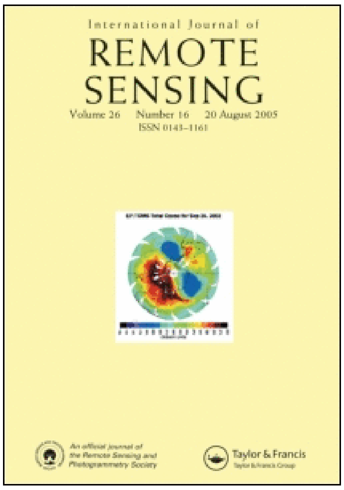

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Dust storm and black cloud influence on aerosol optical properties over Cairo and the Greater Delta region, Egypt

H. El-Askary [ab]; M. Kafatos [c]
[a] Department of Environmental Sciences, Faculty of Science, Alexandria University, Alexandria, Egypt [b] National Authority for Remote Sensing and Space Science (NARSS), Cairo, Egypt [c] Center for Earth Observing and Space Research, George Mason University, Fairfax, VA 22030, USA

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Dust storm and black cloud influence on aerosol optical properties over Cairo and the Greater Delta region, Egypt

H. EL-ASKARY*†‡ and M. KAFATOS§

†Department of Environmental Sciences, Faculty of Science, Alexandria University, Moharem Bek, Alexandria, Egypt

‡National Authority for Remote Sensing and Space Science (NARSS), Cairo, Egypt

§Center for Earth Observing and Space Research, George Mason University, Fairfax, VA 22030, USA

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We have analysed aerosol and cloud properties, obtained from moderate resolution imaging spectroradiometer (MODIS) data, over Cairo and the Greater Delta region during the spring months of March, April and May (MAM) and the autumn months of September, October and November (SON) in the years 2004, 2005 and 2006. During these two time periods, we have examined dust storms, dense haze and a smog-like phenomenon known, locally, as the 'black cloud'. Our work is based on the aerosol optical depth (AOD), fine mode fraction (FMF) and cloud properties (cloud top temperature (CTT), cloud top pressure (CTP), atmospheric infrared sounder (AIRS) temperature profiles and water vapour column). High anomalous water vapour is detected, which we believe is as a result of pollution aerosols rather than dust and is hence acting as cloud condensation nuclei (CCN). The CTT shows increasing and decreasing trends, corresponding to the dust occurring at ~750–800 hpa and pollution episodes at >900 hpa, respectively as observed from the CTP. Temperature inversion conditions, as well as adverse weather conditions, contribute to the pollution observed by preventing pollutants from escaping to the higher atmosphere.

1. Introduction

The Intergovernmental Panel on Climate Change (Houghton *et al.* 2001) report indicates an observed warming over the past 50 years, with human activities contributing greatly. The IPCC report highlights the warming due to greenhouse gases, yet places a big emphasis on urban pollution impacts on surface energy budget (Grimmond and Oke 1995, Houghton *et al.* 2001, Arnfield 2003, Shepherd and Jin 2004). Urban areas, Cairo in particular, with rapid land use and land cover changes, are centres of significant human activities that affect the local climate. Past studies have identified the paths and scales of transport and transformation of air pollutants released from Europe towards Eastern Mediterranean and North Africa (Luria *et al.* 1996, Millan *et al.* 1997, Kallos *et al.* 1998). Emissions of atmospheric constituents from the African continent include both trace gases and aerosols. These emissions are derived from wind blown dust, biomass burning, biogenic emissions and anthropogenic industrial activities (Piketh and Walton 2004).

*Corresponding author. Email: helaskar@gmu.edu

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Cairo (longitude 31°13′ E, latitude 30°2′ N), the site of the study reported in this paper together with the Greater Delta region extending from ~29° to 31° N, is located on both banks of the Nile River, near the beginning of the river's delta in northern Egypt. Cairo is the largest city of Africa with a population of 16 million people, where more than one third of the national industry is located; hence, it is a rapidly expanding city, which leads to many environmental problems. Cairo and the Greater Delta region have recorded much higher air pollution episodes over the last 7 years compared to the past few decades. Cairo is located at the junction of climate systems impacted by the western desert through blown sand and dust storms, as well as local anthropogenic activities. As a result, it is characterized by complicated meteorology, varying with time of year and getting worse during 'black cloud' episodes that are characterized by the increasing production of different air pollutants from diverse sources. El Minir (2005) found that wind and relative humidity are also important meteorological parameters influencing the behaviour of air pollutants affected by the air mass history. These factors result in a dense smog-like event known locally as black cloud, which prevails during the months of September to November, but is most dominant over Cairo during October of each year and which is characterized by very high levels of pollutants. Increasing business and industrial activities in Cairo city, accompanied by a shortage in institutional capabilities for monitoring and control, in addition to the environmental impact negligence that prevails over many of the production sectors, have contributed to excessive air pollution problems that have reached crisis level. Since 1999, a black cloud has often appeared, above the Nile Delta and Cairo, during October and has been well reported by the media (Navarro 2006). During that time of year, farmers burn rice straw, a by-product from the rice harvest, to clear fields for the next crop. The lower topographic nature of Cairo also contributes as well to pollutants blocking and suppressing the motion of suspended particulates, due to the presence of the Nile valley between Giza (western highs) and Mokatam (eastern highs). The weakening or diminishing of the trade wind systems over the Mediterranean, leading to poor ventilation during this period, is another reason for black cloud occurrence. The trade wind system over the Eastern Mediterranean, known as etesian, in the Aegean Sea is from north to south and quite strong during daytime hours. A description of this trade wind system and its role over Egypt is described in Kallos *et al.* (1998).

