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Review

Megacities as hot spots of air pollution in the East Mediterranean

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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.

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, Fig. 1 and Fig. 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 (Ladstätter-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

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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°N, 28.97°E	30.03°N, 31.30°E	37.96°N, 23.71°E	35.33°N, 25.66°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. (°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	1984–2004 – Thissio	2001–2009
Annual mean	2.7	Urban; suburban; rural	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 (°C max surface temp. change)	1°	≤2.1°	Exceeding 4° 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 and Katsoulis, 2006	Gerasopoulos et al., 2005, 2006a,b; Vrekoussis et al., 2006

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 south-east 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., in press). 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 southwestern 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

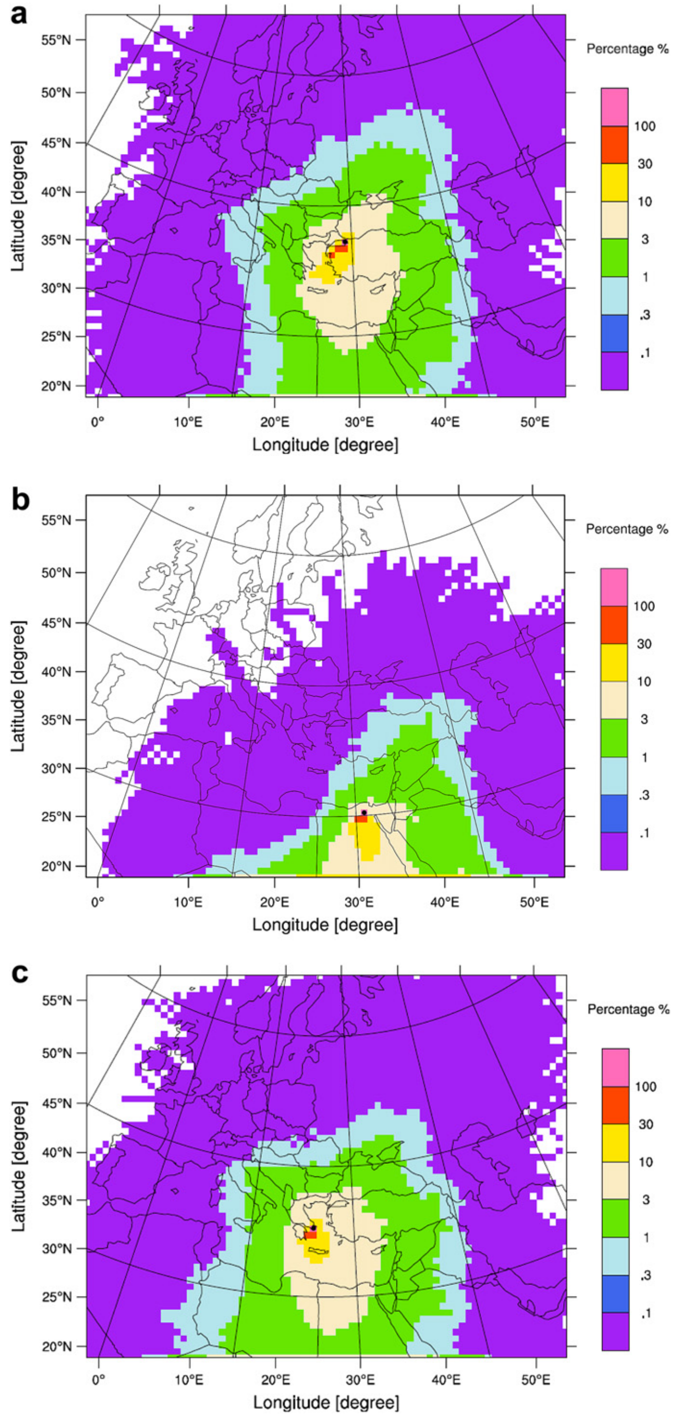

Fig. 1. Map for the probability of arrival of trajectories starting from (a) Istanbul, (b) Cairo, (c) Athens, over the 30-years period based on NCEP 6-hourly meteorological data at 2.5° resolution, see text. Dot points indicate the city of Istanbul, Cairo and Athens respectively.

