief presentation of the ozone measurements at the various cities is presented.

4.1.1. *Istanbul*

Im *et al.* (2008) reported O_3 observations at two different urban locations within GIA located at both its European (8±7 ppbv) and the Asian (11±8 ppbv) parts from 2001 to 2005. The highest ozone levels were observed during sunny and warm summer days (maximum temperatures >25 °C) with southwesterly surface winds. Recent observations of ozone levels in semi-urban and rural stations in the GIA during the period 2007-2009 (Im *et al*., 2009), provide insight to the background levels of ozone in the extended area. They show higher ozone levels than the urban stations, reaching 30-35 ppbv on average, for high ozone seasons.

4.1.2. *Cairo*

Ozone in the southwestern Cairo area has been observed to exhibit a seasonal and diurnal cycle with levels reaching 70 ppbv in summer (Egyptian Environmental Affairs Agency, http://www.eeaa.gov.eg/ eimp/news8.html). Year-long, mean levels often exceed the Egyptian and European Union air quality standards of 60 ppbv for daytime (8-h) O_3 mixing ratios. Khoder (2009) reported a year (Dec 2004-Nov 2005) of observations of ground level O_3, nitrogen dioxide (NO_2) and nitric oxide (NO) concentrations at Giza in the GCA with daytime mean O_3 values of 91 ppbv during summer (Table 3). Air masses reaching Cairo during summer originate from the Aegean and the Cretan Seas. Thus, considering the Finokalia regional background values (60 ppbv), the observed mean value of 91 ppbv in Cairo indicates that despite O_3 titration from the local NO_x emissions, significant photochemical O_3 production occurs. This is additionally supported by high VOC levels (Abu-Allaban *et al.*, 2009) in the GCA, in agreement with the satellite observations shown in Figure 3. Maxima in O_3 levels occur in summer due to local photochemical production and long range transport whereas the highest levels of NO_x are found in winter. The diurnal cycles of O_3 revealed a uni-modal mid-day peak year-around. The diurnal variations in NO_x concentrations during the winter and summer showed two daily peaks linked to traffic density.

4.1.3. *Athens*

Kalabokas *et al.* (1999a,b) analyses of 11-year observations from the Greek Ministry of Environment air pollution network in Athens since 1987, show a significant downward trend for almost all primary pollutants in all stations. Comparison between the 3-year periods 1988-1990 and 1995-1997 gave the highest reduction in the center of GAA of 52%, 34%, 26% and 20% for SO_2, CO, NO_x and black smoke, respectively. The concentrations of the secondary gaseous pollutants remained essentially at the same levels since 1990, even though different characteristics (e.g. in ozone trends) may me observed for different site types (Hatzianastassiou *et al.*, 2007). Observations of O_3 prior to 2000 (Kalabokas and Repapis, 2004) at three stations in the GAA and the surroundings were found to exhibit characteristic seasonal variation of rural ozone concentrations, with lowest winter afternoon values at about 25 ppbv in December–January and average summer afternoon values at about 60 ppbv in July–August. These values are comparable to observations at Finokalia (Gerasopoulos *et al.*, 2005; 2006b) and indicate significant contribution from long range transport sources rather than local photochemistry.

The increased regional background in Athens is also supported by the CO-NOx molar ratios in GAA (Figure 4, derived from Table 3) that are between 20 and

30, whereas in GIA are lower ranging from 9.8 (Sarachane) to 12.6 (Kadikoy) close to those in Mexico City (11) and higher than for Tokyo (8.5) and US cities (6.7 in 2003) (Parrish *et al.,* 2009). Both in GIA and GAA, CO–to-NOx molar ratios are lower than the mean ratio of 41 observed in Beijing that has been attributed to significant regional contribution to CO levels in that megacity (Parrish *et al.,* 2009). Ratios higher than 50 are derived from the observations by Elminir *et al.* (2005) for a GCA residential site and point to the different CO sources characteristics (like older cars, domestic combustion and open fires) in GCA than in the other megacities. These ratios are however much lower than those of about 100 to more than 300 observed during summertime at Finokalia where long range transport is the dominant source for CO.

4.2. Airborne particulate matter

The Mediterranean is one of the areas with the highest AOD in the world, also seen from space (Hatzianastassiou *et al.*, 2009), which presents high temporal variability due to the short lifetime of PM in the troposphere (of the order of a week). Two-year (2005-2006) mean observations of AOD at 443nm over the area from MISR (Multiangle Imaging Spectro Radiometer) and of the aerosol small mode fraction derived from MODIS (Moderate Resolution Imaging Spectroradiometer, using the Giovanni daily data of NASA GES DISC), are depicted in Figures 2c and 2d. Although the annual mean AOD distribution is marked by the Sahara dust contribution, relatively high levels of AODs are also seen over the Aegean and the Black Sea. In addition, Figure 2d indicates the existence of significant fraction (about 0.5 to 0.6) of fine particles in the region that are commonly associated with pollution sources. Synergistic analysis of MODIS AOD and aerosol index TOMS data, used as proxy for absorbing dust aerosol, enabled a first evaluation of the local anthropogenic contribution to the AOD over the GAA and GCA at 15-30% and 25-50%, respectively, during summer (Hatzianastassiou *et al.*, 2009).

Ground- based observations over the area show high concentrations of aerosols, in both PM_{10} and $PM_{2.5}$ fractions (Querol *et al.*, 2009), with $PM_{2.5}/PM_{10}$ ratios around 0.5 (Table 3), in agreement with the satellite observations in Figure 2d. In the Eastern Mediterranean, PM_{10} has a similar seasonal behavior as $PM_{2.5}$, with maxima in spring and fall in the eastern basin due to African dust transport. This is also seen by lidar (Papayannis *et al*., 2008), sun photometer (Fotiadi *et al.*, 2006) networks and satellite based-sensors (Papayannis *et al.*, 2005; Kalivitis *et al*., 2007). PM_1 behaves differently showing small maxima during summer and is mainly dominated by pollution components (Gerasopoulos *et al.*, 2007; Koçak *et al.*, 2008).

In the background coarse mode aerosol ($PM_{1.3\text{-}10}$) dust and ionic components contribute about 40% and 50%, respectively and organics about 10% (Koulouri *et al.*, 2008a). Mineral dust transport events are found to contribute about 8-12 $\mu g\ m^{-3}$ to the background PM_{10} annual mean levels in the East Mediterranean, whereas an additional 5-10 $\mu g\ m^{-3}$ is attributed to transported anthropogenic regional sources and sea-spray loads (Querol *et al.*, 2009). Re-suspension of dust is likewise a significant and highly uncertain component of aerosols in the cities. Recent aerosol mass spectrometer measurements of ultra fine aerosols on Crete Island during late spring (Hildebrandt *et al.*, 2010), revealed highly oxidized background organic aerosol throughout the campaign, regardless of the source region. These observations of aged particles in air masses that circulated and were photochemically processed over the extended region, support the role of the East Mediterranean basin as the ‘pressure-cooker’ of transported air pollution. Compared to the colder Central and North Europe, the high temperatures in the Mediterranean impose a low thermal stability of ammonium nitrate in summer and favor the formation of nitric acid rather than ammonium nitrate in the area (Querol *et al.,* 2009; Mihalopoulos *et al.,* 1997).

High sulfate background loadings in the East Mediterranean are mostly attributed to the long-range transport of SO_2 (Zerefos *et al.,* 2000). In addition, significant interactions exist in the Mediterranean between natural and anthropogenic components in the atmosphere, both in the gas and aerosol phases. Observations and modeling have shown that on a mean yearly basis, marine biogenic emissions contribute up to 20% to the total sulphate production (Kouvarakis and Mihalopoulos, 2002). They also demonstrate that the reaction of dimethyl sulfide of marine origin with nitrate radicals, which are mainly of anthropogenic origin, is responsible for about 17% of the total HNO_3 production plus particulate nitrate formation (Vrekoussis *et al*., 2006). The deposition of these species is of great environmental significance since it provides nutrients to the ocean. During summer in the eastern Mediterranean, sulphate on fine particles is produced via gas phase reactions whereas almost 90% of the supermicron nss-sulphate is formed via heterogeneous pathways, coating natural aerosols (Mihalopoulos *et al.,* 2007).

4.2.1. *Istanbul*

Hourly PM_{10} levels are monitored by the metropolitan Municipality of Istanbul at the urban network stations of GIA since late 90's. GIA experiences high and variable levels of PM_{10} and $PM_{2.5}$ particles (Table 3). Ozdemir *et al.* (2009) reported average PM_{10} levels of about 66 $\mu g \cdot m^{-3}$ observed at 10 Istanbul municipality stations during the last 10 years with values ranging from 47 $\mu g \cdot m^{-3}$ to 115 $\mu g \cdot m^{-3}$.

A significant fraction of studied PM_{10} episodes has been attributed to regional transport of African dust and anthropogenic emissions. Kindap *et al.* (2006) calculated that almost 50% of the wintertime PM_{10} episodes in 2002 are associated with air masses coming from Eastern Europe. Karaca and Camci (2010) attributed about half of the studied high PM_{10} levels in Istanbul in 2008 to distant source contributions. On the other hand, Im et al. (2010) studied the effect of local emissions on a 5-day PM episode in January 2008 using the high resolution emission inventory of Markakis et al. (2009) and attributed 90% of the elevated PM_{10} levels to local anthropogenic emissions, combined with very low persisting vertical mixing. This is in agreement with Koçak *et al.* (2010), who evaluated the contribution of the anthropogenic sources to PM_{10} levels at about 90%, in an independent analysis of the same episode.

Recently, more than one year of aerosol observations at the background Bõgaziçi University sampling station in Bosporus strait coast, provided the first complete chemical characterization measurements in GIA (Theodosi *et al*., 2010). They measured 9 different water-soluble ions, water soluble organic carbon (WSOC), organic and elemental carbon (OC, EC) and several trace metals, between November 2007 and June 2009. Trace elements related to human activities obtained peak values during winter due to domestic heating, whereas natural origin elements peaked during the spring period due to dust transport from Northern Africa. During winter, OC was found to be mostly primary and strongly linked to fuel oil combustion and traffic, as EC. Both OC and EC concentrations increased during winter due to domestic heating. The mean OC/EC ratio was about 2, lower than those in Athens and Finokalia, but close to those observed in GCA (Table 3), indicating an overall dominance of primary pollution. The higher WSOC to OC ratio observed during summer was mostly attributed to the presence of secondary, oxidised and more soluble organics. Source apportionment PMF analysis of these long term observations indicates that approximately 80 % of the PM_{10} in Istanbul is anthropogenic in origin (Koçak *et al.*, 2010). Secondary aerosols maximize during summer and are mainly due to long-range transport sources that account for 20% of the PM_{10} mass over the studied 1.5-years period. Adding the contributions of crustal and sea salt (10.2 and 7.5 % of the observed mass, respectively), regional sources can explain at least 38% of PM mass, in line with the earlier mentioned studies.