Moreover, adverse weather conditions with weak winds result in a prevalent upper-air high-pressure system over the Delta during such episodes, as well as nighttime cloudless skies, which contribute to decreasing the surface temperature, leading to a steep thermal inversion at a few hundred metres above the surface (Kandil *et al.* 2006). The result of this pollution problem is a haze over the city with particulate matter in the air reaching three times the normal levels. It is estimated that 10 000 to 25 000 people a year in Cairo die due to air pollution-related diseases, as reported by the government. Yet, even though it is a serious health and environmental problem, not enough research has been carried out in studying pollution impacts on the aerosol optical properties. The present work is an initial and first attempt to study the dust versus pollution impact on the aerosol characteristics in this region. The impact of dust, smoke and pollution aerosols generated from dust storms, agricultural by-product burning and human activities in Cairo and the Greater Delta region on reflecting solar and emitted thermal radiation from clouds is investigated using satellite data.

2. Aerosol optical properties and their relation to the black cloud

The moderate resolution imaging spectroradiometer (MODIS) has been successfully retrieving aerosol properties over land since early 2000 from Terra and since mid 2002 from Aqua. The aerosol optical depth (AOD) has been validated with known errors bars; however the fine mode weighting (FMW) of the AOD is accurate only under certain conditions. Pollution impact on the aerosol optical properties and long-range transport has been well studied over Asia and other regions. Recent studies, using different sensors over optical and microwave spectra, have analysed aerosol optical properties during dust and pollution events over Northern India and East Asia (Uno *et al.* 2001, Carmichael *et al.* 2002, Di Girolamo *et al.* 2004, Singh *et al.* 2004, Ramanathan *et al.* 2005, El-Askary *et al.* 2006, Prasad *et al.* 2006). Dust storms have also been widely investigated over Egypt through a multisensor approach utilizing the differing dust behaviour over ultraviolet, visible and microwave regions of the spectrum (El-Askary *et al.* 2003), as well as Saharan dust transportation (Kallos *et al.* 2006). However, a lot still needs to be done for Africa and especially for North Africa, where one of the highest populated cities of the world is present.

El-Askary (2006) has recently presented a detailed seasonal analysis of the aerosol parameters over Cairo and the Greater Delta region from 2000 to 2005. High AOD values were found over Cairo and the Greater Delta region during the spring and autumn times of the year using MODIS data. These times represent the periods of dust storms occurrence (April and May) and, more recently, the occurrence of black cloud (September and October).

Here, we examine the impact of dust and anthropogenic pollution on the aerosol optical properties and their impact on cloud characteristics (cloud top temperature (CTT), cloud top pressure (CTP) and water vapour column). We use level 3 MODIS gridded atmosphere daily global product, which contains daily average values of atmospheric parameters related to atmospheric aerosol particle properties, namely AOD and fine mode fraction (FMF). The MODIS AOD and FMF parameters for the spring and autumn seasons of 2005, March, April and May (MAM) and September, October and November (SON), are studied. FMF is the fraction of the AOD contributed to by fine aerosols (effective radius 0.1–0.25 μm) (Kaufman *et al.* 2005). The AOD is a measure of the opaqueness of air, where high values of AOD indicate poor visibility. The AOD parameter, obtained from the MODIS data, is used as an indicator for showing dust storm and black cloud impacts on the optical properties of the aerosols forming the atmosphere. The AOD data from the MODIS sensor is used in this study to measure the relative amount of aerosols suspended in the atmosphere and hence how much effect they have on the CTT and CTP.