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 2.7 m s^{-1}. 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 700 m 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 6 h at a 2.5° 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). Fig. 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., in press) whereas Cairo outflow is mainly affecting the

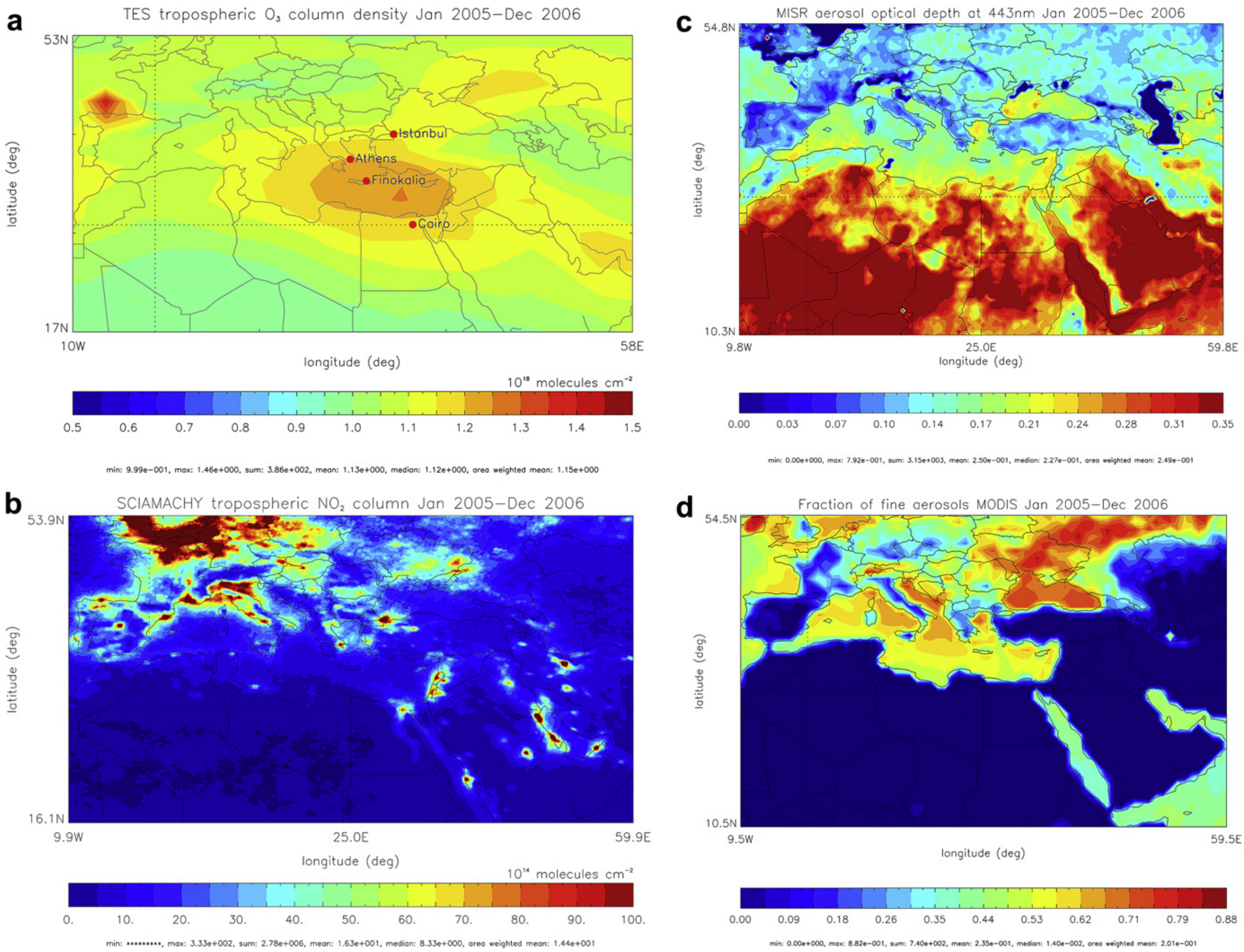

Fig. 2. (a) Tropospheric O_3 column as deduced from TES (Tropospheric Emission Spectrometer) satellite sensor gridded in 2° × 4° lat × lon – The locations of Istanbul, Athens, Cairo and Finokalia are indicated; (b): Tropospheric NO_2 column from SCIAMACHY; (c) MISR aerosol optical thickness (AOT) at 443 nm in 0.5° × 0.5° and (c) MODIS aerosol small mode fraction in 1° × 1° 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 Leptoukh, 2007).

