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Chapter 7

Air Pollution from Space

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Additional information is available at the end of the chapter

1. Introduction

The South Eastern Mediterranean region is an atmospheric cross road where aerosols of different origins can be observed. Atmospheric pollution due to particulate matter from natural and anthropogenic sources is a continuing problem in many areas of Cyprus. Particulate matter (**PM**) is a major component of urban air pollution and has a significant effect on human health. High quality PM monitoring with a fine spatial and temporal resolution may help decision making to assess the efficiency of control strategies and also may be useful for informing the general public about air pollution levels and hazards. The AIRSPACE research project was established with the main aim of combining remote sensing data (mainly MODIS) with concurrent in-situ observations (sunphotometric, LIDAR and ground level PM measurements) for monitoring air pollution in an integrated manner. AIRSPACE aims to develop a novel methodology based on in-situ experimental observations in order to use satellite retrieval as a tool for monitoring air particulate pollution. This methodology was applied in Cyprus with an emphasis on urban areas and, to a lesser extent, industrial regions. Observations from passive and active ground-based and satellite techniques for Aerosol Optical Thickness (AOT) retrieval, in combination with PM_{10} and $PM_{2.5}$ concentrations at sites near different PM sources, have been considered. Several factors, such as aerosol vertical distribution, that affect the relationship between PM ground measurements and AOT, were considered. Data sets from three types of sites (urban, near urban and rural) were used to develop a statistical model for the estimation of PM mass concentrations using AOT measured from remote sensing techniques and meteorological parameters. Furthermore, the ground truth observations collected within AIRSPACE project were used to assess qualitative and quantitative performance of a chemical model forecast of PM concentrations throughout Cyprus.

Midletton et al. (2008) reported that in Nicosia, Cyprus for every 10-μg/m^3 increase in PM_{10} daily average concentrations there was a 0.9% (95%CI: 0.6%, 1.2%) increase in all-cause and 1.2% (95%CI: -0.0%, 2.4%) increase in cardiovascular admissions. A recent study regarding dust storm events in Nicosia, Cyprus, found a 2.43% (95% CI: 0.53, 4.37) increase in daily cardiovascular mortality associated with each 10-μg/m^3 increase in PM_{10} concentrations on dust days in comparison with non-dust days (Neophytou et al., 2013).

2. Background

Air pollution in large cities is one of the major issues to be addressed by local and global communities due to its widespread presence, which can have a deleterious impact on human life (Hadjimitsis, 2009). As air pollution is a major environmental health risk, by reducing the levels of air pollutants, countries will reduce the incidence of disease from respiratory infections, heart disease and lung cancer (WHO, 2011). Actions by policy makers and public authorities at the national, regional and international levels are required in order to control the exposure to air pollutants (EEA, Air Quality in Europe, 2012 - Report). Transboundary and domestic air pollution is of high concern among the EU member states. In 2010, about 21% of the EU urban population was exposed to concentrations of PM_{10} above the limit value established by the European Environmental Agency (EEA, Air Quality in Europe, 2012 - Report). The WHO, USEPA (U.S. Environmental Protection Agency) and EEA have established an extensive body of legislation which establishes standards and objectives for a number of air pollutants such as PM_{10} (coarse particles), $PM_{2.5}$ (fine particles) and O_3 (WHO, Fact sheet No 313, 2011; USEPA, NAAQS, 2012; EEA, AAS, 2012).

Current research focused on the study of regional and intercontinental transport of air pollutants, such as particulate matter ($PM_{10,\ 2.5}$), points to a need for additional data sources to monitor air pollution in multiple dimensions, both spatially and temporally. To address this issue, earth observations from satellite sensors can be a valuable tool for monitoring air pollution due to their ability to provide complete and synoptic views of large areas.

Although air quality monitoring stations have been established in major cities, there is an increased need to establish mobile stations for additional coverage, as such stations provide a means for alerting the public regarding air quality. However, measuring stations are localised and do not provide sufficient tools for monitoring air pollution, since air quality is highly variable. The use of earth observations to monitor air pollution in different geographical areas, especially cities, has received considerable attention from researchers (see Wald et al., 1999; Grosso and Paronis, 2012; Hadjimitsis, 2009; Hadjimitsis et al., 2010; Jones and Christopher, 2007; Michaelides et al., 2011; Nisantzi et al., 2012; Retalis and Sifakis, 2010; Retalis et al., 2003;

Retalis et al., 1999; Vidot et al., 2007). Several researchers (Chudnovsky et al., 2013; Gupta et al., 2006; Koelemeijer et al., 2006; van Donkelaar et al., 2010) have focused on the use of satellite sensors on air pollution studies, especially their ability for systematic monitoring and synoptic coverage. The use of sunphotometers and LIDAR systems are found to be suitable tools for assisting the air pollution monitoring studies (Ansmann et al., 2012; Amiridis et al., 2008; Engel-Cox et al., 2006; Papayannis et al., 2007a,b; Pitari et al., 2013). This study presents the integrated use of satellite remote sensing, sunphotometers and LIDAR for monitoring air pollution in the Cyprus area.

3. Resources

3.1. CIMEL Sunphotometer

The sunphotometer observations used in this study were performed by a CIMEL sun-sky radiometer, which is part of the AERONET Global Network (http://aeronet.gsfc.nasa.gov). The CIMEL sunphotometer allows for measurements of direct solar irradiance and sky radiance at 8 wavelengths; 340, 380, 440, 500, 670, 870, 1020 and 1640 nm. The technical specifications of the instrument are given in detail by Holben et al. (1998).

Figure 1. CUT-TEPAK AERONET station

The instrument is located on the roof of the building of the Department of Civil Engineering and Geomatics of Cyprus University of Technology (CUT) (34.675ºN, 33.043ºE elevation: 10 m). The CUT_TEPAK AERONET station is located in the center of Limassol, 500m away from the sea. The sunphotometric station has been in operation since April 2010. Figure 1 features the CUT-TEPAK AERONET Cimel sun-photometer.

3.2. MICROTOPS Sunphotometer

For the study sites where CIMEL's data were not available, such as Nicosia, Larnaca and Paphos, a handheld MICROTOPS II sunphotometer was used in order to retrieve AOT measurements. The sun-photometer is equipped with five accurately aligned optical collimators and internal baffles to eliminate internal reflections. Microtops II provides AOT and water vapor retrievals at five channels, which are determined using the Bouguer-Lambert-Beer law. In order to achieve measurements with great accuracy, the sunphotometer was mounted on a tripod at the same location each time. To avoid cloud contamination, measurements were taken during cloud-free daylight hours. Figure 2 shows the MICROTOPS II handheld sunphotometer used.