We have analysed the above data during the spring (MAM) when the desert dust dominates, while in the autumn (SON), the desert dust is absent and the anthropogenic aerosol component is maximized. Figure 1 shows the AOD and FMF variations during MAM and SON of 2005 over Cairo and the Greater Delta region. The AOD shows a high dominancy of the pollutants and dust aerosols during the months of September and October and April and May, respectively. Anthropogenic pollutants during SON belong to the fine mode size category, while dust particles belong to the coarse mode category. Hence, higher AOD values during MAM than during SON are attributed to large dust loading in the atmosphere, while higher FMF in SON than MAM are due to the urban/industrial car and fuel emissions. The high FMF peak observed during March is due to the lower dust

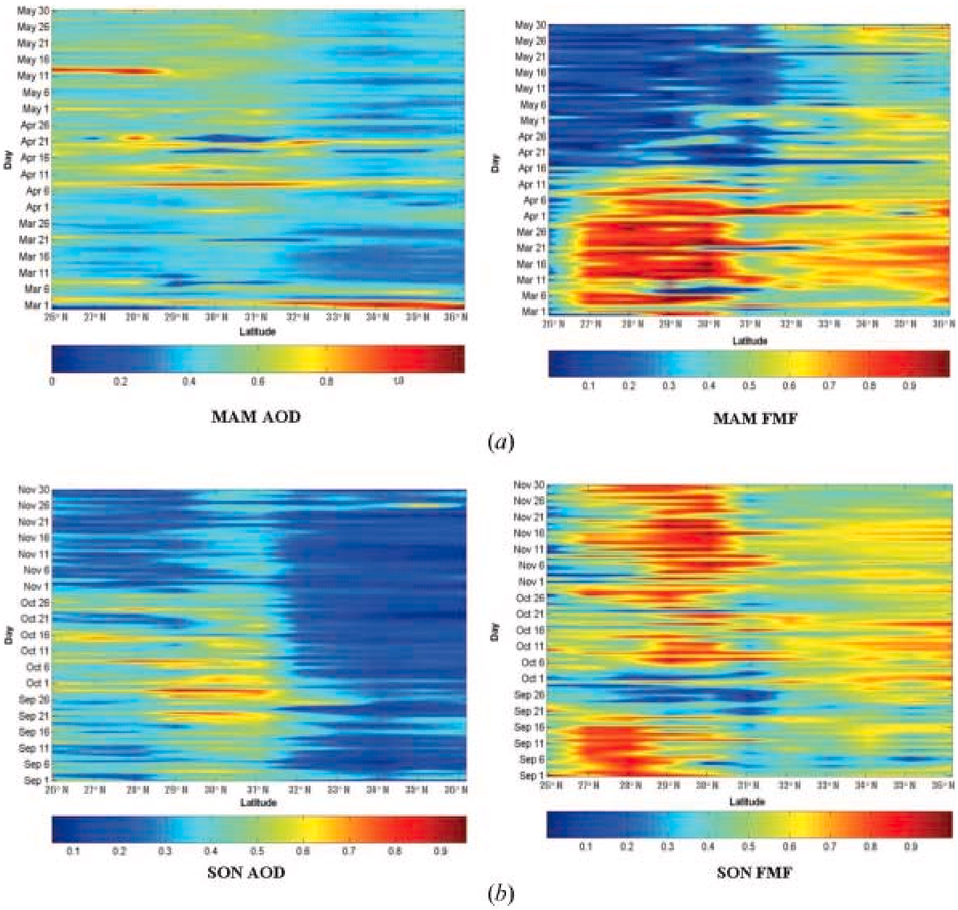

Figure 1. TERRA/MODIS time–latitude map, averaged over longitude, showing the temporal variability of daily AOD and FMF over Cairo and the Greater Delta region during (*a*) spring time (MAM) and (*b*) autumn time (SON).

storm abundance during this month as compared to April and May. A sharp boundary at 32° N, with little variation north and south of it, is observed due to the fact that, at this cut-off point, we entered the Mediterranean, which is not a part of the Greater Delta region that is characterized by a highly vegetated and not bright surface.

3. Dust and pollution aerosol cloud interactions

The MODIS precipitable water product consisting of the water vapour column is essential in understanding the aerosol properties and aerosol–cloud interactions (Jin *et al.* 2005). The level 2 data are generated at 1 km spatial resolution of the MODIS instrument using the near-infrared algorithm during the day and at 5×5 pixels, 1 km pixel resolution for both day and night. El-Askary *et al.* (2003) found that, in the optical region of the electromagnetic spectrum, dust storms have a very high albedo and hence appear quite bright. They found that high reflectance and anomalous water vapour could serve as indicators of dust storms due to the nucleation process. In that context, Rosenfeld (2001) studied the impact of smoke and dust on the