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° × 1° Granier et al., 2005). The new EDGAR v4 inventory now becoming available, is making significant improvement by increasing the resolution to 0.1° × 0.1° (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, 2010a,b), in high spatial (2 × 2 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. (in press), 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.

Table 2
Anthropogenic emissions from Istanbul (reference year 2007: Markakis et al., 2009), Athens (reference year 2003; Markakis et al., 2010a,b) and Cairo (reference year 2005; van Aardenne et al., 2009; Doering et al., 2009; # Cairo inventory concerns $PM_{2.5}$ 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
NO_x										
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	11.0	2.6		43.8	36.9			0.8		62.3
PM_{10} #										
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

Cairo shows different emissions fingerprint: Residential combustion and Industries being the major emitters of CO and NO_x whereas NMVOC emissions are mostly from solvents use seconded by road transport. A significant portion of NO_x ($\sim$50%) and SO_2 ($\sim$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 centers 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; Tayanç, 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 (El 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^{-1} 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 (Fig. 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., 2009; Vrekoussis et al., 2009a,b, 2010). 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 (Kallos et al., 2007; Querol et al., 2009a,b) 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 wintertime and the faster photochemical destruction during summertime. Fig. 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 (Fig. 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., 2009a,b). This distribution nicely contrasts to the O_3 distribution shown in Fig. 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 3 $\times$ 10^{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 Fig. 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/NO_x 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 ($\sim$18 DU lower than over Finokalia, based on TOMS/OMI 2005–2008 data in 0.25° $\times$ 0.25° 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 $\pm$ 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 $\pm$ 7 ppbv) and the Asian (11 $\pm$ 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),

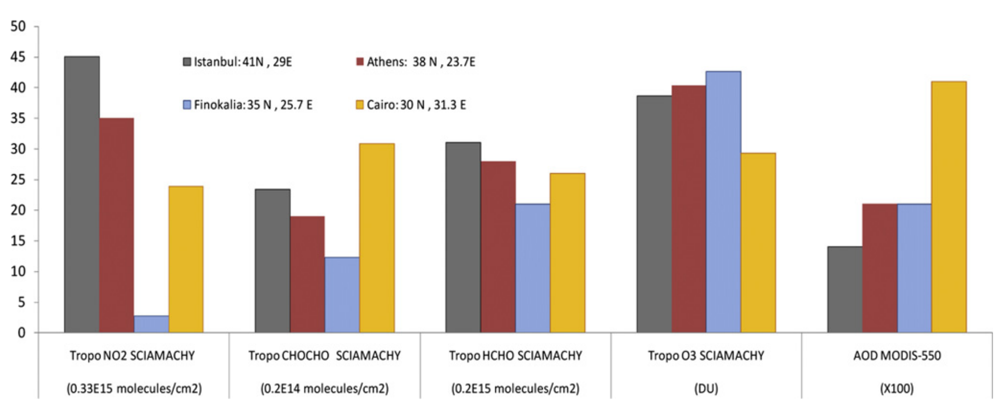

Fig. 3. Satellite observations of air pollutants over GIA, GCA, GAA and Finokalia in the East Mediterranean. Mean over the period 2003–2009 from SCIAMACHY: Tropospheric columns of NO_2 in 10^{15} molecules cm^{-2} and CHOCHO and HCHO in 10^{14} molecules cm^{-2} (multiplied by 3, 5 and 5 respectively) in a grid of 0.25° $\times$ 0.25° 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° $\times$ 1° grid (multiplied by 100).