Figure 2. MICROTOPS II handheld sunphotometer

3.3. CUT LIDAR System

For the vertical distribution of aerosols, the LIDAR system located at CUT, in Limassol, Cyprus (34.675ºN, 33.043ºE, 10 m above sea level) was used. The LIDAR records daily measurements between 08:00 UTC and 09:00 UTC (consistent with MODIS overpass) and provides continuous measurements for the retrieval of the aerosol optical properties over Limassol, Cyprus inside the Planetary Boundary Layer (PBL) and the lower free troposphere, thus providing information for the load, the size and the sphericity of the aerosols.

The LIDAR transmits laser pulses at 532 and 1064 nm simultaneously and collinear with a repetition rate of 20 Hz. This system is based on a small, rugged, flashlamp-pumped Nd-YAG laser with pulse energies around 25 and 56 mJ at 1064 and 532 nm, respectively. An achromatic beam expander reduces the divergence to less than 0.15 mrad. Elastically backscatter signals at two wavelengths (532nm, 1064nm) are collected with a Newtonian telescope with primary mirror diameter of 200 mm and an overall focal length of 1000 mm. The field of view (FOV) of the telescope is 2 mrad. The mirror and cover plate coatings are optimized for the wavelength range from 532 nm to 1064 nm. A plain cover plate protects the mirrors. Behind the field stop two plano-convex with a focal length of 80 mm output parallel rays. The LIDAR covers the whole range starting at the full overlap of the LIDAR (~300 m) up to tropopause level. Three channels are detected, one for the wavelength 1064 nm and two for 532 nm. The two polarization components at 532nm are separated in the receiver by means of polarizing beamsplitter cubes (PBC). A special optomechanical design allows the manual ±45°-rotation of the whole depolarization detector module with respect to the laser polarization for evaluating the depolarization calibration constant of the system. The CUT depolarization LIDAR operates at 532nm and it is possible to rotate the detection box including the polarization beam-splitter cube in order to calibrate the instrument (Freudenthaler et al., 2009). Firstly, the backscattered LIDAR signals (P and S) were recorded using the normal orientation of the LIDAR detection box. For the next two steps, the LIDAR detection box is rotated by ±45º, and the P and S signals are recorded. The operation principal of this method is based on the fact that same amount of energy is sent to P and S channels, at "opposite" directions (Freudenthaler et al., 2009). Photomultiplier tubes (PMTs) are used as detectors at all wavelengths except for the signals at 1064 nm (avalanche photodiode, APD). A transient recorder that combines a powerful A/D converter (12 bit at 20 MHz) with a 250 MHz fast photon counting system (Licel, Berlin) is used for the detection of 532 nm radiation, while only analog detection is used at 1064nm. The raw signal spatial resolution is 7.5 meters. The CUT LIDAR system is featured in Figure 3.

3.4. Surface monitoring

3.4.1. PM_{10} concentration monitoring

For the surface monitoring of particulate matter (PM) concentrations, DustTrak (TSI, Model 8533) (Chan et al., 2002) was used at all sites. The DustTrak was selected to provide weekly monitoring of PM_{10} concentrations during morning hours from 08:00 to 13:00 UTC. It records the PM temporal variability with satisfactory time resolution. DustTrak's nominal flow rate of 1.7 l/min is obtained by an internal pump integral to the sampler. The monitor is factory calibrated for the respirable fraction of standard ISO12103-1, A1 test dust (Arizona Test Dust), which is representative of a wide variety of aerosols. It measures concentrations in the range of 0.001– 100 mg/m^3, with a resolution of 0.1% of the reading or 0.001 mg/m^3. Before each measurement, the instrument is zeroed and its flow rate is checked. PM_{10} concentrations have been recorded continuously since March 2011. The instrument is located, on the roof of the Cyprus International Institute (CII) in Limassol, at 10 m above ground level in order to avoid the measurements being affected by localized pollution such as passing cars. PM_{10} concentrations were also recorded by DustTrak (TSI, Model 8520) at Nicosia, Larnaca and Paphos. One TSI DustTrack has been operated by Frederick University since July 2011 and is located at the top of the Frederick University library building in Nicosia, at 10 m above ground level. The second DustTrack has been operated by CUT's scientific team during 15-day campaigns at Larnaca and Paphos. All sampling points were selected to ensure exposure to wind and to be free of other obstacles. Figure 4 features the TSI Dust Trak.

Figure 3. CUT's Depolarization Lidar System

Figure 4. TSI DUST-Track

3.4.2. PM_{10} sampling and elemental composition determinations

Under the AIRSPACE project, the Harvard School of Public Health (HSPH) and Cyprus International Institute for Environmental and Public Health (CII) were responsible for providing comprehensive and reliable data on the air pollution throughout Cyprus based on ground level measurements.

Air pollution near ground level measurement sites were established in the four cities of Cyprus: Nicosia, Larnaca, Limassol and Paphos. These sites were located at positions thought to be representative of air pollution in each city. In Nicosia, the site is located on the roof of the Frederick University library building, on the same site where the DustTrak and sunphotometer were operated. The Larnaca site is located in the center of the city, on the roof of the tax agency building. The Limassol site is located on the roof of the CII building in the center of the city and Paphos site is on the roof of the economics department of Paphos Municipality. In Figure 5 the setup of the Harvard samplers is presented.

Figure 5. Harvard Samplers

3.4.3. Satellite observations

The Moderate Resolution Imaging Spectro-Radiometer (MODIS) observations from the TERRA and AQUA satellites both measuring spectral radiance in 36 channels (412–14200 nm), in with resolutions between 250 m and 1 km (at nadir) were used to provide a climatology for Cyprus. In polar orbit, approximately 700 km above the Earth, MODIS views a swath of approximately 2300 km resulting in near daily global coverage of Earth's land/ocean/atmosphere system. The swath is broken into 5-min ''granules'', each approximately 2,030 km long.

Aerosol products are reported at 10 km resolution (at nadir). Details of file specification of MODIS L2 aerosol products can be found at the website http://modis.gsfc.nasa.gov/.