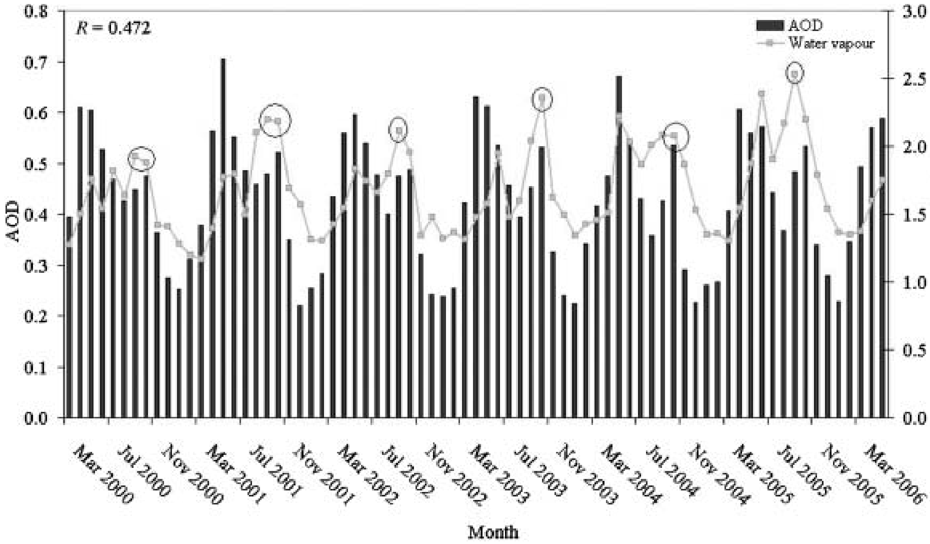

Figure 2. Monthly averages of AOD versus water vapour column (cm) over Cairo and the Greater Delta region from March 2000 to May 2006, showing high water vapour peaks in September and October of each year.

precipitation patterns. Similarly, this can be applied to the anthropogenic pollutants scenario discussed in this paper; however, there are some differences due to the different physical nature of the aerosols in these cases. Figure 2 shows the monthly averages of the water vapour column versus the AOD, indicating a note worthy relation (correlation coefficient=0.472) as the aerosol particles act as nucleation centres. It is evident that high values of water vapour column are observed during the autumn of each year from 2000 to 2006, mainly through September and October, matching the pollution episodes. Autumn is not a rainy season. Lower correspondence is observed during MAM, yet it is still high, as dust particles still act as nucleation centres. However, during the wintertime, which is a rainy season, less water vapour is observed as particles are flushed with the precipitation. Figure 3(*a*) shows lower water vapour column values in MAM (revealed from the correlation coefficient) with the AOD values shown in table 1.

Correlation coefficients above 0.5 and 0.25 are significant at a 95% level, according to the number of samples (Bendant and Piersol 1971). In general, spring (<3 cm) values indicate the presence of dry and dusty air as compared with the SON column (>3 cm), except for the outlier observed in early March. However, in April through to May, with higher concentrations of dust, we find higher values of water vapour column than March, as well as September through to October, where, due to more pollution, we find higher values of water vapour column than November. This behaviour in both episodes matches the general trend of the AOD during the same time frames corresponding to the dust and black cloud occurrences, respectively. Such aerosol particles have an affinity for water vapour and hence help in their formation.

Aerosol relation with water vapour has an implication for the radiative forcing directly and indirectly (Tegen *et al.* 1996, Houghton *et al.* 2001, Hsu *et al.* 2003). Aerosols cause a reduction in cloud droplet size and hence lead to suppression in precipitation, a situation that is observed over Cairo in both aerosol-related