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	<30	Istanbul[a]	Ozdemir et al., 2009
	2001–2005	8 ± 7	Saraçhane-Europe	Im et al., 2009
	2008–2009	11 ± 8	Kadikoy-Asia	
		25.3 ± 16.8	Buyukada	Im et al., 2009
		19.9 ± 14.2	Kandilli	Im et al., 2009
O_3 ppbv		Day/Dial	Cairo (Giza)	Khoder 2009
	Winter 2005	44/30		
	Spring 2005	65/48		
	Summer 2005	91/64		
	Fall 2005	58/43		
	2002	23.4	Abbassiya	Elminir, 2005
O_3 ppbv	1987–1996	(12:00–18:00 LT)		
	Winter (Dec.–Jan.)	~25	Athens	Kalabokas and Repapis, 2004
	Summer (Jul–Aug)	~60		
O_3 ppbv	1997–2004	49 ± 11		
	July–Aug.	58 ± 10	Finokalia-Crete	Gerasopoulos et al., 2006b
	Dec	36 ± 7		
NO_2 ppbv	2001–2005	25.0 ± 18.9 (NO: 24.0 ± 46.3)	Kadıköy	Im et al., 2008
		8.8 ± 7.8 (NO: 2.0 ± 5.8)	Sarachane	
NO_2 ppbv	Dec. 2004–Nov. 2005 (hourly)	60–150	Cairo-Giza	
	Winter (hourly)	80–200 (NO: 95–200)	Cairo-Giza	Khoder, 2009
	Summer (hourly)	60–130 (NO: 45–125)	Cairo-Giza	Khoder, 2009
	2002	~40	Abbassiva	Elminir, 2005
NO_2 ppbv	1987–1997	57.0 ± 5.3 (NO: 140.5 ± 9.6)	Athens-Patission	Kalabokas et al., 1999b
		18.0 ± 4.0 (NO:31.9 ± 18.0)	Maroussi	
		42.6 ± 4.3 (NO:73.5 ± 18.0)	Athinas	
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	1.2 ± 1.0	Sarachane	Im et al., 2008
		1.0 ± 1.2	Kadikoy	
CO mg m^{-3}	2002	~6 (4–10)	Cairo – Abbassiya	Elminir, 2005
CO mg m^{-3}	1987–1997	6.2 ± 1.2	Athens-Patission	Kalabokas et al., 1999b
		1.9 ± 0.6	Maroussi	
		3.8 ± 0.5	Athinas	
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	Istanbul[a]	Ozdemir et al., 2009
		(7.5–45)		
SO_2 µg m^{-3}	Winter 1999–2000	125 ± 21.6	Cairo (Giza)	Khoder, 2002
	Summer 2000	83 ± 17.6		
SO_2 µg m^{-3}	1995–1997	25 ± 3	Athinas-Athens	Kalabokas et al., 1999b
		40 ± 4	Patission-Athens	
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	47.1	Istanbul	Karaca et al., 2005
	1998–2008	66 (47–115)	[a]	Ozdemir et al., 2009
	Nov 2007–Jun 2009	39.1	Background-Boğaziçi Univ.	Theodosi et al., 2010
PM_{10} (bulk aerosol)	2005: Win., Spr., Sum., Fall	215, 190, 115, 165	Cairo (Giza & El-Gomhoreya)	Favez et al., 2008a,b
µg m^{-3}	2001–2002	170 ± 25	Cairo (17 sites)	Zakey et al., 2008
		140 ± 40	Background-Cairo	Zakey et al., 2008
PM_{10} µg m^{-3}	Jun1999–May 2000	75.5 ± 27.5	Athens	Chaloulakou et al., 2003
PM_{10} µg m^{-3}	2001–02 and 2004–05	28 ± 30	Finokalia-Crete	Gerasopoulos et al., 2006a, 2007;
	2004–2006	32.5 ± 27.7		Koulouri et al., 2008a,b
$PM_{2.5}$ µg m^{-3}	Jul 2002–Jul 2003	20.8	Istanbul	Karaca et al., 2005
$PM_{2.5}$ µg m^{-3}	2001–2002	85 ± 12	Cairo (17 sites)	Zakey et al., 2008
$PM_{2.5}$ µg m^{-3}	Jun1999–May 2000	40.2 ± 16.7	Athens-Aristotelous	Chaloulakou et al., 2003
	2004–2006	23.7 ± 10.7	Athens-Lykovrissi	Koulouri et al., 2008b
		29.3 ± 10.4	Athens-Goudi	Koulouri et al., 2008b
$PM_{2.5}$ µg m^{-3}	2004–2006	18.2	Finokalia-Crete	Gerasopoulos et al., 2007
		17.9 ± 12.4		Koulouri et al., 2008a,b
OC/EC	Nov 2007–Jun 2009	1.98 (PM_{10})	Istanbul – urban Background	Theodosi et al., 2010
OC/EC	March–April 2005	1.4 ± 0.3 (morning)	Cairo:El-Gomhoreya and	Favez et al., 2008a
		2.9 ± 0.5 (early afternoon)	Giza	Favez et al., 2008b
	2005	2.5–5.0 Bulk aerosol		Favez et al., 2008b
OC/EC	June–July 2003	3.9 ± 0.9 ($PM_{2.5}$)	Athens	Sillanpaa et al., 2006
		24 ± 17 ($PM_{2.5-10}$)		
OC/EC	July 2004–July 2006	4.0 ($PM_{1.3}$)	Finokalia-Crete	Koulouri et al., 2008a
		4.0 ($PM_{1.3-10}$ non-dust cases)		