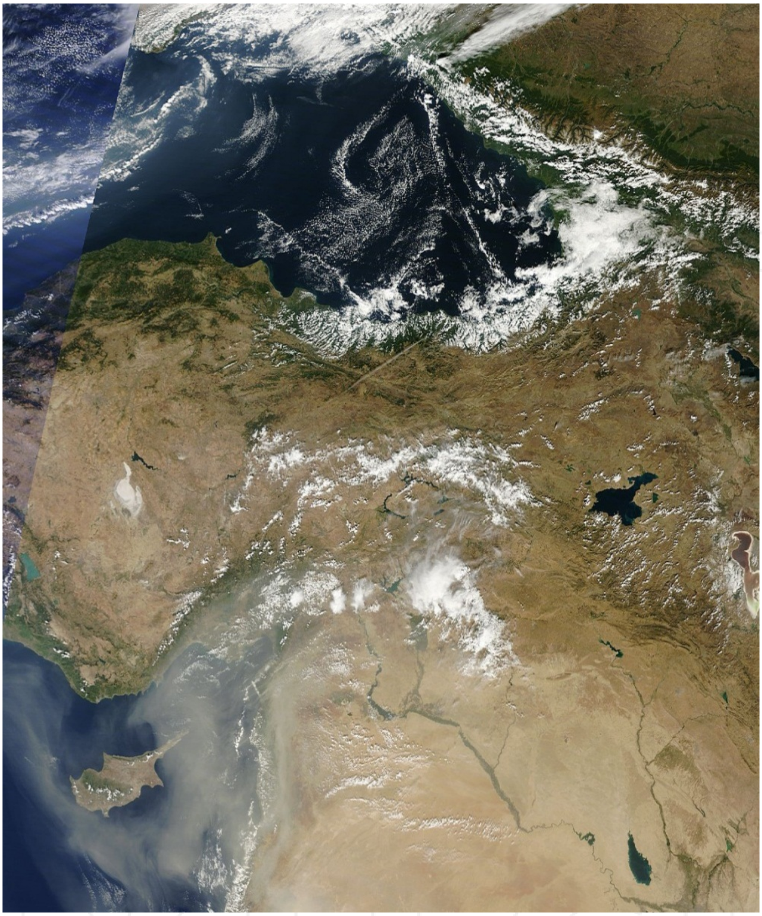

Figure 6. MODIS image for Eastern Mediterranean region

4. Methodology, study area and data

4.1. Method

The overall methodology is described below (see Fig. 7):

1. **Satellite data products from the MODIS sensor:** Aerosol optical thickness (AOT) and aerosol size/type data were collected for the years 2002-2010 over Cyprus.

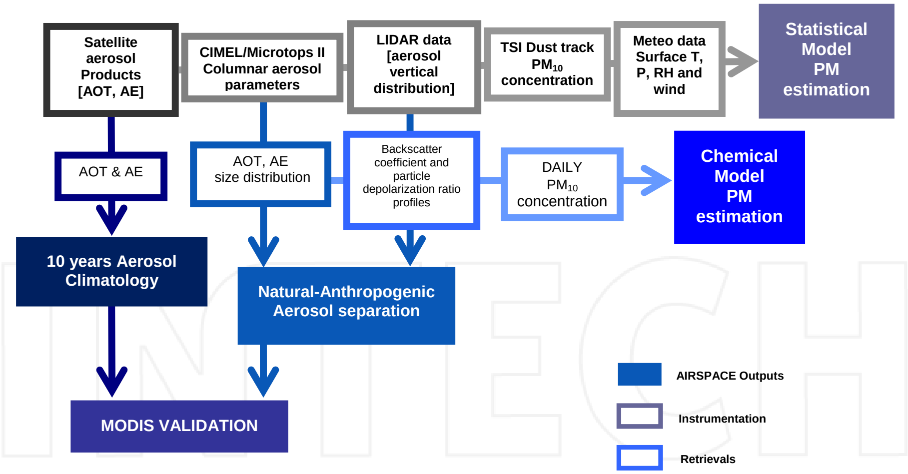

Figure 7. Overall Methodology of the Airspace project

2. **Vertical profile of the aerosol backscatter:** A light detection and ranging (LIDAR) system was established in Limassol in April 2010, consisting of a laser capable of measuring aerosol backscatter and aerosol depolarization ratio in the atmosphere as a function of height. This allows the AOT, and hence the scaling to aerosol concentration, to be quantified below the boundary layer since this fraction best represents the PM measurements in a well-mixed boundary layer.

3. **Integrated aerosol optical thickness for the entire atmospheric column:** A sunphotometer station was installed in the centre of Limassol (at the CUT premises), where pollution from both industrial and urban sources exist. This further assists in the calibration and verification of satellite derived AOT data. Moreover, two hand-held sunphotometers were used to measure urban, industrial and dust pollution.

4. **Measurements of particulate matter (PM) concentration levels:** PM_{10} and $PM_{2.5}$ hourly concentration values were collected using portable PM samplers available from the CUT Remote Sensing Laboratory and Harvard University / CII. Additionally, the Harvard samplers used and located in Limassol, Nicosia, Larnaca and Paphos regions were used to provide chemical characterization of the collected aerosols.

5. **Meteorological data from the entire area of Cyprus:** Relative humidity measurements combined with the AOT fraction below the boundary layers, derived by the LIDAR, were incorporated into the statistical PM-AOT models, for improving the PM concentration estimation. Classification of the synoptic situations in Cyprus was also taken into account.

6. **Simulation results from dispersion/air pollution model:** A modeling system that incorporates a fully interactive coupling between the chemistry-aerosol and meteorology (radiation and cloud-physics) portions of the model was created, allowing real-time

simultaneous prediction of air quality (in terms of PM aerosol mass) and weather for 72 hours. The model forecasts have been statistically evaluated against surface observations.

4.1.1. Study areas in Cyprus and general characteristics

An overview of the available instrumentations at the selected sites is given in Figure 8.

Figure 8. Overview of the available instrumentations at the selected sites within AIRSPACE project. Limassol was the main site (LIDAR, AERONET, PM), Nicosia validation site (MicrotopsII, PM); 15-day campaigns were conducted at Larnaca and Paphos.

Meteorological conditions: Cyprus is characterized by a subtropical - Mediterranean climate with very mild winters (mainly in the coastal areas) and hot summers. Snowfall occurs mainly in the Troodos Mountains in the centre of the island. Rain occurs mostly during the winter period, with summer being generally dry. Temperature and rainfall are both correlated with altitude and, to a lesser extent, distance from the coast. The prevailing weather conditions on the island are hot, dry summers (from mid-May to mid-September) and rainy, rather changeable winters (from November to mid-March). These are separated by short autumn and spring seasons.

During the summer period (a season of high temperatures with almost cloudless skies), the island is often under the influence of a shallow trough of low pressure extending from the great continental depression centred over Western Asia. During winter, Cyprus is mainly affected by frequent small depressions traversing the Mediterranean Sea from west to east between the continental anticyclone of Eurasia and the generally low pressure belt of North Africa. These depressions result in disturbed weather usually lasting no more than a few days and producing most of the annual precipitation (the average rainfall from December to February is typically about 60% of the average annual total precipitation). Relative humidity averages between 60% and 80% during the winter period and between 40% and 60% during the summer period. Fog is infrequent and visibility is generally very good. Sunshine is abundant all year round, particularly from April to September when the average duration of bright sunshine exceeds 11 hours per day. Winds are generally light to moderate with high variability when it comes to direction. Gales are infrequent over Cyprus and are mainly confined to exposed coastal areas as well as areas at high elevation.