4.2.2. *Cairo*

There have been a number of studies that evaluated the long-term surface aerosol observations in Cairo (Abu-Allaban *et al*., 2002; 2007) along with chemical composition (Favez *et al*., 2008a,b). These studies showed that the area is characterized by elevated levels of surface PM, with annual averages around 100 μg m^{-3} and above (Table 3). Favez *et al*. (2008a,b) reported more than 2 years (Jan. 2003- May 2006) of weekly observations of bulk aerosols at two GCA urban sites (Table 3), along with their chemical characterization with respect to selected ionic species and carbonaceous aerosols (sum of EC and OC). Dust aerosols displayed high background levels (50 μg m^{-3}) all year long, maximizing during the dust storm periods (Favez *et al*., 2008a). About 40% of Ca^{2+} on these dust aerosols was found to be associated with ions of anthropogenic origin like $SO_4^{=}$, NO_3^- and/or Cl^-, pointing out human driven processes that alter the chemical characteristics of dust and thus its climatic impact on a regional scale. High concentration levels of non-sea-salt Cl^- (up to 15 μg m^{-3} on a monthly basis), likely of industrial origin, were observed in autumn and winter. During autumn, biomass burning aerosols originating from rice straw burning in the Nile Delta, known as the ‘‘Black Cloud’’ event, have been estimated to account for 12%, 35% and 50% of Cairo EC, water insoluble organic carbon (WIOC) and WSOC mass concentrations, respectively.

Overall, non-dust aerosols were equally distributed between carbonaceous aerosols and ions, and their concentrations were about 100 μg m^{-3} in autumn and winter, and 60 μg m^{-3} in spring and summer. Remarkably, relatively low WSOC/OC ratios (about 1/3) were obtained all the year-long. Favez *et al.* (2008b) further investigated the carbonaceous content in the sub micron fraction of aerosols at an urban site in GCA in spring 2005. They found well-marked diurnal patterns for the WSOC/EC and WIOC/EC ratios, with minima during the traffic-influenced morning period and maxima during the intense photochemical periods, suggesting significant formation of both WSOC and WIOC during the afternoon. Applying the EC-tracer method, they evaluated that freshly-formed secondary OC accounts for more than 50% of OC concentrations measured during the early afternoon period. This fresh SOC was calculated to be mainly (~60%) composed of WIOC species. The latter (unexpected) result has been tentatively attributed to low ambient relative humidity and high anthropogenic volatile organic compounds in Cairo (Favez *et al.*, 2008b).

4.2.3. *Athens*

Grivas *et al.* (2008) analysed PM_{10} concentration data collected by the Greek air quality monitoring network at 8 sites over the GAA, for the period of 2001-2004. Daily concentrations, averaged over the whole study period, ranged between 32.3 and 60.9 μg m^{-3} and the four-year average concentration of PM_{10} at five sites exceeded the annual limit value of 40 μg m^{-3}, while most of the sites surpassed the allowed percentage of exceedances of the daily limit value (50 μg m^{-3}). The urban sites were mainly affected by primary, combustion-related processes and especially vehicular traffic, as deduced from the examination of the diurnal distribution of particulate levels and by factor analysis. On the contrary, suburban background sites were subject to particle transport from more polluted neighbouring areas and secondary particle formation through gaseous precursors, both processes supported by favourable meteorological conditions. The association of the PM_{10} levels with backward trajectories indicated that a notable part of area-wide episodic events could be attributed to trans-boundary transport of particles (Querol *et al.,* 2009b).

5. Air pollution and impacts.

5.1.Climate

In the Mediterranean, aerosols reduce the solar radiation absorption by the sea by about 10%, alter the heating profile of the lower troposphere and exert a cooling effect five times higher than the warming induced by the greenhouses gases (Lelieveld *et al.,* 2002; Vrekoussis *et al.,* 2005). As a consequence, evaporation and moisture transport, in particular towards North Africa and the Middle East, are reduced. Satellite observation analysis (Rosenfeld, 2000) supported that aerosols caused important perturbations to cloud microstructure and convection, probably decreasing precipitation. Querol et al. (2009) analysis of available aerosol data in the Mediterranean pointed out three very important climate relevant features of the aerosols in the area: the increasing gradient of dust from the west towards the east; the change of hygroscopic behavior of mineral aerosols (dust) via nitration and sulphation; and the abundance of highly hygroscopic aerosols during high insolation (low cloud formation) periods. Radiative forcing by aerosols also influences the energy budget of the Mediterranean and the Black Sea, however the consequences of this are still poorly understood. A changing energy budget and anomalous winds are expected to influence the ocean circulation (Tragou and Lascaratos, 2003). Therefore, aerosols may affect several components of the eastern Mediterranean atmosphere-ocean system including the regional water cycle. These aerosol-generated effects are already substantial today, even though sulphate from Europe has actually decreased in the past two decades (Smith *et al.,* 2010) through the abatement of acidification.

5.2.Health - ecosystems

During summer the persistent northerly winds carry large pollution loads from Europe that can deposit onto the Mediterranean sea, for instance, nitrate and phosphorus containing aerosols, which affect the water quality and could contribute to eutrophication (Kouvarakis *et al*., 2001; Markaki et al., 2003). In addition, O_3 levels in the regions downwind pollution sources are also often exceeding phytotoxicity levels (Kourtidis *et al.*, 2002).

Furthermore, ageing of aerosols, such as coating of dust by pollution compounds (Falkovich *et al.*, 2004) or chemical trapping of nitrogen on pollen particles (Franze *et al*., 2005), can be harmful for human health. Katsouyanni (1995) points out that air pollution effects on health, partly determined by specific mixtures of air pollutants, may be altered by other environmental, behavioural and social patterns. She also points out that the health effects of the interactions between pollutants and photochemical oxidants can be enhanced in the Mediterranean under high temperatures and humidity patterns. She stresses that even if the health effects of air pollution only slightly increase the risk to an individual, they are likely to be important for public health because of the ubiquitous exposure of the population.

El Mowafi and Atalla (2005) cited that approximately 3% of the GCA population is chronically exposed to PM_{10} levels above 100□$\mu g.m^{-3}$, compared to 48% exposed to 100-50□$\mu g.m^{-3}$ and 49 % exposed to 50-5□$\mu g.m^{-3}$ PM_{10}. Based on ambient air pollutant concentrations Gurjar *et al.* (2008) have classified Cairo as a megacity with extremely poor air quality, where measures for air pollution reduction need to be taken urgently. It is estimated that 10,000 to 25,000 people a year in Cairo die due to air pollution-related diseases. These findings indicate the significant benefits that could be achieved by implementing the proper abatement measures to improve air quality in Cairo.

6. Conclusions

Significant effort is recently paid on understanding atmospheric composition change in the East Mediterranean due to human activities, supporting the role of the basin as the ‘pressure-cooker’ of transported air pollution from distant anthropogenic sources but also from surrounding urban centres. Air masses are mixed and aged in the area under favourable meteorological conditions with high solar radiation. Background O_3 observations show an increasing gradient towards the south that partially compensates O_3 titration by NO_x in the urban sites. The increased regional background contribution in Athens, Cairo and Finokalia compared to GIA are in line with the observed CO/NO_x molar ratios. In GIA, CO/NOx molar ratio is close to that observed in Mexico City and Tokyo whereas in GCA is double or triple, indicating significant regional contribution to CO levels. This ratio maximizes at the background atmosphere ranging from about 100 to more than 300 observed during summertime at Finokalia, where long range transport is the dominant source for CO. GCA experiences also high levels of NMVOC that point to a high O_3 formation potential of NO_x in this region. Satellite observations of HCHO and CHOCHO seem to indicate different NMVOC speciation and sources over GCA than over GIA and GAA. Due to the non linear dependence of O_3 on NO_x and NMVOC levels, control of NO_x emissions is expected to lead to higher O_3 levels and thus O_3 exceedences in the cities. Available information on NMVOC total amounts, reactivity and chemical speciation is scarce, although the NMVOC/NOx ratio and VOC reactivity is critical for the build-up of air pollution. CO observations in rural areas are also limited, despite the key role of CO in O_3 production. There is a clear need of such reliable and systematic measurements of NMVOC, NO_x and CO in the region to support modelling of air pollution and climate impacts.

PM, even in the urban regions, is also shown to have a significant contribution by long range transport of African dust or distance anthropogenic pollution sources over the region. Data analysis has shown that a significant number of PM exceedences, registered in Istanbul and Athens as long range transport episodes, are associated with regional pollution or natural dust transport. PMF analysis of ground based aerosol chemistry observations indicates that local anthropogenic sources account for about 60% of PM levels in GIA and an additional 20% of PM levels is associated with transported anthropogenic pollution. Based on satellite derived AOD, the local anthropogenic emissions in GAA and GCA have been estimated to contribute by15-30% and 25-50% to the total AOD, respectively. These estimates need to be reconciled with ground based observations. On an annual mean basis, in the East Mediterranean the background PM_{10} contains about 8-12 $\mu g\ m^{-3}$ of transported mineral dust and an additional 5-10 $\mu g\ m^{-3}$ is attributed to transported anthropogenic regional sources and to sea-spray loads. Dust transport increases towards the east of the basin and dust aerosols are coated by pollution components that modify their climate relevant properties. The climatic impact of this mixture remains to be determined. The first limited number of available PM_1 data show that their composition and variability is tightly linked to the anthropogenic sources in the area. OC/EC observations help elucidating the ageing of pollution air masses and the contribution of photochemistry versus primary sources. Further studies of PM_1 mass and chemical characterisation will elucidate the sources and impact of PM pollution in the area.

Acknowledgements

This work has been supported by the EU FP7 project CITYZEN. Analyses and visualizations of TES, MISR and MODIS data used in this study were produced with the Giovanni online data system, developed and maintained by the NASA Goddard

Earth Sciences Data and Information Services Center (GES DISC). We thank Drs. J. van Aardenne and U. Doering for the emission inventory developed for the Mediterranean in the frame of the EU FP6 project CIRCE. We also thank the reviewers for their useful comments. Scientific discussions within the IGAC SSC and the iCACGP are acknowledged.