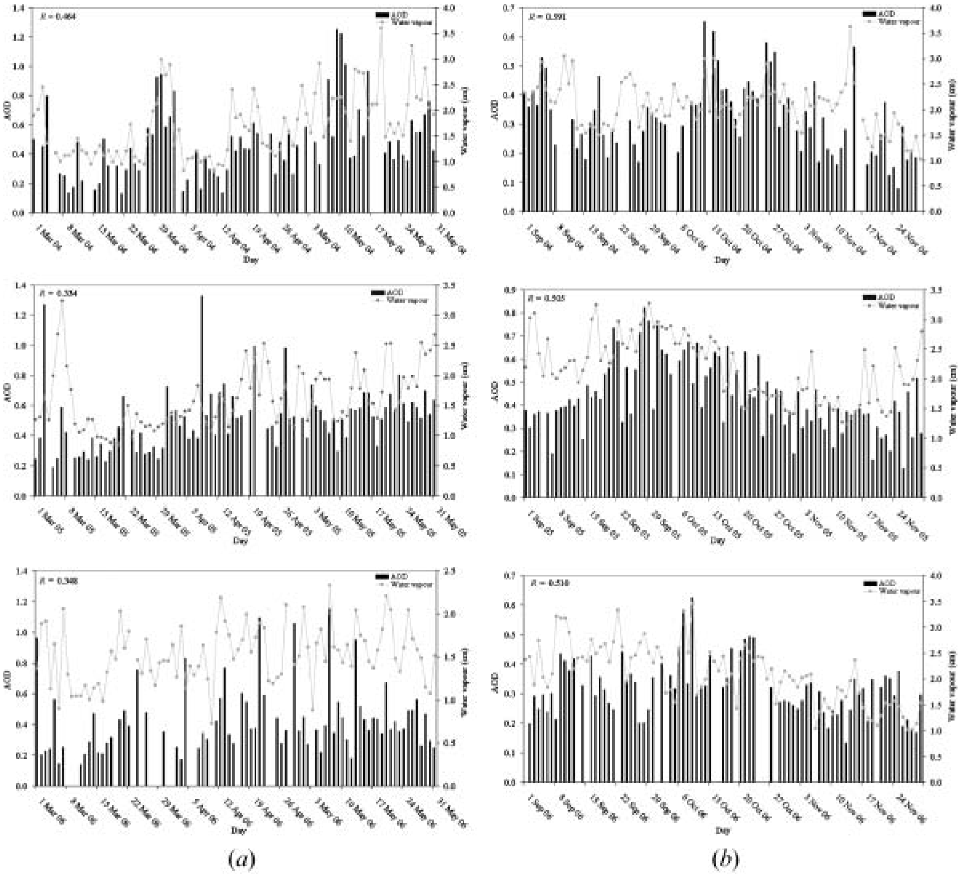

Figure 3. Daily variability of AOD versus water vapour column (cm) over Cairo and the Greater Delta region for the years 2004, 2005 and 2006 during (*a*) spring time (MAM) and (*b*) autumn time (SON). The correlation coefficient, *R*, is also given in each case.

episodes. The direct effect results in radiation scattering due to the increase in the aerosol particle sizes accompanied by uptakes of water vapour. The black cloud episode is comprised mainly of anthropogenic pollutants acting as cloud condensation nuclei (CCN), leading to the formation of water vapour cover (indirect effect). Dust and anthropogenic aerosols act as CCN and hence lead to the formation of water vapour clouds, yet dust particles absorb more water and hence decrease the water vapour content. A slowly increasing water vapour column is observed from March through to May of the years 2004, 2005 and 2006, which

Table 1. Trends, values and correlation coefficients, *R*, of atmospheric parameters for MAM and SON for the years 2004, 2005 and 2006.

Year	CTT (MAM) trend	CTT (SON) trend	CTP (MAM) value	CTP (SON) value	AOD_WV* (MAM) *R*	AOD_WV (SON) *R*
2004	+0.0164	−0.2998	~750 mb	>900 mb	0.464	0.591
2005	+0.0136	−0.2297	~800 mb	>900 mb	0.334	0.505
2006	+0.0132	−0.1204	~800 mb	>900 mb	0.348	0.510

*AOD_WV refers to Aerosol Optical Depth vs Water Vapour.

reflects the higher abundance of water vapour particles during dust episodes (El-Askary *et al.* 2003) (figure 3(*a*)). However, the highest spring water vapour column value observed is still lower than the one during September through to November. Anthropogenic pollutants are finer than dust particles (figure 1). Therefore, they are more able to act as nucleation centres, as evidenced from the higher abundance of water vapour column from September through to November of the years 2004, 2005 and 2006, as revealed from the correlation coefficient with the AOD values shown in table 1 (figure 3(*b*)). We conclude that is suggestive of the hygroscopicity of anthropogenic pollutants being higher than that of dust, as noted by Hegg *et al.* (1997) and Sabbah *et al.* (2001). The meteorological conditions during spring are rapidly changing along the North African coast. This feature is strongly related to dust production, together with the soil starting to dry out.

The low topography of Cairo, falling in between the eastern and western highs, together with the weak wind currents during SON favours the formation of blocking clouds, given that the high concentration of air pollutants serve as additional CCN for nucleation. The aerosol behaviour, with respect to the water vapour column, is elaborated through the CTT and CTP separate representations during the dust and pollution episodes as the differing height of the atmospheric boundary layer and temperature influence concentration of pollutants and dust in both episodes (Devasthale *et al.* 2005). It is well known that the increase in cloud cover due to the presence of aerosols leads to a further increase in the reflection of solar radiation, hence higher CTT is expected at higher aerosol levels. Figure 4 shows the CTT behaviour over Cairo and the Greater Delta region during MAM and SON time frames for the years 2004, 2005 and 2006. The CTT during MAM of the three years shows a slightly increasing trend when departing from March (low dust) and entering April and May (high dust), reflecting the increase in the aerosol content towards the dust season, as shown in table 1. Dust aerosols during MAM are found at higher altitudes, yet are low compared to the anthropogenic aerosols revealed from the CTP values shown in table 1 and figure 5(*a*). The reason that they are found at higher altitudes as compared to SON aerosols is due to the normal temperature gradient during this particular time of the year over Cairo. Hence, in the absence of the inversion layer and, in the case of occurrence, would be an elevated type inversion, which is not found to be the case during the black cloud season (Kandil *et al.* 2006).