Aerosol sources: Two main types of air pollutant sources can be identified: anthropogenic and natural. Notable natural sources include dust from inland wind erosion, transboundary sources and sea salt. Cyprus' arid climate results in large portions of surface area having very low index of vegetative cover. This, combined with very low levels of moisture for a substantial part of the year, results in the overall vulnerability to wind erosion. Furthermore, Cyprus presents a high ratio of shoreline when compared to surface area, with maximum distances inland from the shore being in the order of 30-40 km and the three of the four urban centres located on the coast. Therefore, sea salt can have a significant effect on the concentrations of particulates in the majority of the island's area. Finally, the transportation of dust from the surrounding eastern Mediterranean and African areas (most notably from northern Africa) significantly affects air quality (Nisantzi et al, 2012).

Local anthropogenic sources also contribute to PM concentrations on the island. The main anthropogenic PM sources include traffic (both highways and inner city traffic), industrial zones, urban agglomerations, agriculture, mines and quarries and localized emissions from a series of activities such as power stations and cement factories.

To monitor air quality in Cyprus within the AIRSPACE project, the instrumentations discussed in this section has been used.

4.2. The dataset

4.2.1. Ground based measurements

For the purposes of the project, Limassol was selected as the main ground based site for the development and the application of the AIRSPACE methodology. The main instrumentation used for the aerosol observation in a daily basis was a backscatter-depolarization LIDAR system for the study of the vertical aerosol distribution as well as the sunphotometer for the columnar aerosol information, both located at the premises of CUT, in Limassol (see Figure 9) (34.675ºN, 33.043ºE, 10m above sea level), since 2010. The LIDAR records daily measurements between 08:00 UTC and 09:00 UTC (consistent with the MODIS overpass) and to perform continuous measurements for the retrieval of the aerosol optical properties such as depolarization ratio and backscatter coefficient over Limassol, inside the Planetary Boundary Layer

(PBL) and the lower free troposphere. Additionally, the AERONET sun-photometer provides daily aerosol information including AOT and aerosol size distribution.

Figure 9. Satellite image of Limassol

For the purposes of the AIRSPACE project, Nicosia was selected as a validation site (in addition to the Limassol main site), for ground based measurements of PM_{10} and AOT. Two locations in Nicosia were used as test sites: Strovolos municipality building (N35.144°, 33.343° E) during the period September 2011 to December 2011 and Pallouriotissa Frederick University Research Centre building (N35.181°, 33.379° E) during the period February 2012 to June 2012 and the period October 2012 to January 2012. The Strovolos area is mainly commercial with heavy traffic at peak hours while the Pallouriotissa site is residential.

For both sites, a TSI Dust Trak model 8520 was used for measuring the mass concentration of particulate matter of diameter less than 10 micrometers (PM_{10}). The Dust Trak is a light scattering laser photometer which determines PM_{10} concentrations by measuring the amount of scattering light, which is proportional to the volume concentration of aerosols, in order to determine the mass concentration of aerosols (Nisantzi et al., 2012). The Dust Track features an integrated pump, internal memory and data-logger for automatic storage of measured values at programmable intervals. The device was programmed to begin PM_{10} recordings every morning at 08:00 UTC for a 5-hour period to coincide with the satellite MODIS TERRA and AQUA overpass except at weekends.

Adjacent to the Dust Trak, a Microtops II model 540 sunphotometer was set up to measure the AOT. This is a 5-channel hand-held sunphotometer which measures and stores data at 5 different wavelengths. In addition to the Dust Track and the sunphotometer which were set up originally at the Strovolos site and then moved to the Pallouriotissa site, the Harvard Impactors were assembled at the Pallouriotissa site only (next to the other two devices) for chemical analysis of PM_{10}, $PM_{2.5}$, EC-OC and nitrate concentrations.

The in-situ data were collected in conjunction with satellite data (MODIS) to validate a novel statistical model developed within AIRSPACE using AOT retrievals to estimate air particulate pollution.

For Larnaka, two sets of measurements took place: one using the Dust Track along with the Sun photometer for a period of three weeks in August of 2011 (8^{th}-26^{th}) on a site at the centre of Larnaka city (34.916° N, 33.630° E), for the first set of measurements: PM_{10} recordings every morning at 08:00 UTC for a 5-hour period and subsequent measurements using the MICRO-TOPS sun photometer at 08:00 UTC and at 11:00 UTC to coincide with the MODIS TERRA and AQUA overpasses. A second set of measurements was provided by the Harvard Impactor situated on top of the tax agency building (34.919° N, 33.631° E) in Larnaka. This station provided measurements of PM_{10}, $PM_{2.5}$, EC-OC (elemental & organic carbon) and nitrate concentrations.

For air pollution ground level measurements, the Harvard Impactor stations were established by HSPH and CII: Limassol, Nicosia, Larnaca and Paphos. The sampling commenced on 12 January 2012 and ended on 12 January 2013. Samples were collected every six days, on 24-hr basis from 08:00 to 08:00 next day (UTC), at all sites except Limassol, where the sample collection was done every three days. Samples were collected for $PM_{2.5}$, PM_{10}, EC-OC) and nitrates using the Harvard Impactors. For quality assurance and control, collocated and blank samples were collected for each sample at the Limassol site, according to a predetermined schedule. Standard Operating Procedure (SOP) was followed for each measurement at each site. Filters were collected and sent to HSPH for chemical analysis. The parameters measured included fine particles ($PM_{2.5}$): mass, reflectance, nitrate, trace elements and EC-OC; and inhalable particle (PM_{10}): mass, reflectance and trace elements. Chemical analysis included Thermal Optical Transmitance (TOT) to measure EC-OC particle concentration, gravimetric mass determination and X-Ray fluorescence to determine trace elemental composition of $PM_{2.5}$ and PM_{10}. Samples up to 19 June 2012 have been analyzed the remaining samples have undergone chemical process for analysis.

5. Results

As described previously, Limassol was the main site for the development of the AIRSPACE methodology for the estimation of the PM levels. The ground based data were used to validate the satellite data. Complementary to the Limassol site, Nicosia's and Larnaca's site observations were used to validate the performance of the models. In this section, the major results from the AIRSPACE project are analysed in some detail.

5.1. Dataset validation

In the AIRSPACE project, both ground based and satellite observations were used to provide aerosol related information for South Eastern Mediterranean region. The first goal of the AIRSPACE project was the validation of the satellite observations in Cyprus, an area affected by aerosol from different sources and surrounded by sea. The ground based observations performed over Limassol and Nicosia were used as the main sites for the validation of the satellite observations.

To incorporate both the spatial and temporal variability of aerosol distribution, the MODIS retrievals at 10 km x 10 km resolution and the AERONET direct Sun measurements at 15-minute intervals (Holben et al., 1998) need to be co-located in space and time.