References

Abu-Allaban, M, Gertler, A.W., Lowenthal, D.H., 2002. A preliminary apportionment of the sources of ambient PM10; PM2.5; and VOCs in Cairo, Atmospheric Environment 36, 5549–5557.

Abu-Allaban ,M , Lowenthal , D.H., Gertler, A.W. ,Labib, M., 2007. Sources of PM10 and PM2.5 in Cairo's ambient air, Environmental Monitoring and Assessment, 133:417–425 DOI 10.1007/s10661-006-9596-8.

Abu-Allaban, M, Lowenthal, D.H., Gertler, AW., Labib, M., 2009. Sources of volatile organic compounds in Cairo's ambient air, Environmental Monitoring and Assessment, 157:179–189 DOI 10.1007/s10661-008-0526-9.

Acker, J.G., Leptoukh, G., 2007. Online Analysis Enhances Use of NASA Earth Science Data, Eos, Trans. AGU, Vol. 88, No. 2, 14 -17.

Balis, D., Amiridis, V., Zerefos, C. , Gerasopoulos, E., Andreae, M.O., Zanis, P. , Kazantzidis, A. , Kazadzis, S., Papayannis, A., 2003. Raman lidar and sunphotometric measurements of aerosol optical properties over Thessaloniki, Greece during a biomass burning episode, Atmospheric Environment, 37, 4529-2538.

Bardouki, H., Liakakou, H., Economou, C., Smolik, J., Zdimal, V., Eleftheriadis, K., Lazaridis, M., Mihalopoulos, N., 2003. Chemical composition of size resolved atmospheric aerosols in the Eastern Mediterranean during summer and winter. Atmospheric Environment 37, 195–208.

Chaloulakou, A., Kassomenos, P., Spyrellis, N., Demokritou, P., Koutrakis, P. 2003. Measurements of PM10 and PM2.5 particle concentrations in Athens, Greece, Atmospheric Environment, 37, 649-660

CIA The World Factbook 2009 https://www.cia.gov/library/publications/the-world-factbook/fields/2102.html?countryName=&countryCode=&regionCode=r

Demirov, E., Pinardi, N., 2002. Simulation of the Mediterranean Sea circulation from 1979 to 1993: Part I. The interannual variability, Journal of Marine Systems 33– 34, 23– 50.

Doering, U, van Aardenne, J., Monni, S., Pagliari, V., Orlandini, L. and San Martin, F., 2009. CIRCE report D8.1.3 Update of gridded emission inventories, addition of period 1990-2005 and the years 2010, 2015, 2050, Project FP6: 6.3 – No. 036961 - CIRCE, .

Elminir, H.K., 2005. Dependence of urban air pollutants on meteorology, Science of the Total Environment, 350, 225– 237.

Ezber Y., Sen, O. L. , Kindap, T., Karaca, M. , 2007. Climatic effects of urbanization in Istanbul: a statistical and modeling analysis, International J. Climatology 27: 667–679.

Falkovich, A. H., G. Schkolnik, E. Ganor, Y. Rudich, 2004. Adsorption of organic compounds pertinent to urban environments onto mineral dust particles, J. Geophysical Research., 109, D02208, doi:10.1029/2003JD003919.

Favez, O., H. Cachier, J. Sciare, S.C. Alfaro, T.M. El-Araby, M.A. Harhash, and M.M. Abdelwahab, 2008a, Seasonality of major aerosol species and their transformations in Cairo megacity, Atmospheric Environment, 42, 1503–1516.

Favez, O., J. Sciare, H. Cachier, S.C. Alfaro, M.M. Abdelwahab, 2008. Significant formation of water-insoluble secondary organic aerosols in semiarid urban environment, Geophysical Research. Letters, 35, L15801, doi:10.1029/2008GL034446.

Fotiadi, A., Hatzianastassiou, N., Drakakis, E., Matsoukas, C., Pavlakis, K.G., Hatzidimitriou, D., Gerasopoulos, E., Mihalopoulos, N., Vardavas, I., 2006. Aerosol physical and optical properties in the Eastern Mediterranean Basin, Crete, from Aerosol Robotic Network data, Atmospheric Chemistry and Physics, 6, 5399-5413.

Franze, T., Weller, M.G., Niessner, R., and Pöschl, U. , 2005. Protein Nitration by Polluted Air, Environmental Science and Technology. 2005, 39, 1673-1678, DOI: 10.1021/es0488737

Gangoiti, G., Alonso, L., Navazo, M., Garcia, J.A., Millan, M. , 2006. North African soil dust and European pollution transport to America during the warm Seaton: Hidden links shown by a passive tracer simulation, J. Geophysical Research, 111, D10109, doi:10.1029/2005JD005941.

Gerasopoulos, E., Kouvarakis, G., Vrekoussis, M., Kanakidou, M., Mihalopoulos, N., 2005. Ozone variability in the marine boundary layer of the Eastern Mediterranean based on 7-year observations. J. Geophysical Research 110, doi:10.1029/2005JD005991.

Gerasopoulos, E., Kouvarakis, G., Babasakalis, P., Vrekoussis, M.,Putaud, J.-P ., Mihalopoulos, N., 2006a. Origin and variability of particulate matter (PM10) mass concentrations over the Eastern Mediterranean, Atmospheric Environment, 40(25), 4679-4690.

Gerasopoulos E., Kouvarakis, G., Vrekoussis, M., Donoussis, Ch. Mihalopoulos, N., Kanakidou, M., 2006b. Photochemical ozone production in the Eastern Mediterranean, Atmospheric Environment, 40, 3057-3069.

Gerasopoulos, E., Koulouri, E., Kalivitis, N., Kouvarakis, S., Makela, T., Hillamo, R., Mihalopoulos, N., 2007. Size-segregated mass distributions of arosols over Eastern Mediterranean: seasonal variability and comparison with AERONET columnar size-distributions, Atmospheric Chemistry and Physics, 7, 2551-2561.

Granier C., A. Guenther, J. F. Lamarque, et al., “POET, a database of surface emissions of ozone precursors,” 2005, http://www.aero.jussieu.fr/projet/ACCENT/POET.php

Grivas, G., Chaloulakou, A., Kassomenos, P, 2008. An overview of the PM_{10} pollution problem, in the Metropolitan Area of Athens, Greece. Assessment of controlling factors and potential impact of long range transport, Science of the Total Environment, 389, 165-177.

Gülsoy, G., Tayanç, M., Ertürk, F., 1999. Chemical analysis of the major ions in the precipitation of Istanbul, Turkey, Environmental Pollution 105, 273–280.

Gurjar, B.R., Butler, T.M., Lawrence, M.G., Lelieveld, J., 2008. Evaluation of emissions and air quality in megacities, Atmospheric Environment 42, 1593–1606.

Hatzianastassiou, N., A. Gkikas, N. Mihalopoulos, O. Torres, B.D. Katsoulis, 2009. Natural versus anthropogenic aerosols in the eastern Mediterranean basin derived from multiyear TOMS and MODIS satellite data, J. Geophysical Research., 114, D24202, doi:10.1029/2009JD011982.

Hatzianastassiou, N., Katsoulis, B. D, Antakis, B., 2007. Extreme Nitrogen Oxide and Ozone Concentrations in Athens Atmosphere in Relation to Meteorological Conditions, Environmental Monitoring and Assessment, 128:447–464, DOI 10.1007/s10661-006-9338-y.

Hildebrandt, L., Engelhart, G.J., Mohr, C., Kostenidou, E., Lanz, V.A., Bougiatioti, A., DeCarlo, P.F., Prevot, A.S.H., Baltensperger, U., Mihalopoulos, N., Donahue, N.M., Pandis, S.N., 2010. Aged organic aerosol in the Eastern Mediterranean: the Finokalia Aerosol Measurement Experiment – 2008, Atmospheric Chemistry and Physics, 10, 4167-4186, doi:10.5194/acp-10-4167-2010,.

Hudson, R.D., Frolov, A.D., Andrade, M.F., Follette, M.B., 2003. The total ozone field separated into meteorological regimes. Part I: defining the regimes. Journal of Atmospheric Sciences 60 (14), 1669–1677.

Hubert-Ferrari, A., Armijo, R., King, G., Meyer, B., Barka, A. , 2002. Morphology, displacement, and slip rates along the North Anatolian Fault, Turkey, J. Geophysical Research, 107(B10), 2235, doi:10.1029/2001JB000393.

Im, U., Tayanç, M., Yenigün, O., 2008. Interaction patterns of major photochemical pollutants in Istanbul, Turkey, Atmospheric Research, doi:10.1016/j.atmosres.2008. 03.015

Im, U., Tayanç, M., Yenigün, O., 2006. Analysis of major photochemical pollutants with meteorological factors for high ozone days in Istanbul, Turkey. Water, Air, and Soil Pollution 175, 335–359.

Im, U., Markakis, K., Unal, A., Kindap, T., Poupkou, A., Incecik, S., Yenigun, O., Melas, D., Theodosi, C., Mihalopoulos, N. , 2010. Study of a winter PM episode in Istanbul using high resolution WRF/CMAQ modeling system. Atmospheric Environment, 44, 3085-3094.

Im, U., Tek, A., Kindap, T., Topçu ,S., Incecik, S., Yenigun, O., Odman, M.T., Tayanc, M., 2009. Investigation of tropospheric ozone levels in urban and semi-urban areas of Istanbul. 7th International Conference on Air Quality - Science and Application (Air Quality 2009), Istanbul, 24-27 March 2009.

Intergovernmental Panel on Climate Change (IPCC) (2007): Climate Change 2007: The Physical Science Basis. Summary for Policymakers. Paris, February 2007.

Kalabokas, P.D., Volz-Thomas, A., Brioude, J., Thouret, V., Cammas, J.-P., Repapis, C.C. , 2007. Vertical ozone measurements in the troposphere over the Eastern Mediterranean and comparison with Central Europe, Atmospheric Chemistry and Physics, 7, 3783-3790.

Kalabokas, P.D., Viras, L.G., Repapis C.C. , 1999a. Analysis of 11-year record (1987-1997) of air pollution measurements in Athens, Greece, Part I: primary air pollutants Global Nest: the Int. J., 1(3), 157-167.