However, the CTT during SON of the three years shows a decreasing trend from September to November, reflecting the higher levels of aerosols at the beginning and decreasing in concentration towards November, as shown in table 1. It is evident that, during the pollution episodes, lower CTTs were achieved due to the decreasing trend, as compared to the dust episodes that show an increasing trend in the CTT values (Devasthale *et al.* 2005). This implies that anthropogenic aerosols have an indirect impact in the thermal infrared, compared to the dust aerosols. Anthropogenic pollutants during SON are found at a very low altitude, less than 1 km closer to the earth's surface, as revealed from the CTP values (>920 mb). Such low elevation is occupied because the pollutants are being prevented from rising by an inversion layer, which keeps the air from naturally being ventilated. This, in turns, keeps any aerosol and pollution below the temperature inversion layer, resulting in an increase of the concentration of pollutants. This creates a permanent haze that develops a hazardous situation, causing severe respiratory problems. The permanent occurrence of anthropogenic aerosols compared to the varying dust

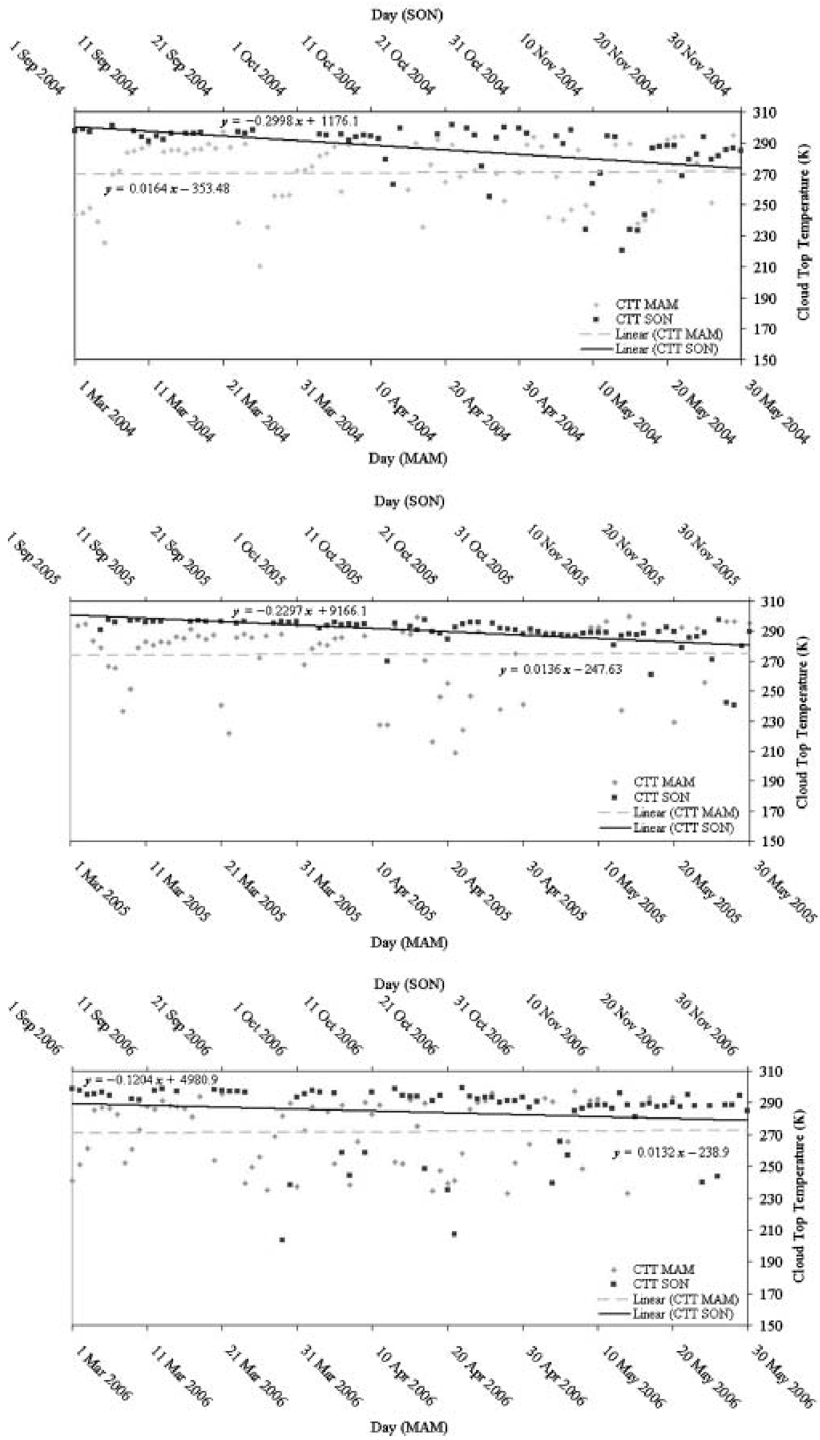

Figure 4. Temporal variability of the CTT over Cairo and the Greater Delta region during spring (MAM), showing dust impact on the increasing trend of CTT (grey line) and during autumn (SON), showing anthropogenic impact on the decreasing trend of CTT (black line) for years (*a*) 2004, (*b*) 2005 and (*c*) 2006.

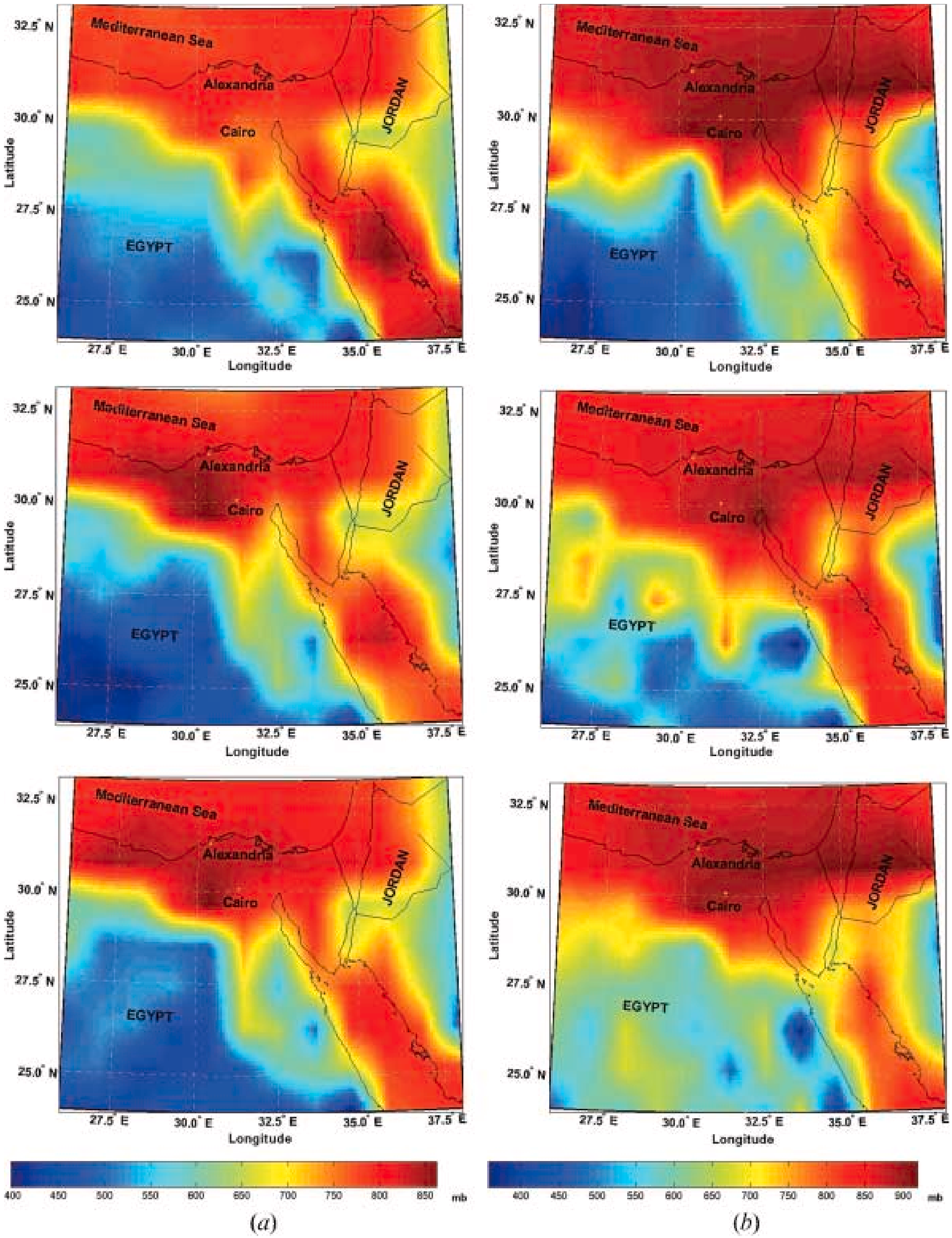

Figure 5. The CTP over Cairo and the Greater Delta region during (*a*) spring (MAM) of 2004, 2005 and 2006, showing dust occurrence at higher altitudes ~750–800 mb and (*b*) autumn (SON) of 2004, 2005 and 2006, showing anthropogenic aerosols occurrence at lower altitudes >900 mb.

behaviour is evident from the strong decreasing trend of the CTT during SON as compared to the slightly increasing trend of the CTT during MAM.