The AERONET data provide the ground truth for the MODIS validation. The global CUT-TEPAK ground-based AERONET sunphotometer measures aerosol optical thickness in eight channels (340 to 1640 nm). The instrument takes measurements every 15 minutes. From the observations taken within ±30 minutes of MODIS overpass time (Ichoku et al., 2002), mean values of the optical parameters were calculated. Therefore, the maximum number of AERONET observations within the hour of an overpass is 5. Fewer observations within the hour indicate data have been removed by the AERONET Run-Time Cloud Checking procedure.

The study required at least 2 out of possible 5 AERONET measurements to be within ±30 min of MODIS overpasses and at least 5 out of possible 25 MODIS retrievals to be within a 25 km radius centred over the AERONET site. The mean values of the collocated spatial and temporal ensemble were then used in a linear regression analysis and in calculating RMS errors. The AERONET level 1.5 data were cloud screened. Though the level 2.0 data provide final calibration, they are not available for the entire time period of the project. Therefore, the level 1.5 data (instead of level 2.0) were used in the operational MODIS aerosol validation scheme.

A total of 352 points of AERONET site representing the correlated criteria for the MODIS- and AERONET derived AOT were collected in the period from April 2010 to December 2012.

Figure 10 features the correlation of the MODIS AQUA and TERRA sensors and CUT_TEPAK AERONET measurements. The slope of linear regression in the correlation plot between MODIS and AERONET provides an overview of possible differences. The correlation coefficient value of the order of 0.62 for both TERRA and AQUA satellites is due to the coast line of the Limassol site. Limassol's CUT-TEPAK AERONET site is a coastal area, thus the surface inhomogeneity or sub-pixel water contamination has a larger effect than anticipated in continental coastal regions (Nisantzi et al., 2012). The systematic biases overestimations in MODIS retrievals are mainly due to aerosol model assumptions (deviation of 0–20%) andinstrument calibration (2–5%).

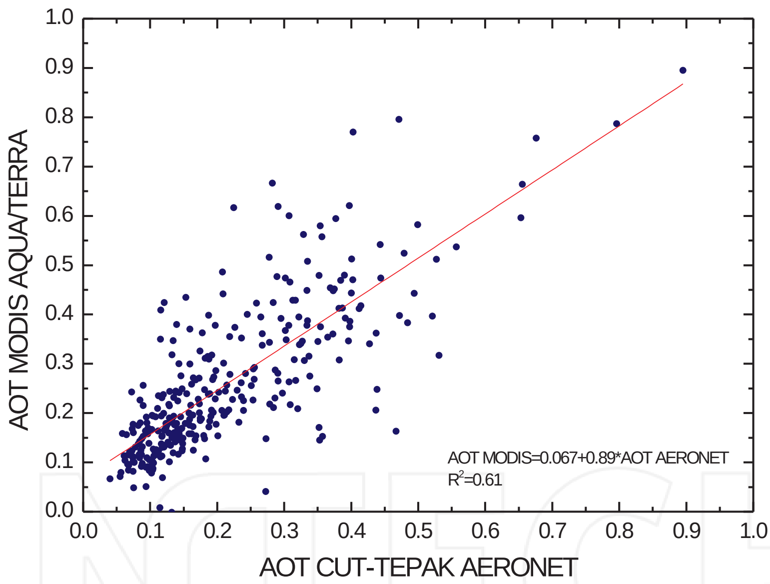

Figure 10. Comparisons of MODIS and AERONET derived at 0.50 nm wavelength, encompassing 352 points from CUT-TEPAK AERONET coastal site. The solid line represents the slopes of linear regression both for AQUA and TERRA MODIS sensors

Using the MICROTOPS II AOT, the procedure was duplicated for the validation of the satellite observations in Nicosia. The number of collocated and synchronized ground based and satellite measurements were statistically low in order to provide correlation factor which can represent a reliable validation study.

5.2. Satellite climatology

In the present work, the Level 2, 10x10km, MOD04 aerosol products (Collection 051) were retrieved for the years 2001 to 2011 from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS). The AOT fields were extracted from the 'Optical_Depth_Land_And_Ocean' parameter which provides the AOT at 550nm derived via the dark-target algorithms and with best quality data (Remer et al., 2005). According to Remer et al. (2009), the AOT fields for this product have been respectively validated to within the error bounds of (0.04+0.05AOT) and ±(0.05+0.15AOT) at 550nm.

Based on the above AOT data, subsets for the area of Cyprus were extracted and mean monthly climatology maps were constructed for the period 2001-2011. For the area considered, the number of days with valid TERRA AOT measurements ranged approximately from 1000 to 2300 (which amount to 25%-57% time coverage), as shown in Figure 11. The highest number of valid measurements was observed over the central area of Cyprus (in the vicinity of Troodos Mountain), whereas near the coastline, this number decreased.

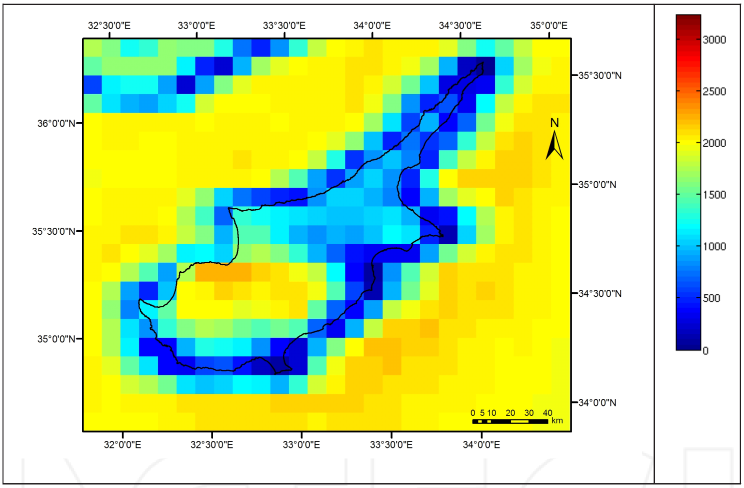

Figure 11. Number of valid TERA AOT observations for the period 2001-2011

The maps for each month are presented in Figure 12. The seasonal cycle of the aerosol load is well depicted. Minima are observed during winter months and maxima during spring and summer when intense phenomena associated with dust transport from Sahara desert are more frequent. The respective monthly average values for the three urban sites of Nicosia, Larnaca, and Limassol (marked as LE, LA and LM, respectively, on the maps) and the background site of Agia Marina, (marked as AM) have been calculated. In general, the background site is characterised by lower aerosol loads (ranging from 0.1 to 0.28) there observed at the urban sites. Limassol (the main port city) presents the highest values for the period January-May and Nicosia (the capital city) from June to December. For this latter period, Larnaca presents intermediate values. The two distinct maxima associated with dust transport phenomena are observed at all sites in May and August. The value for the first peak in May is approximately the same for all urban sites (~0.40) but for August, the levels for Nicosia are higher (~0.45) compared to the other two urban sites (~0.35 for Larnaca and Limassol).