Kalabokas, P.D., Viras, L.G., Repapis C.C., Bartzis, J.G. , 1999b. Analysis of 11-year record (1987-1997) of air pollution measurements in Athens, Greece, Part II: Photochemical air pollutants , Global Nest: the Int. J., 1(3), 169-176.

Kalabokas P.D., Repapis , C.C. 2004. A climatological study of rural surface ozone in central Greece, Atmospheric Chemistry and Physics, 4, 1139–1147.

Kalivitis, N., Gerasopoulos, E., Vrekoussis, M., Kouvarakis, G., Kubilay, N., Hatzianastassiou, N., Vardavas, I., Mihalopoulos, N. , 2007. Dust transport over the Eastern Mediterranean from TOMS, AERONET and surface measurements, J. Geophysical Research., 112, D03202, doi:10.1029/2006JD007510.

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

Kallos, G., Kotroni, V., Lagouvardos, K., Papadopoulos, A. , 1998. On the long-range transport of air pollutants from Europe to Africa. Geophysical Research Letters 25, 619-622.

Kallos, G., Astitha, M., Katsafados, P., Spyrou, Ch., 2007. Long-range transport of anthropogenically and naturally produced particulate matter in the Mediterranean and North Atlantic: Current state of knowledge, J. of Applied Meteorology and Climatology, 46, 1230-1251.

Kanakidou, M., Mihalopoulos, N., Kalivitis, N., Tsigaridis, K., Kouvarakis, G., Koulouri, E., Gerasopoulos, E., Vrekoussis, M., Myriokefalitakis, S. , 2007. Natural contributions to particulate matter levels over Europe – the experience from Greece, In CEST2007: A-585-592. http://www.srcosmos.gr/ srcosmos/showpub.aspx?aa=9717

Karaca F., Camci, F., 2010. Distant source contributions to PM10 profile evaluated by SOM based cluster analysis of air mass trajectory sets, Atmospheric Environment 44, 7, 892-899 doi:10.1016/j.atmosenv. 2009.12.006

Karaca, F., Alagha, O., Erturk, F., 2005. Statistical characterization of atmospheric PM10 and PM2.5 concentrations at a non-impacted suburban site of Istanbul, Turkey. Chemosphere 59, 1183-1190.

Kassomenos, P.A., Katsoulis, B. D., 2006, Mesoscale and macroscale aspects of the morning Urban Heat Island around Athens, Greece, Meteorol Atmos Phys 94, 209–218, DOI 10.1007/s00703-006-0191-x

Katsouyanni, K. ,1995. Health Effects of Air Pollution in Southern Europe: Are There Interacting Factors?, Environmental Health Perspectives, 103, S2, 23-27, Http://www.jstor.org/stable/3432445

Kindap, T., Unal, A., Chen, S.H., Hu, Y., Odman, M.T., Karaca, M., 2006. Long-range aerosol transport from Europe to Istanbul, Turkey. Atmospheric Environment 40: 3536–3547.

Kindap T., 2008. Identifying the Trans-Boundary Transport of Air Pollutants to the City of Istanbul Under Specific Weather Conditions, Water Air Soil Pollut 189:279–289, DOI 10.1007/s11270-008-9618-y.

Kindap, T., et al., 2009. Potential Threats from a Likely Nuclear Power Plant Accident: a Climatological Trajectory Analysis and Tracer Study" Water, Air, & Soil Pollution, 198, 1-4.

Khoder M.I., 2002. Atmospheric conversion of sulfur dioxide to particulate sulfate and nitrogen dioxide to particulate nitrate and gaseous nitric acid in an urban area, Chemosphere 49, 675–684.

Khoder M.I., 2009. Diurnal, seasonal and weekdays–weekends variations of ground level ozone concentrations in an urban area in greater Cairo, Environ Monit. Assess, 149:349–362 DOI 10.1007/s10661-008-0208-7

Koçak M., Mihalopoulos, N. Kubilay, N., 2008. Contributions of natural sources to high PM10 and PM2.5 events in the eastern Mediterranean, Atmospheric Environment, 41 (18): 3806- 3818.

Koçak M., N., Theodosi Ch., C. Theodosi, P. Zarmpas, U. Im, A. Bougiatioti, O. Yenigun, Mihalopoulos N., 2010. Particulate matter (PM10) in Istanbul: Origin, source areas and potential impact on surrounding regions, Atmospheric Environment, under review, 2010.

Koulouri, E. et al. ,2008a. Chemical Composition and sources of fine and coarse aerosol particles in the Eastern Mediterranean, Atmospheric Environment, 42, 6542–6550.

Koulouri E, Grivas G, Gerasopoulos E, Chaloulakou A, Mihalopoulos N, Spyrellis N, 2008b. "Study of size-segregated particle (PM1, PM2.5, PM10) concentrations over Greece", Global NEST Journal 10 (2) : 132-139.

Kourtidis, K., et al., 2002. Regional levels of ozone in the troposphere over eastern Mediterranean, J. Geophysical Research., 107(D18), 8140, doi:10.1029/ 2000JD000140.

Kouvarakis, G., Mihalopoulos, N. ,2002. Seasonal variation of dimethylsulfide in the gas phase and of methanesulfonate and non-sea–salt sulfate in the aerosols phase in the Eastern Mediterranean atmosphere. Atmospheric Environment 36 (6), 929–938.

Kouvarakis, G., Tsigaridis, K., Kanakidou, M., Mihalopoulos, N. , 2000. Temporal variations of surface regional background ozone over Crete Island in the southeast Mediterranean. J. Geophysical Research 105, 4399–4407.

Kouvarakis, G., N. Mihalopoulos, T. Tselepides, S. Stavrakakis, 2001. On the importance of atmospheric nitrogen inputs on the productivity of Eastern Mediterranean, Global Biogeochemical Cycles, 15, 805-818.

Kouvarakis, G., Bardouki H., Mihalopoulos, N, 2002, Sulfur budget above the Eastern Mediterranean: relative contribution of anthropogenic and biogenic sources, Tellus B., 54B, 201-212.

Ladstätter-Weißenmayer A., M. Kanakidou, J. Meyer-Arnek, E. V. Dermitzaki, A. Richter, M. Vrekoussis, F. Wittrock, J. P. Burrows, 2007. Pollution events over the East Mediterranean: Synergistic use of GOME, ground based and sonde observations and models, Atmospheric Environment, doi:10.1016/j.atmosenv.2007.05.031, 41, 7262–7273.

Lawrence, M. G., Butler, T. M., Steinkamp, J., Gurjar, B. R., Lelieveld, J., 2007: Regional pollution potentials of megacities and other major population centers, Atmospheric Chemistry and Physics, 7, 3969-3987, doi:10.5194/acp-7-3969-2007.

Lelieveld, J., Berresheim, H., et al., 2002. Global air pollution crossroads over the Mediterranean. Science 298, 794–799.

Lelieveld, J., Hoor, P., Jöckel, P., Pozzer, A., Hadjinicolaou, P., Cammas, J.-P., and Beirle, S., 2009: Severe ozone air pollution in the Persian Gulf region, Atmospheric Chemistry and Physics, 9, 1393-1406.

Liakakou, E., Bonsang, B., Williams, J., Kalivitis, N. , Kanakidou, M., Mihalopoulos, N., 2009. C2–C8 NMHCs over the Eastern Mediterranean: Seasonal variation and impact on regional oxidation chemistry, Atmospheric Environment, doi:10.1016/j.atmosenv.2009.07.067

Markaki, Z., Oikonomou, K., Kocak, M., Kouvarakis, G., Chaniotaki, A., Kubilay, N., Mihalopoulos, N., 2003. Atmospheric deposition of inorganic phosphorus in the Levantine Basin, Eastern Mediterranean: spatial, temporal variability and its role on the productivity of the Eastern Mediterranean Sea. Limnol. Oceanogr. 48, 1557–1568.

Markakis, K., Im, U., Unal, A., Melas, D., Yenigun, O., Incecik, S., 2009. A computational approach for the compilation of a high spatially and temporally resolved emission inventory for the Istanbul Greater Area. 7th International Conference on Air Quality Science and Application, 24-27 March 2009, Istanbul.

Markakis, K., Poupkou, A., Melas, D., Tzoumaka, P, Petrakakis, M., 2010. A computational approach based on GIS technology for the development of an anthropogenic emission inventory for air quality applications in Greece. Water, Air & Soil Pollution 207:157–180.

Markakis, K., Poupkou, A., Melas, D., Zerefos, C., 2010. A GIS based methodology for the compilation of an anthropogenic PM_{10} emission inventory in Greece. Environmental Pollution Research 1 (2):71-81

Melas, D., Ziomas, I.C., Zerefos, C.1995. Boundary layer dynamics in an urban coastal environment under sea breeze conditions, Atmospheric Environment, 29, 3605-3617.

Melas, D., Ziomas, I., Klemm, O., Zerefos, C., 1998. Anatomy of sea breeze circulation in Greater Athens under weak large-scale ambient winds. Atmospheric Environment 32, 2223-2237.

Mihalopoulos, N., Stephanou, E. , Kanakidou, M., Pilitsidis, P. Bousquet, S., 1997. Tropospheric aerosol ionic composition above the eastern Mediterranean area, Tellus, 49B, 314– 326.

Mihalopoulos N., Kerminen, V-M., Kanakidou, M, Berresheim , H., Sciare, J., 2007. Formation of particulate sulfur species (sulfate and methanesulfonate) during summer over the Eastern Mediterranean : A modelling approach, Atmospheric Environment doi:10.1016/j.atmosenv. 2007.04.039.

El Mowafi, S. A., Atalla, A. G., 2005. Strategies for controlling mobile emissions in Cairo, Management of Environmental Quality: An International Journal, 16, 5, 548-559, ISSN: 1477-7835. www.emeraldinsight.com/1477-7835.htm

Nasralla, M.M., 2001. Greater Cairo Air Quality Profile. Egyptian Environmental Affair Agency, Cairo, Egypt.

OECD, 2008. OECD Territorial Reviews, Istanbul, Turkey. ISBN-978-92-64-04371-8 http://browse.oecdbookshop. org/oecd/pdfs/browseit/0408051E.PDF

Ozdemir, H., Im, U., Markakis, K., Agacayak, T., Unal, A., Kindap, T., Khan, M., 2009. Impacts of Istanbul emissions on regional air quality: quantification using Model-3 Framework and trajectory analysis. 8th Annual CMAS Conference, Chapel Hill, USA, October 19-21

Papayannis, A., et al., 2008. Systematic lidar observations of Saharan dust over Europe in the frame of EARLINET (2000–2002), J. Geophysical Research., 113, D10204, doi:10.1029/2007JD009028.