Figure 6 shows the vertical temperature profiles obtained from the atmospheric infrared sounder (AIRS) level 3 daily global girrded data products during the month of October over Cairo and Alexandria, the second biggest city, for comparison.

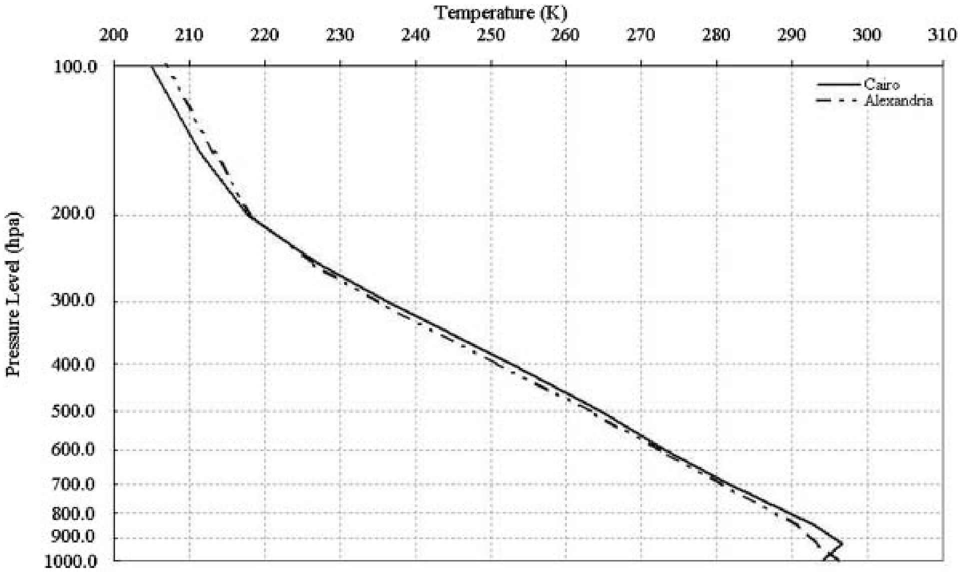

Figure 6. AIRS temperature vertical profile over Cairo and Alexandria on 2 October 2005.

AIRS level 3 files contain geophysical parameters that have been binned and averaged into 1×1 grid cells daily. This profile revealed the occurrence of an inversion layer in the lower troposphere in the vicinity of less than 1 km above the ground's surface over Cairo. Meanwhile, over the same day, a regular negative temperature gradient is observed over Alexandria, which is located 250 km away from Cairo. Such a temperature inversion layer, together with the continuous unregulated emissions, harvest by-products burning, traffic and other human activities, contributes, to a great extent, to the higher aerosol emission, as observed from the AOD and FMF products.

4. Conclusions

Higher AOD persists over northern Egypt, Cairo and the Greater Delta region; this is a distinct pattern that is not present over the rest of Egypt, with dust aerosols dominating the spring, while urban/industrial emissions prevail during the autumn months. Fine mode aerosols constitute the majority of the haze during SON months and are found to be significantly coupled with an increase in the water vapour column and the strongly decreasing CTT. Since Cairo ranks among the leading megacities of emissions (with the industrialization likely to grow in the future), the role of pollution particles on cloud-related parameters should be further investigated, in addition to sourcing attributes to these types of pollutants. These particles are important to be well identified because, depending upon the type of particles produced, human pollution can either have a warming or cooling influence on the climate and can either increase or decrease regional rainfall.

The 7 year monthly data of the AOD versus the water vapour column indicate, to a great extent, the impact of the dust and pollution episodes on the local climate. Specifically, it is clear that anthropogenic aerosols, rather than dust aerosols, lead to increasing nucleation processes and hence produce a higher water vapour column, even during a dry season. However, in the rainy season (winter: December, January and February), we observe a lower water vapour column as it flushes out with the occurrence of precipitation, because of the dry climate of the region. Highest peaks during September and October of each year show the importance of water vapour column in studying and understanding the aerosol behaviour. Further analysis would be of great importance especially through using ground-based measurements to validate satellite data products. This would help in characterizing aerosol physical composition (most importantly spectral dependence of AOD as related to aerosol size distribution for different types of pollutants and the contribution of the fine aerosols to the total AOD at different wavelengths).

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