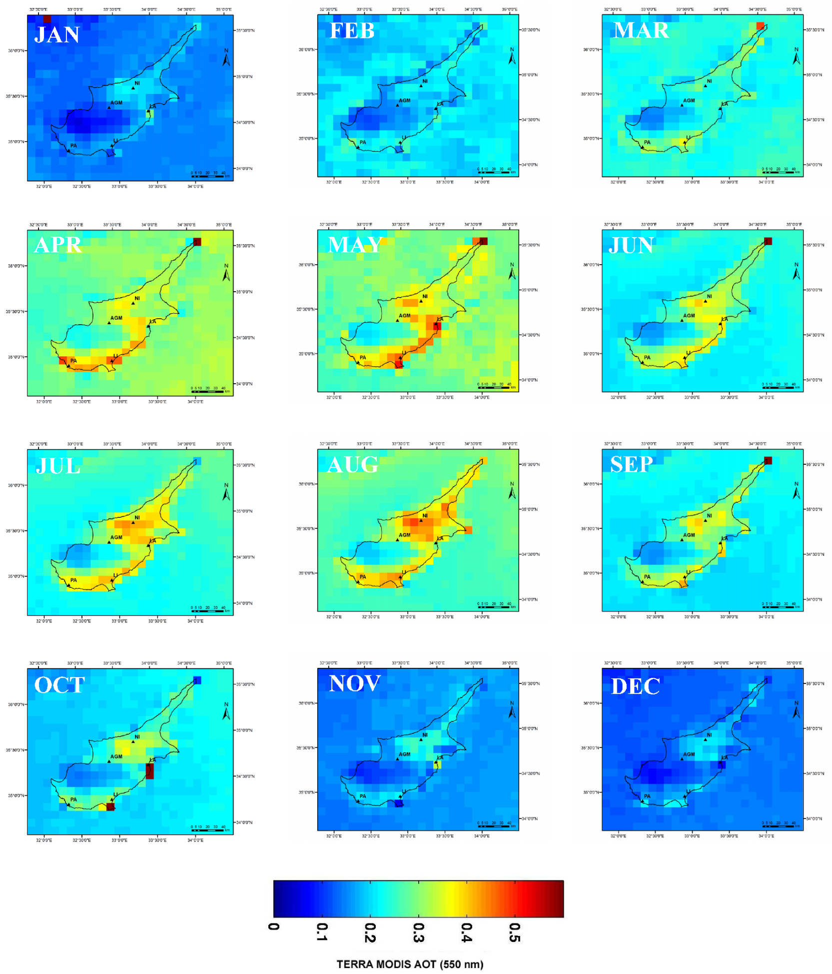

Figure 12. Average monthly AOT. (LE, LA, LM, and AM mark the sites of Nicosia, Larnaca, Limassol and Ag. Marina)

5.3. PM surface analysis

One element of the AIRSPACE program in Cyprus was the measurement of ground level PM concentrations by Harvard Impactors.

Statistics for the Limassol site show that for the first six months of observations the mean value for PM_{10} is 32.1 μg/m^3, for $PM_{2.5}$ 13.4 μg/m^3 and for total carbon 2.3 μg/m^3 with standard deviations of 20.9, 4.6 and 1.1 μg/m^3, respectively.

PM_{10} and $PM_{2.5}$ were analysed, for trace elements such as sulfur, magnesium, aluminum, sodium, silicon, chlorine, potassium and calcium. Statistics for some of those trace elements for $PM_{2.5}$ are shown below, in Table 1.

	Mean (μg/m^3)	SD (μg/m^3)	Median (μg/m^3)
Sodium	0.27	0.15	0.23
Magnesium	0.06	0.08	0.05
Aluminum	0.16	0.29	0.07
Silicon	0.29	0.55	0.13
Sulfur	1.29	0.73	0.99
Chlorine	0.07	0.17	0.02
Potassium	0.11	0.06	0.10
Calcium	0.20	0.37	0.12

Table 1. Trace elements statistics for the first 6 months sampling, for $PM_{2.5}$ cut off

Figure 13 and14 indicate the 6 month timeseries of the $PM_{2.5}$ and PM_{10} concentrations, as well as the elemental, organic and total carbon levels from the Limassol filters.

Analysis of these initial samples revealed evidence of a dust storm event recorded on 12 March 2012, with PM_{10} and $PM_{2.5}$ concentrations reaching up to 156.6 μg/m^3 and 29.4 μg/m^3, respectively. These values are several times higher than the typical values shown during the sampling period and well above the 24-hour limit value set by EEA, especially for PM_{10}.

PM10 and PM2.5 concentrations show a small increase from the start of the sampling (January 2012) until June 2012, indicating a temporal relationship.

5.4. Statistical model

Based on the data collected a statistical model was established for estimation of PM concentrations from AOT measurements. Using a general linear regression model, the AOT retrieved by MODIS was used to predict ground-level PM_{10} concentrations in Limassol, Cyprus.

The proposed model by Liu et al. (2007) is given in equation 1:

$$Ln(PM_{10}) = \beta_0 + \beta_1(\log AOT) + \beta_2(\log AE) + \beta_3(WVdep) + \beta_4(\ln(T)) + \beta_5(\ln(RH)) + \beta_6(\ln(WS)) + \beta_7(Wd) + \beta_8(P) + \beta_9(PBL) \quad (1)$$

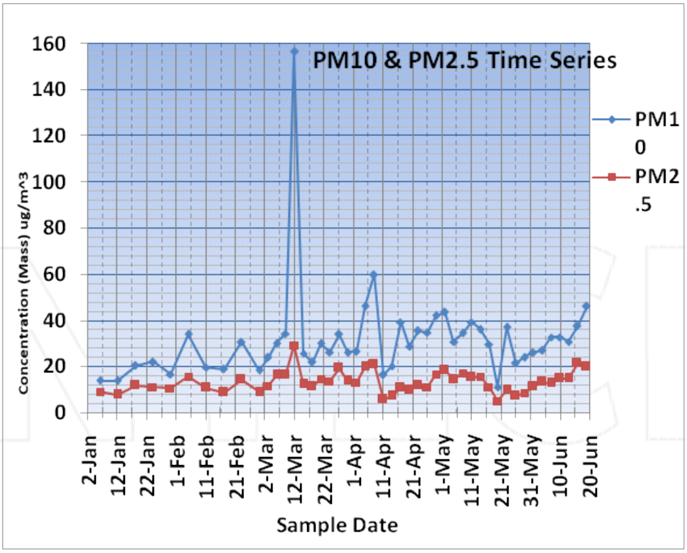

Figure 13. Time series of PM_{10} and $PM_{2.5}$ at the Limassol site for the first 6 months' samples