Papayannis, A., et al., 2005. Measurements of Saharan dust aerosols over the Eastern Mediterranean using elastic backscatter-Raman lidar, spectrophotometric and satellite observations in the frame of the EARLINET project, Atmos. Chem. Phys., 5, 2065-2079.

Parrish, D.D., Kuster, W.C., Shao, M., Yokouchi, Y., Kondo, Y., Goldan, P.D. , de Gouw, J.A., Koike, M.,Shirai, T., 2009. Comparison of air pollutant emissions among mega-cities, Atmospheric Environment, 43, 6435-6441.

Querol, X., Alastuey, A., Pey, J., Cusack, M., Pérez, N., Mihalopoulos, N., Theodosi, C., Gerasopoulos, E., Kubilay, N., Koçak, M., 2009. Variability in regional background aerosols within the Mediterranean, Atmospheric Chemistry and Physics 9, 4575-4591.

Querol, X., Pey, J., Pandolfi, M., Alastuey, A., Cusack, M., Pérez, N., Moreno, T., Viana, N., Mihalopoulos, N., Kallos, G., Kleanthous, S., 2009. African dust contributions to mean ambient PM10 mass-levels across the Mediterranean basin. Atmospheric Environment, 43,4266- 4277.

Robaa, S.M., 2003. Urban-suburban/rural differences over Greater Cairo, Egypt, Atmósfera, 157-171.

Rosenfeld, D., 2000. Suppression of rain and snow by urban and industrial pollution, Science, 287, 1793-1796.

Sillanpää, M, Hillamo, R, Saarikoski, S, Frey, A, Pennanen, A, Makkonen, U, Spolnik, Z, Van Grieken, R, Branis, M, Brunekreef, B, Chalbot, M-C, Kuhlbusch, T, Sunyer, J, Kerminen, V-M, Kulmala, M, Salonen, RO., 2006. Chemical composition and mass closure of particulate matter at six urban sites in Europe. Atmospheric Environment 40:S212–S223

Smith, S. J., van Aardenne, J., Klimont, Z., Andres, R., Volke, A., Delgado Arias, S., 2010. Anthropogenic sulfur dioxide emissions: 1850–2005, Atmospheric Chemistry and Physics Discussions, 10, 16111-16151, doi:10.5194/acpd-10-16111-2010.

Tayanç, M., 2000. An assessment of spatial and temporal variation of sulfur dioxide levels over Istanbul, Turkey, Environmental Pollution, 107, 61–69.

Theodosi, C., Im, U., Bougiatioti, A., Zarmpas, P., Yenigun, O., Mihalopoulos, N., 2010. Aerosol chemical composition over Istanbul, Science of the Total Environment, 408 (12), 2482-2491.

Thomas Brinkhoff, 2009. The Principal Agglomerations of the World, http://www.citypopulation.de

Tragou, E., and Lascaratos, A. 2003. Role of aerosols on the Mediterranean solar radiation, J. Geophysical Research., 108, doi:10.1029/2001JC001258.

van Aardenne, J.A., Doering, U., Monni, S., Pagliari, V., Orlandini, L., San Martin, F., CIRCE report D8.1.1 Emission inventory for the entire past period 1990-2005 on 0.1x0.1 grid, Project FP6: 6.3 – No. 036961 - CIRCE, 2009

Vestreng, V., Rigler, E., Adams, M., Kindbom, K., Pacyna, J.M., van der Gon, H.Dr, Reis, S., Travnikov, O., 2006. Inventory Review 2006, Emission Data reported to LRTAP Convention and NEC Directive, Initial review of HMs and POPs. Technical report MSC-W 1/2006.

Vrekoussis, M., Liakakou, E., Koçak , M., Kubilay, N., Oikonomou, K., Sciare, J., Mihalopoulos, N. 2005. Seasonal variability of optical properties of aerosols in the Eastern Mediterranean. Atmospheric Environment 39, 7083–7094.

Vrekoussis M., Liakakou, E., Mihalopoulos, N., Kanakidou, M., Crutzen, P.J., Lelieveld, J. 2006. Formation of HNO_3 and NO_3^- in the anthropogenically-influenced eastern Mediterranean marine boundary layer, Geophyical. Reseasrch Letter, 33, L05811, doi:10.1029/ 2005GL025069.

Vrekoussis, M., Wittrock, F., Richter, A., and Burrows, J. P., 2009: Temporal and spatial variability of glyoxal as observed from space, Atmospheric Chemistry and Physics, 9, 4485–4504.

Vrekoussis M., Gerasopoulos, E., Mihalopoulos, N., Im, U. , et al., 2009. Spatial and temporal variability NO_2 mixing ratios inferred from satellite and ground-based observations above SE Europe: Role of Megacities, in the proceedings of the 7th International Conference on Air Quality –Science and Application, 24-27 March 2009, Istanbul. ISBN: 978-1-905313-64-8, published by University of Hertfordshire 2009.

Zerefos, C., Ganev, K., Kourtidis, K., Tzortziou, M., Vasaras, A., Syrakov, E., 2000. On the origin of SO_2 above northern Greece, Geophysical Reseasrch Letters, 27, 365– 368.

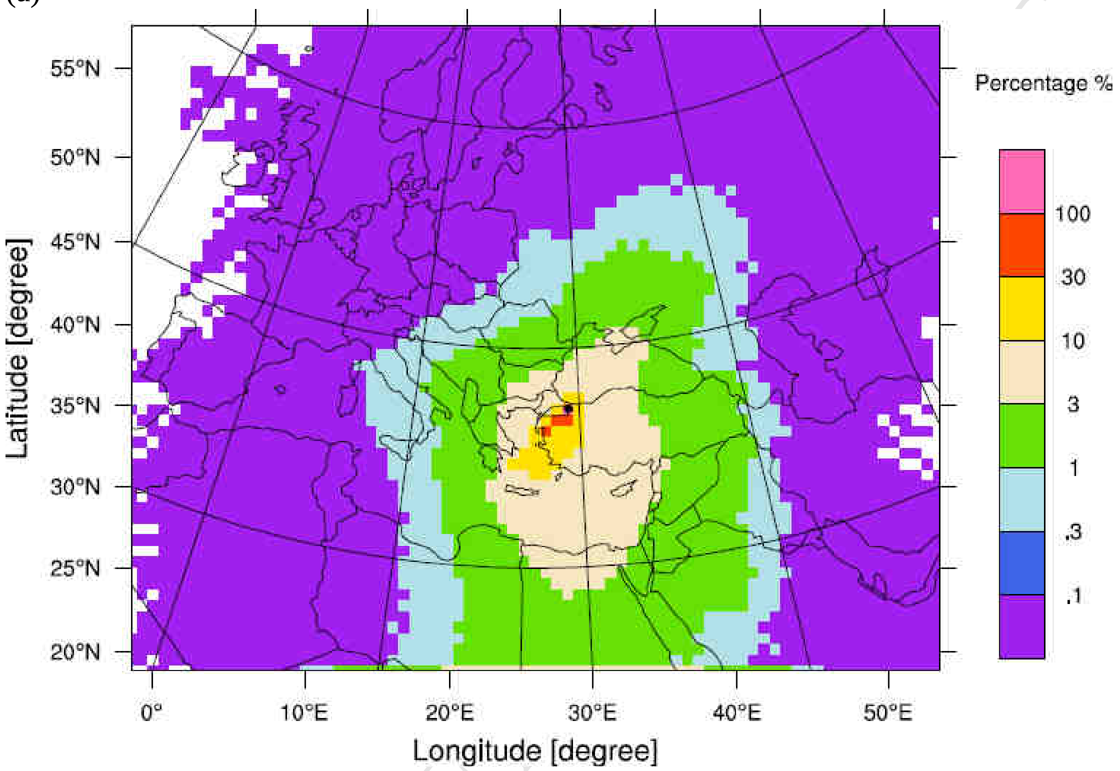
Zakey, A. S., and Omran, M. A., 1997. 1st LAS/WMO International Symposium on Sand and Dust Storms, WMO Programme on Weather Prediction Research Report Series Project No. 10, World Meteorological Organization (WMO), Technical Document No. 864.

Zakey, A. S, Abdel-Wahab, M. M., Pettersson, J. B. C, Gatari, M. J., Hallquist, M., 2008. Seasonal and spatial variation of atmospheric particulate matter in a developing megacity, the Greater Cairo, Egypt. Atmósfera 21,2, 171-189. ISSN 0187-6236.

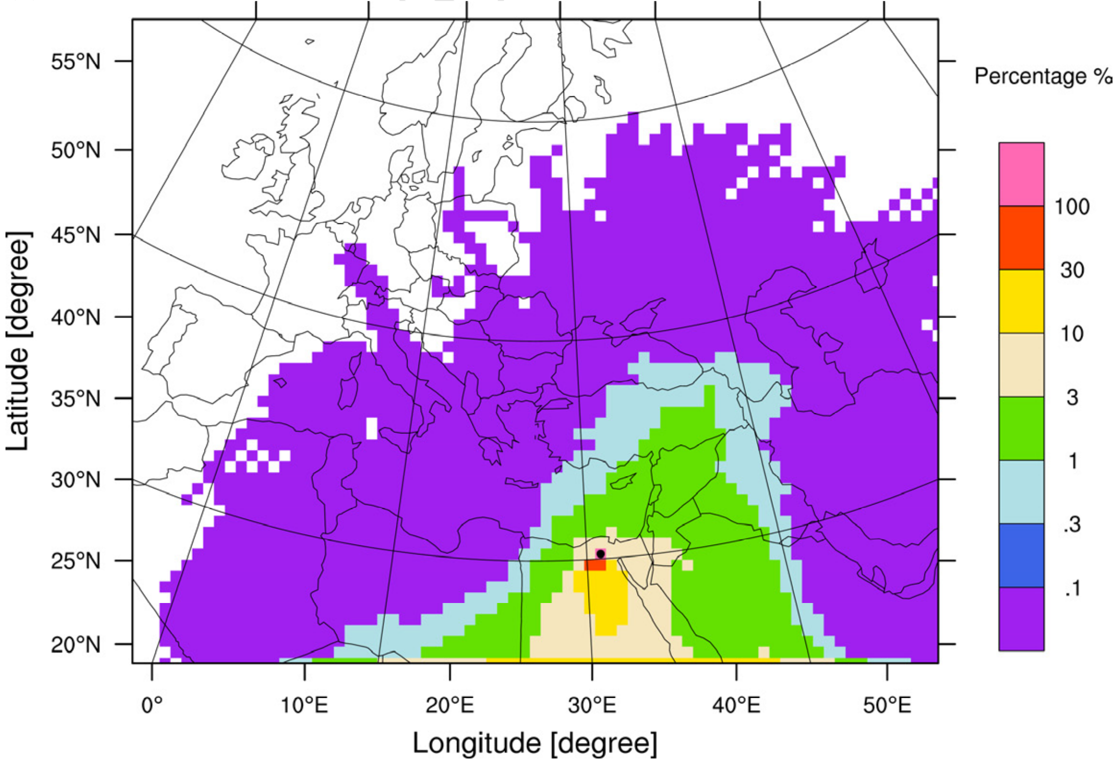
Figures

Figure 1: Map for the probability of arrival of trajectories starting from (a) Istanbul, (b) Cairo, (c) Athens, over the 30 years period based on NCEP 6-hourly meteorological data at 2.5^o resolution, see text. Dot points indicate the city of Istanbul, Cairo and Athens respectively.