[a] 10 municipality stations.

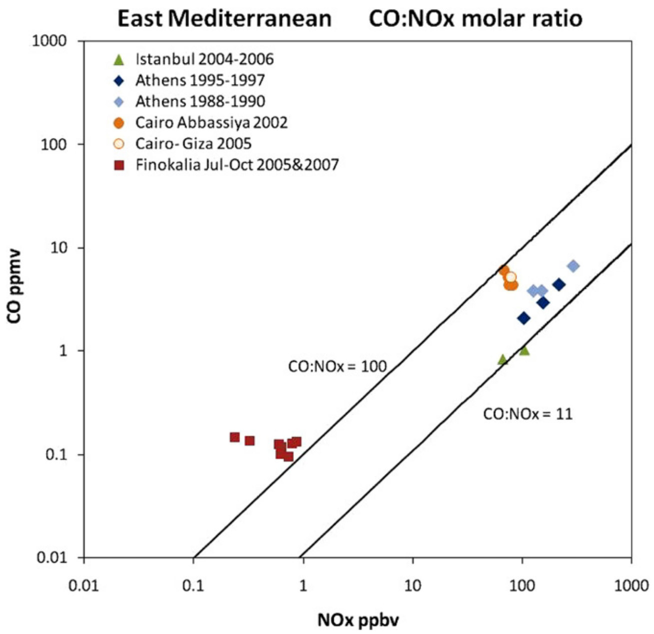

Fig. 4. Relationship between mean observations of CO (ppmv) and NO_x (ppbv) levels in Istanbul, Athens, Cairo and Finokalia based on data reported in Table 3 and references therein. Lines correspond to the CO:NO_x molar ratios of 11 and 100.

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 Fig. 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 an 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–NO_x molar ratios in GAA (Fig. 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-NO_x 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 (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 443 nm 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 Fig. 2c and d. 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, Fig. 2d indicates the existence of significant fraction (about 0.5–0.6) 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., 2009a,b), with $PM_{2.5}/PM_{10}$ ratios around 0.5 (Table 3), in agreement with the satellite observations in Fig. 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 ($PM_{1.3-10}$) 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 μg m^{-3} to the background PM_{10} annual mean levels in the East Mediterranean, whereas an additional 5–10 μg m^{-3} is attributed to transported anthropogenic regional sources and sea-spray loads (Querol et al., 2009a,b). 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., 2009a,b; Mihalopoulos et al., 1997).

High sulphate 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 (Bardouki et al., 2003). 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 90s. 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 μg m^{-3} observed at 10 Istanbul municipality stations during the last 10 years with values ranging from 47 μg m^{-3} to 115 μg 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. (in press), 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 Bogaziçi 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, oxidized 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., in press). 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^{-2}, 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 exceedences 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., 2009a,b).

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. (2009a,b) 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 μg m^{-3}, compared to 48% exposed to 100–50 μg m^{-3} and 49% exposed to 50–5 μg 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 10,000–25,000 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 centers. 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/NO_x 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 $NMVOC/NO_x$ 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 modeling 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 μg m^{-3} of transported mineral dust and an additional 5–10 μg 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 characterization will elucidate the sources and impact of PM pollution in the area.

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