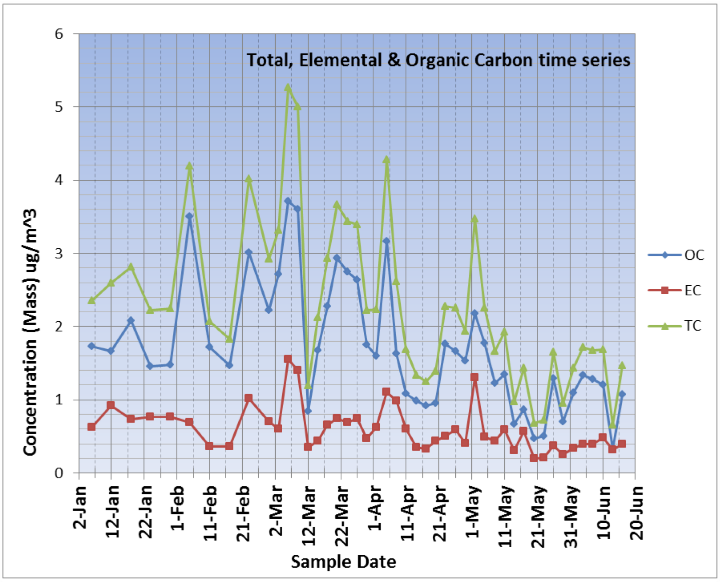

Figure 14. Time series of total, organic, elemental and total carbon for Limassol site for the first 6 months samples

Where βi are the regression coefficients, AOT is the Aerosol Optical Thickness, AE is the Angstroem Exponent, WV is the Water Vapour (in g/Kg), T is the surface temperature (in C), WS is the wind speed (in m/s), Wd the wind direction (in degrees), P is the pressure at surface level (in hPa) and PBL is the Planetary boundary layer height (in meters).

The available data set in AIRSPACE project are given in Table 3:

Parameters	**Instrument**
Aerosol Optical Depth	CIMEL
Angstrom Exponent	CIMEL
Total Column Water Vapour	CIMEL
PM 10	Dust Track TSI
PBL height	LIDAR
Meteorologiacal Data	METAR-LRCA (Akrotiri Air Base, Cyprus)

Table 2. AIRSPACE dataset used for the statistical model

Based on the proposed methodology, the performance of the multi-regression model was examined by introducing one predictor (Xi) at a time, together with the initial predictor, the AOT at 500nm (Xi i=0). For each predictor Xi, the following options (j) were considered, in order to increase the sensitivity of the model linked Xi :

# option	**Type of parameter involved**
1	Ln(Xi)
2	Xi
3	Deparcures from mean value of Xi
4	Ratio of mean value of Xi

Table 3.

From the above options (j=1 to 4), the one with the highest correlation coefficient (CCij) between predicted and measured PM_{10} was selected. In each iteration step k, the maximum values of the CCij = CCik were compared, in order to select the predictor Xik with the highest positive impact. Due to the limited dataset, no evident seasonal dependence was noted. (Cook and Sanford (1982))

The results are presented below. In Figure 15 the correlation coefficient between the predicted and measured PM_{10} is presented for 8 different models. The maximum performance of the model is reached by using the following predictors (in strength order), with a correlation coefficient on the order of CC=0.85

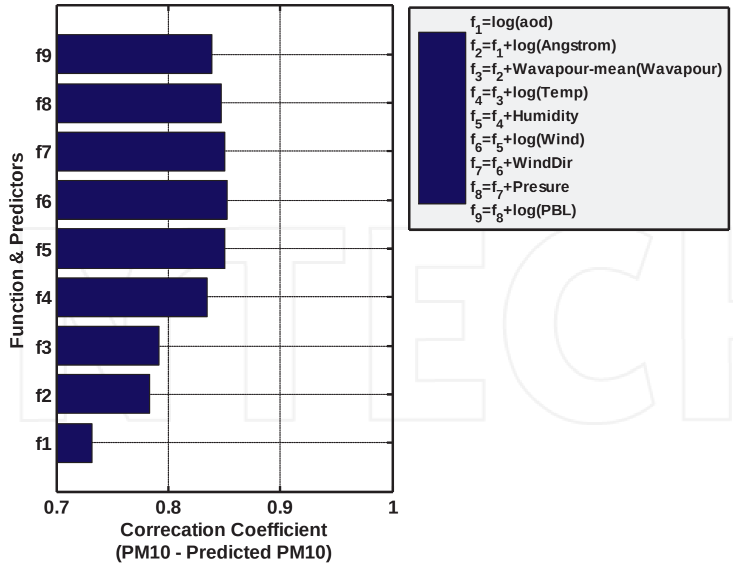

Figure 15. The correlation coefficient between the predicted and measured PM_{10} is presented for 8 different models

	CC= 0.853	**CC=0.850**
	βi	***βi***
Constant Term	-4.117	-4.111
Ln(AOT)	0.952	0.943
Ln(AE)	0.299	0.299
Wavapour-mean(Wavapour)	-0.393	-0.384
Ln(Temp)	0.643	0.6.23
Humidity	0.008	0.008
Ln(Wind)	-0.096	-0.071
WindDir		-0.0004

Table 4. Best correlation coefficients and regression coefficients

The results of the above sensitivity analysis indicate the maximum performance of the model of the order of CC=0.85 as shown in equation 2:

$$Ln(PM_{10}) = -4.11 + 0.952(\log AOT) + 0.299(\log AE) - 0.393(WVdep) + 0.643(\ln(T)) + 0.008(RH) - 0.096(\ln(WS)) \tag{2}$$

Finally, using formula 2 as the best model and the coefficients derived and shown in Table 4, the relationship between the model's prediction and the measured PM10 concentrations is shown in Figure 16. The residuals, i.e, the differences between the measured and the predicted values of the PM concentration are shown in Figure 17. The points in the residual plot in Figure 17 are randomly dispersed around the horizontal axis, thus, a linear regression model is appropriate.