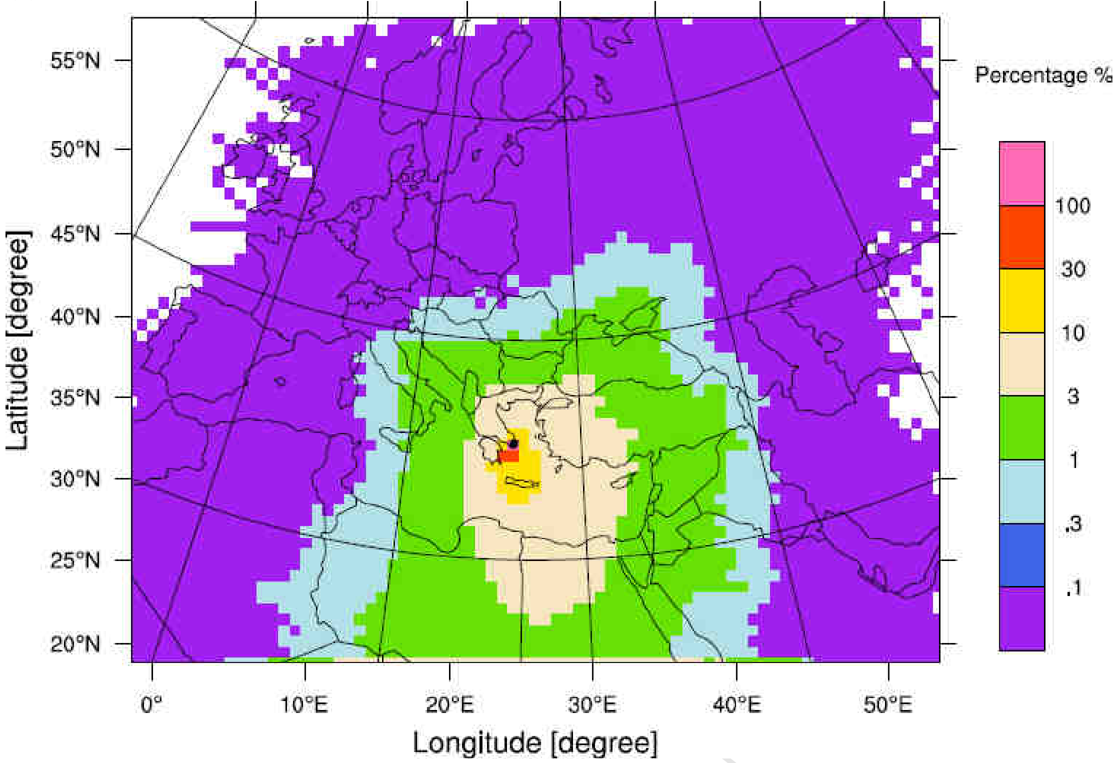
(a)



(b)

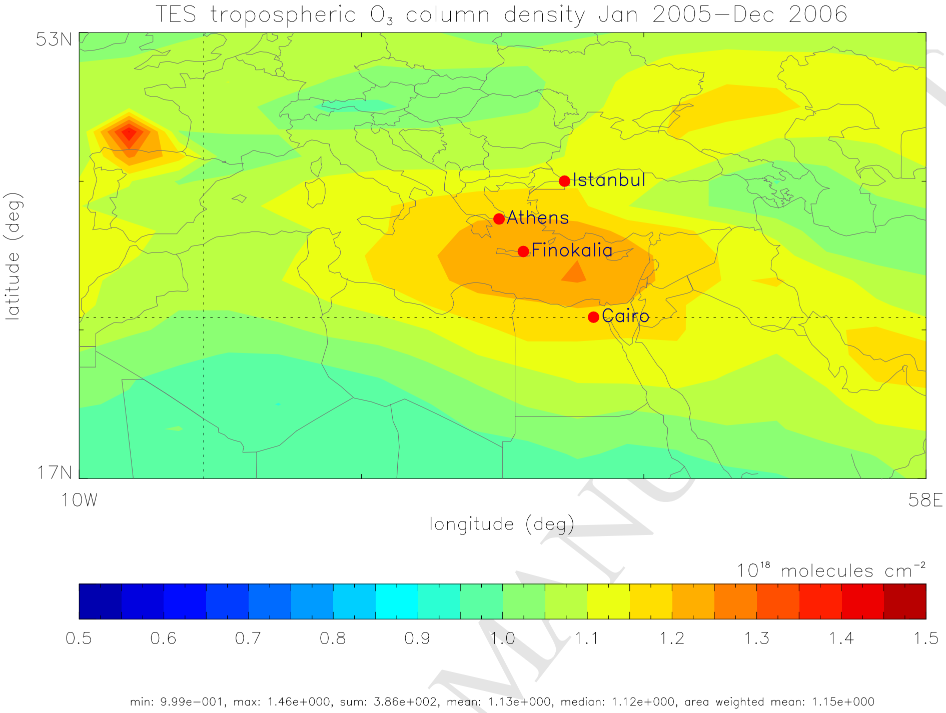


952 (c)

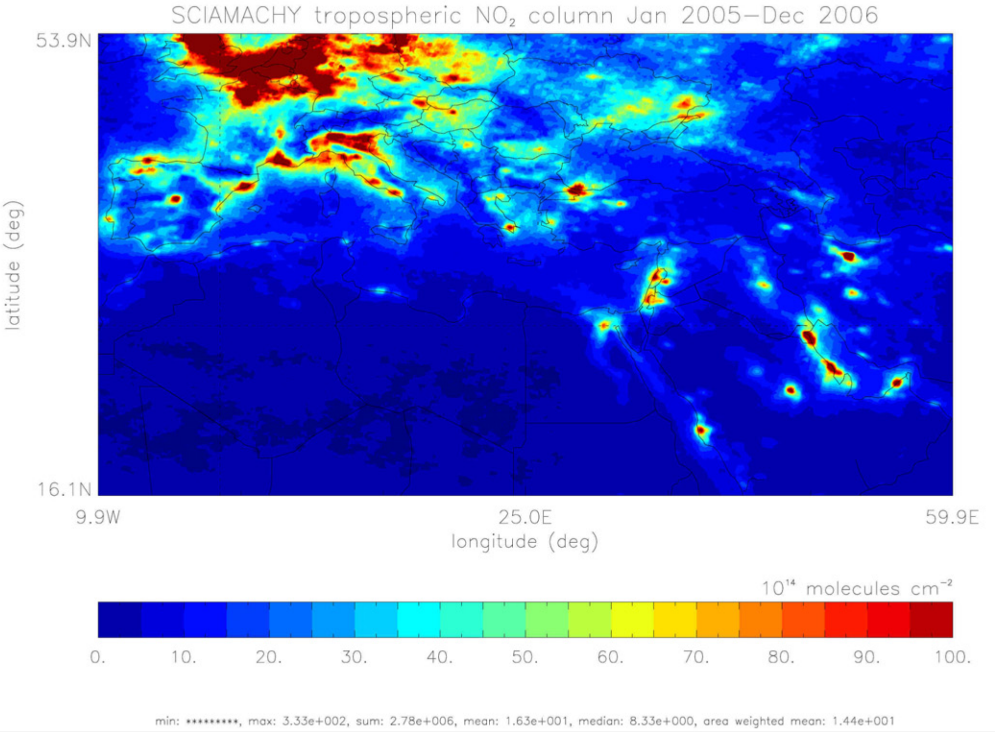

Percentage %
100
30
10
3
1
.3
.1
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
Latitude [degree]
0°
10°E
20°E
30°E
40°E
50°E
Longitude [degree]

953
954

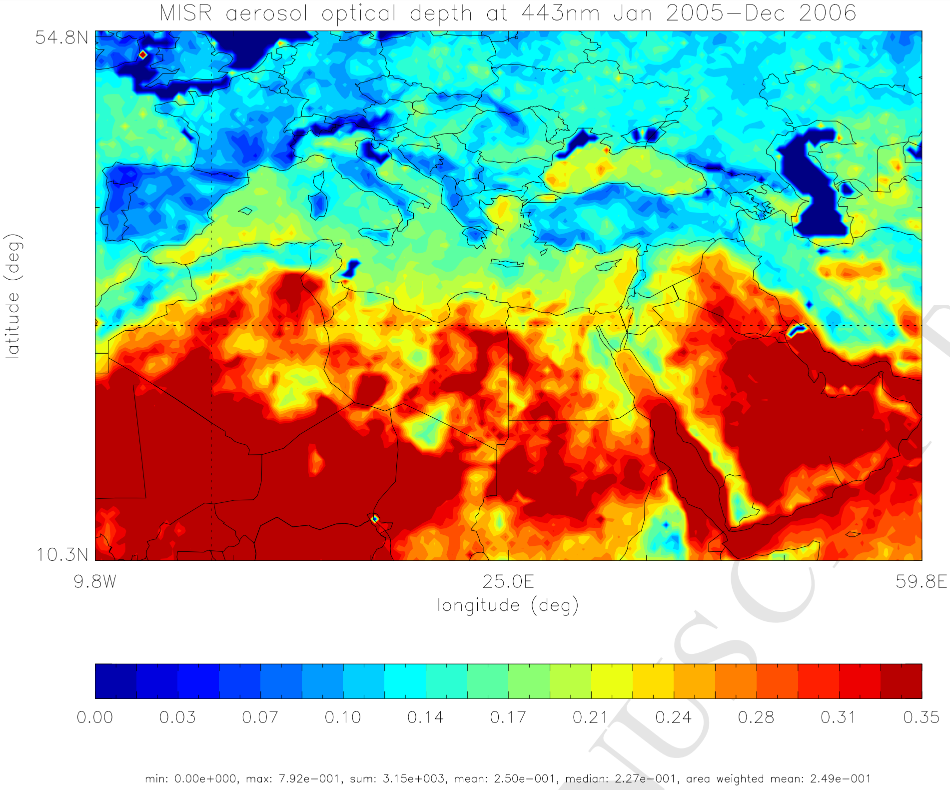
Figure 2: (a) Tropospheric O_3 column as deduced from TES (Tropospheric Emission Spectrometer) satellite sensor gridded in 2^ox4^o lat x lon – The locations of Istanbul, Athens, Cairo and Finokalia are indicated; (b): Tropospheric NO_2 column from SCIAMACHY; (c) MISR aerosol optical thickness (AOT) at 443 nm in 0.5^ox0.5^o and (c) MODIS aerosol small mode fraction in 1^ox1^o resolution. Mean columns for the years 2005-2006. (a, c, d) have been derived from daily data using the Giovanni visualization tool of NASA (Acker and Leptouck, 2007).



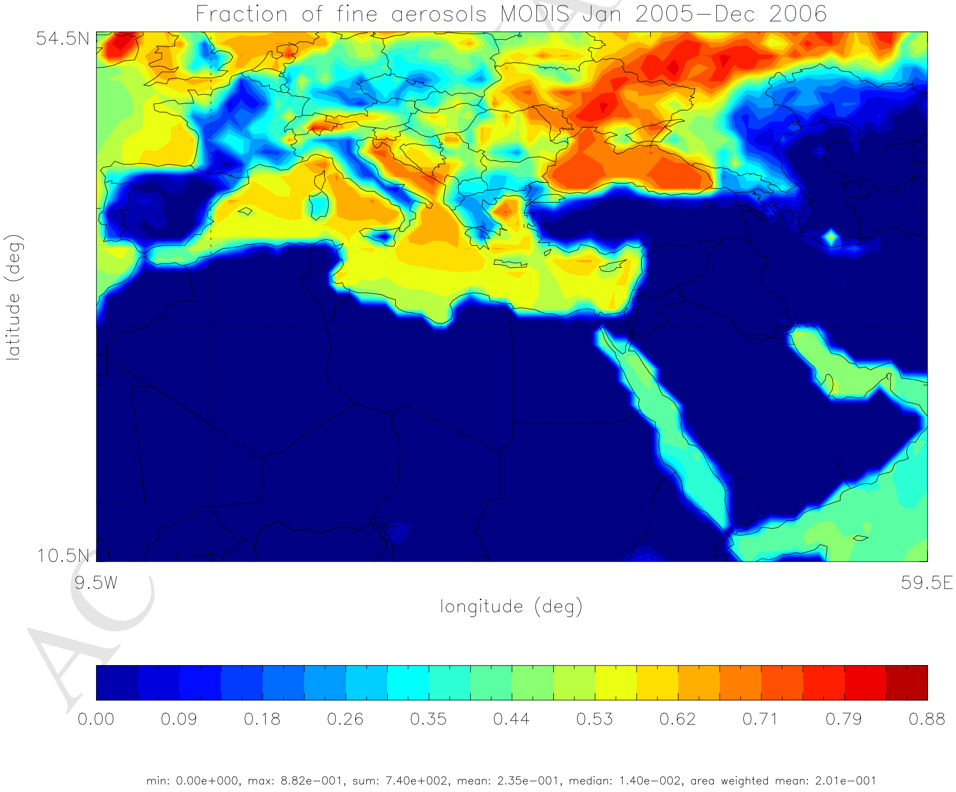
(a)



(b)


MISR aerosol optical depth at 443nm Jan 2005–Dec 2006
54.8N
10.3N
latitude (deg)
9.8W
25.0E
59.8E
longitude (deg)
0.00
0.03
0.07
0.10
0.14
0.17
0.21
0.24
0.28
0.31
0.35
min: 0.00e+000, max: 7.92e–001, sum: 3.15e+003, mean: 2.50e–001, median: 2.27e–001, area weighted mean: 2.49e–001

(c)


Fraction of fine aerosols MODIS Jan 2005–Dec 2006
54.5N
10.5N
latitude (deg)
9.5W
59.5E
longitude (deg)
0.00
0.09
0.18
0.26
0.35
0.44
0.53
0.62
0.71
0.79
0.88
min: 0.00e+000, max: 8.82e–001, sum: 7.40e+002, mean: 2.35e–001, median: 1.40e–002, area weighted mean: 2.01e–001

(d)

Figure 3. Satellite observations of air pollutants over GIA, GCA, GAA and Finokalia in the East Mediterranean. Mean over the period 2003-2009 from SCIAMACHY: Tropospheric columns of NO_2 in 10^{15} molecules cm^{-2} and CHOCHO and HCHO in 10^{14} molecules cm^{-2} (multiplied by 3, 5 and 5 respectively) in a grid of 0.25°x0.25° covering the city. Mean tropospheric column of O_3 as deduced from SCIAMACHY (2003-2009) based on limb-nadir-matching and mean AOD at 550 nm from MODIS (2000-2008) in 1°x1° grid (multiplied by 100).

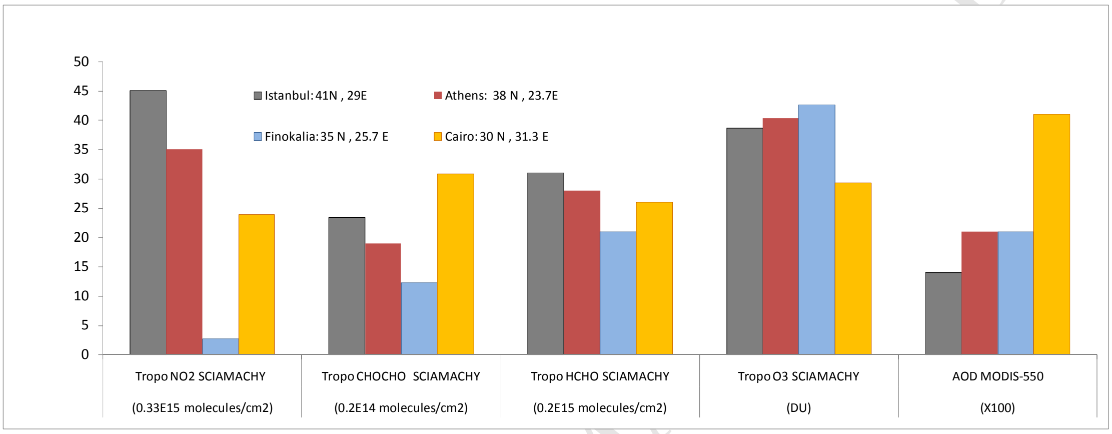


Figure 4. Relationship between mean observations of CO (ppmv) and NOx (ppbv) levels in Istanbul, Athens, Cairo and Finokalia based on data reported in Table 3 and references therein. Lines correspond to the CO:NOx molar ratios of 11 and 100.

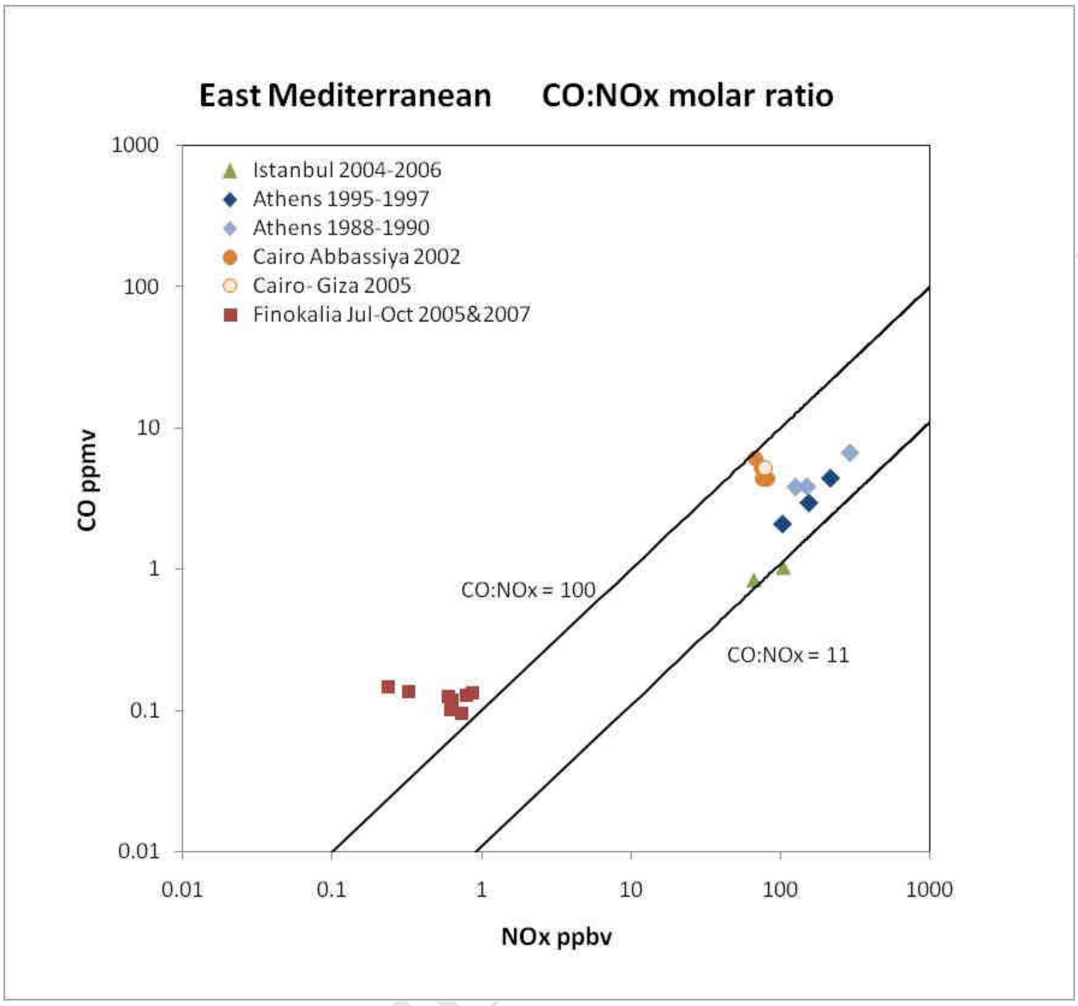


Table 1 – Megacities and receptor location (Finokalia, Crete, Greece) characteristics (reference year 2009). General sources: Thomas Brinkhoff, 2009; http://www.worldclimate.com/ (from data prior to 1990) * Extended region, in brackets highly populated area.

Characteristic	**Istanbul**	**Cairo**	**Athens**	**Finokalia**
Latitude, longitude	41.01^{o}N, 28.97^{o}E	30.03^{o}N, 31.3^{o}E	37.96^{o}N, 23.71^{o}E	35.33^{o}N, 25.66^{o}E
Continent	Europe-Asia	Africa	Europe	Europe
Surface (km^2)	6220	8815* (200)	3808* (450)	-
Population (Millions)	12.5	15.2	4.4	-
Ranked as Megacity	21st	16th	-	Background
population growth % over the last decade	45 29.6 (urban parts) 81 (rural parts)	16.4 (all Egypt) 18 (urban – Egypt)	6	-
Typical air temp. (^{o}C)				2001-2009
winter average	8	15	10	11.6
summer average	28	28	26	24.2
Wind speed m/s	last 30 years	1995-2000 Urban; suburban; rural	1984-2004 – Thissio	2001-2009
Annual mean	2.7		3.3	5.8
Winter	3.0	2.2 3.7 3.1	3.4	5.8
summer	2.4	2.1 4.3 3.5	3.5	6.6
Mean precipitation (mm/yr)	800	25	400	350
Type of climate	Mediterranean (southern part) Cooler + wetter (northern part)	Sub tropical	Mediterranean Hot dry summer Wet mild winter	Mediterranean
Heat island (^{o}C max surface temp. change)	1^{o}	$\leq$2.1^{o}	exceeding 4^{o} in 20% of studied cases	-
References	Ezber et al., 2007; Kindap, 2008	Zakey and Omran, 1997; Khoder, 2009; Zakey et al., 2008; Robaa, 2003	Kallos et al., 1993; Melas et al., 1995; Kassomenos & Katsoulis, 2006	Gerasopoulos et al.., 2005 ; 2006; Vrekoussis et al., 2006

Table 2 – Anthropogenic emissions from Istanbul (reference 2007: Markakis *et al.*, 2009), Athens (reference year 2003; Markakis *et al.*, 2010a,b) and Cairo (reference year 2005; van Aardenne *et al.*, 2009, Duering *et al.*, 2009; # Cairo inventory concerns PM2.5 emissions) greater areas.

	Residential Combustion %	Industry %	Fuel Extr./ Distribution %	Solvent Use %	Road Transport %	Off-road %	Maritime %	Waste %	Energy %	Total Ktons/yr
CO										
Istanbul	10.8	3.7	-	-	83.1	-	0.3	0.7	0.7	437
Athens	8.0	3.2	-	-	75.6	13.0	0.2	-	-	473
Cairo	28.8	31.2			35.5			2.2	2.4	285
NOx										
Istanbul	2.1	2.4	-	-	79.4	2.8	9.5	-	3.2	305
Athens	3.1	22.4	-	-	51.0	17.8	3.1	-	2.6	78
Cairo	4.0	50.2			11.4	3.37		0.12	30.9	222
SO_2										
Istanbul	14.7	23.2	2.3	-	2.3	4.1	17.6	-	35.6	91
Athens	14.9	29.1	8.4	-	3.2	7.2	11.3	-	25.9	31
Cairo	7.6	71.5			4.4					135
NMVOC										
Istanbul	2.6	0.5	-	29.8	44.8	0.4	0.6	20.4	0.2	77
Athens	3.2	2.1	2.0	13.8	70.6	5.7	0.5	-	2.1	93.2
Cairo	11	2.6		43.8	36.9			0.8		62.3
PM10 #										
Istanbul	7.1	64.9	0.1	-	17.4	3.9	3.1	1.7	1.8	61
Athens	18.0	62.7	-	-	13.0	0.8	1.9	3.6	-	21
Cairo #	53.4	4.3			35.9			4.4		6.4

Table 3 – Comparison of surface air pollution levels in Istanbul, Cairo, Athens and Finokalia -Crete (background site) in the East Mediterranean. PM_{10} and $PM_{2.5}$ are particles of diameter smaller than 10 and 2.5 microns, respectively.

Pollutant	Season/Date	Average	Location	Reference
O_3 ppbv	1998-2008 2001-2005 2008-2009	<30 8 ± 7 11 ± 8 25.3 ± 16.8 19.9 ± 14.2	Istanbul * Saraçhane- Europe Kadikoy-Asia Buyukada Kandilli	Ozdemir et al. 2009 Im et al., 2009 Im et al., 2009 “
O_3 ppbv	Winter 2005 Spring 2005 Summer 2005 Fall 2005 2002	Day / Dial 44 / 30 65 / 48 91 / 64 58 / 43 23.4	Cairo (Giza) Abbassiya	Khoder 2009 Elminir et al., 2005
O_3 ppbv	1987–1996 winter (Dec.–Jan.) summer (Jul-Aug)	(12:00-18:00 LT) ~ 25 ~ 60	Athens	Kalabokas and Repapis, 2004
O_3 ppbv	1997-2004 July-Aug. Dec	49 ± 11 58 ± 10 36 ± 7	Finokalia-Crete	Gerasopoulos et al., 2006b
NO_2 ppbv	2001-2005	25± 18.9 (NO: 24± 46.3) 8.8±7.8 (NO: 2 ± 5.8)	Kadıköy Sarachane	Im et al., 2008

NO_2 ppbv	Dec. 2004 - Nov. 2005 (hourly) Winter (hourly) Summer (hourly) 2002	60-150 80-200 (NO: 95-200) 60-130 (NO: 45-125) ~40	Cairo- Giza Cairo- Giza Cairo- Giza Abbassiva	 Khoder, 2009 Khoder, 2009 Elminir et al., 2005
NO_2 ppbv	1987-1997	57±5.3 (NO: 140.5±9.6) 18 ±4 (NO:31.9±18.0) 42.6±4.3 (NO:73.5±18.0)	Athens-Patission Maroussi Athinas	Kalabokas et al., 1999b
NO_2 ppbv	June 2001 – Sept. 2003	0.35±0.31 (NO:0.033±0.020)	Finokalia-Crete	Vrekoussis et al., 2006
CO mg m^{-3}	2004-2006	1.181± 0.957 0.956±1.233	Sarachane Kadikoy	Im et al., 2008
CO mg m^{-3}	2002	~6 (4-10)	Cairo- Abbassiya	Elminir et al., 2005
CO mg m^{-3}	1987-1997	6.2± 1.2 1.9±0.6 3.8±0.5	Athens-Patission Maroussi Athinas	Kalabokas et al., 1999b
CO mg m^{-3}	July-Oct 2005 and Jul-Oct 2007	~ 0.143	Finokalia-Crete	Unpublished data
SO_2 µg m^{-3}	1998-2008	~22 (7.5 - 45)	Istanbul *	Ozdemir et al., 2009
SO_2 µg m^{-3}	Winter 1999-2000 Summer 2000	125±21.6 83±17.6	Cairo (Giza)	Khoder, 2002
SO_2 µg m^{-3}	1995-1997	25±3 40±4	Athinas- Athens Patission-Athens	Kalabokas et al., 1999b
SO_2 µg m^{-3}	1997-1999	2.7±0.9	Finokalia -Crete	Kouvarakis et al., 2002
PM_{10} µg m^{-3}	Jul 2002-Jul 2003 1998-2008 Nov 2007- Jun 2009	47.1 66 (47 – 115) 39.1	Istanbul * Background- Boğaziçi Univ.	Karaca et al., 2005 Ozdemir et al., 2009 Theodosi et al., 2010
PM_{10} (bulk aerosol)	2005: Win., Spr., Sum., Fall	215, 190, 115, 165	Cairo (Giza & El-Gomhoreya)	Favez et al., 2008

$\mu g\ m^{-3}$	2001-2002	170 ±25 140 ±40	Cairo (17 sites) Background -Cairo	Zakey et al., 2008 «
PM_{10} $\mu g\ m^{-3}$	Jun1999-May 2000	75.5 ±27.5	Athens	Chaloulakou et al., 2003
PM_{10} $\mu g\ m^{-3}$	2001–02 & 2004–05 2004-2006	28±30 32.5±27.7	Finokalia-Crete	Gerasopoulos et al, 2006a ; 2007; Koulouri et al., 2008
$PM_{2.5}$$\mu g\ m^{-3}$	Jul 2002-Jul 2003	20.8	Istanbul	Karaca et al., 2005
$PM_{2.5}$ $\mu g\ m^{-3}$	2001-2002	85±12	Cairo (17 sites)	Zakey et al., 2008
$PM_{2.5}$ $\mu g\ m^{-3}$	Jun1999-May 2000 2004-2006	40.2±16.7 23.7±10.7 29.3±10.4	Athens-Aristotelous Athens-Lykovrissi Athens-Goudi	Chaloulakou et al., 2003 Koulouri et al., 2008b “
$PM_{2.5}$ $\mu g\ m^{-3}$	2004-2006	18.2 17.9±12.4	Finokalia-Crete	Gerasopoulos et al., 2007 Koulouri et al., 2008
OC/EC	Nov 2007- Jun 2009	1.98 (PM_{10})	Istanbul – urban Background	Theodosi et al., 2010
OC/EC	March- April 2005 2005	1.4 ± 0.3 (morning) 2.9 ± 0.5 (early afternoon) 2.5 - 5.0 Bulk aerosol	Cairo : El-Gomhoreya and Giza	Favez et al., 2008a « Favez et al., 2008b
OC/EC	June–July 2003	3.9±0.9 ($PM_{2.5}$) 24±17 ($PM_{2.5-10}$)	Athens	Sillanpaa et al., 2006
OC/EC	July 2004-July 2006	4.0 ($PM_{1.3}$) 4.0 ($PM_{1.3-10}$ non-dust cases)	Finokalia- Crete	Koulouri et al., 2008a

*10 municipality stations