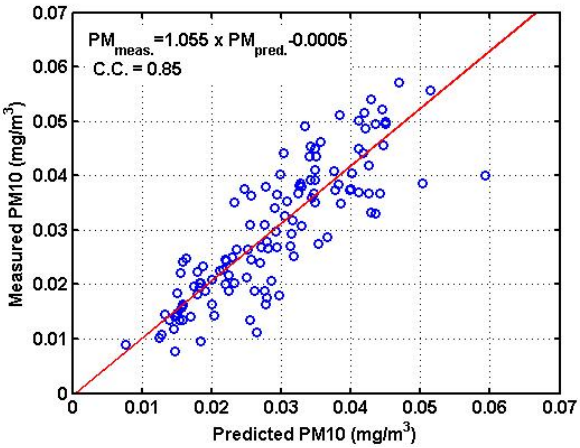

Figure 16. Comparison between predicted and measured PM_{10} by TSI DUST Track at Limassol (Red line : linear fit)

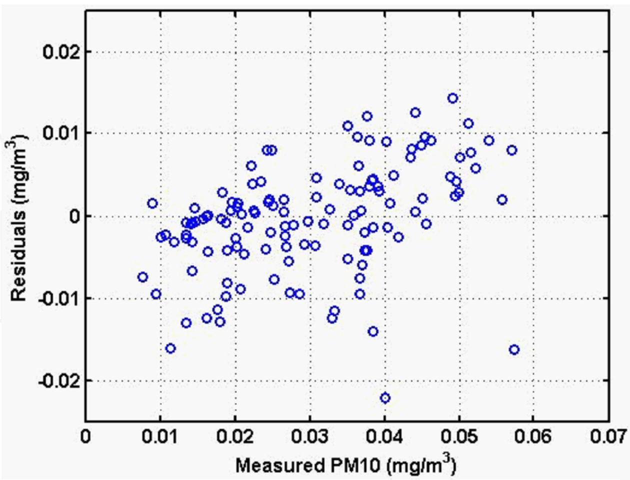

Figure 17. Differences between the measured and the predicted value of the PM concentration (Residual plots)

5.5. Chemical model

Within AIRSPACE project, a high resolution atmospheric Chemistry General Circulation Model (AC-GCM) was used to study the emission, transport and deposition of dust. The Modular Earth Sub-model System (MESSy version 2.41) (Joeckel et al., 2005; 2006; 2010) is an earth system model which is capable of running with multiple representations of processes simultaneously paired to the core atmospheric general circulation model (ECHAM5). The model configuration used in the present study has a spectral resolution of T255L31 (0.5°, 50km) and 31 vertical levels up to 10 hPa. Gleser et al. (2012) emphasized the importance of higher resolution simulations for better dust representation in the model. As this is a global model, no boundary conditions are necessary. All known emission sources are included, while the initial conditions originate from the ERA40 reanalysis data (European Centre for Medium-Range Weather Forecasts - ECMWF) at 0.5-degree resolution. Every 12 hours of operation, the model fields are moved towards the ERA40 data in order to simulate the meteorological conditions, as precised as possible. In order to reduce computational time, the model uses a simplified chemistry module, preserving only the sulfate and NOx interactions which are considered the most important as far as the aerosols are considered. The model output is averaged and stored over 5-hour intervals, which provides an entire diurnal cycle after 5 days. The configuration includes also a simplified sulphate chemistry scheme (Gleser et al., 2012) allowing the production of sulphuric acid and particulate sulphate, which play an important role in transforming dust particles from hydrophobic into hydrophilic, thus affecting their ability to interact with clouds and be removed by precipitation (Astitha et al., 2012). The ammonia (NH_3) reaction with sulphate and corresponding coating with dust (Ginoux et al., 2012) is also considered in this study. Due to the focus on dust episodes, a reduced version of the atmospheric chemistry scheme was applied which did not account for secondary inorganic and organic aerosol species associated with air pollution. The model used ECMWF gridded meteorological data to represent the actual meteorological conditions. To ensure adequate representation of the pollutants and dust in the atmosphere, the model runs for 15 days (spin-off) to create from the meteorology and the emissions the current weather conditions. This strategy ensures that the existing pollutants not represented in the model are removed from the atmosphere, while the sources will produce pollutants that will be dispersed in the atmosphere. After the initial spin-off, the atmospheric conditions represented from the model fields and the pollutant concentrations are considered as close to reality as possible. The model simulation was performed over the period of September to October 2011.

The most significant issue for the operational run of a numerical model prediction of the dust is the complete absence of initial conditions for pollutant and dust concentrations. This enforces the utilization of global models to simulate the atmosphere with extremely accurate emission inventories which are absent or not complete for North Africa and Eastern Mediterranean. The latter is an important source of uncertainty for concentrations. Furthermore, the sparse coverage of measurements for the spatial validation of the model in the region does not provide a clear picture for the evaluation assessment of the model.

The use of a global model necessitated the utilization of a large grid due to computational limitations. The global grid introduced an adequate representation of the topography of the

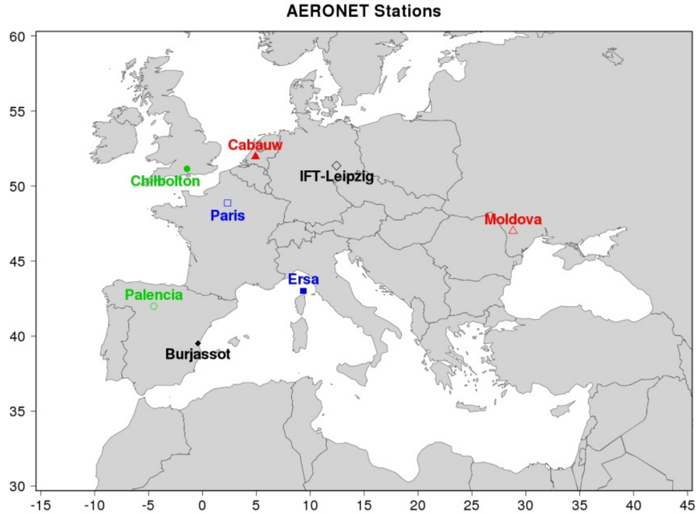

Figure 18. AERONET stations used to evaluate the model results

models and requires special parameterization of processes that often lead to errors. Another restriction is the simplified chemistry used for the simulation. The computational power necessary for the implementation of a full chemistry scheme is not currently available.

The model results were evaluated using the AOT fields provided by the NASA AERONET available from http://aeronet.gsfc.nasa.gov. The data comparison represents the AOT for all aerosols simulated in the model as well as those observed in the atmosphere at 550nm wavelength. The observed AOT was averaged over the 5-hour output intervals in line with the averaged AOT over the same period from the model. Figure 18 shows the eight AERONET stations which observational data were available during the simulation period and which were used in this study. These stations are not necessarily located in dust-dominated regions but can be more strongly affected by other aerosol types, including air pollution.

The scatter plot between the modeled and observed AOT is shown in Figure 19. Different colors and symbols are used for each station ID (see legend). As shown, the model is capable of simulating the AOT in general. However, at some stations (Leipzig, Palencia, Paris) the model tends to underestimate the observed AOT. This is explained by the use of the reduced atmospheric chemistry scheme in the model that does not fully account for urban air pollution in addition to the unresolved physics at small scales in the global models. However, the comparison of the output of the model for the AOT with the measured values from the AERONET network indicates that the simulated atmosphere is valid in areas with similar climatological and industrial characteristics to Cyprus, while for areas with heavy industry, there is a significant deviation which can be justified from the reduced chemistry module used for the runs.

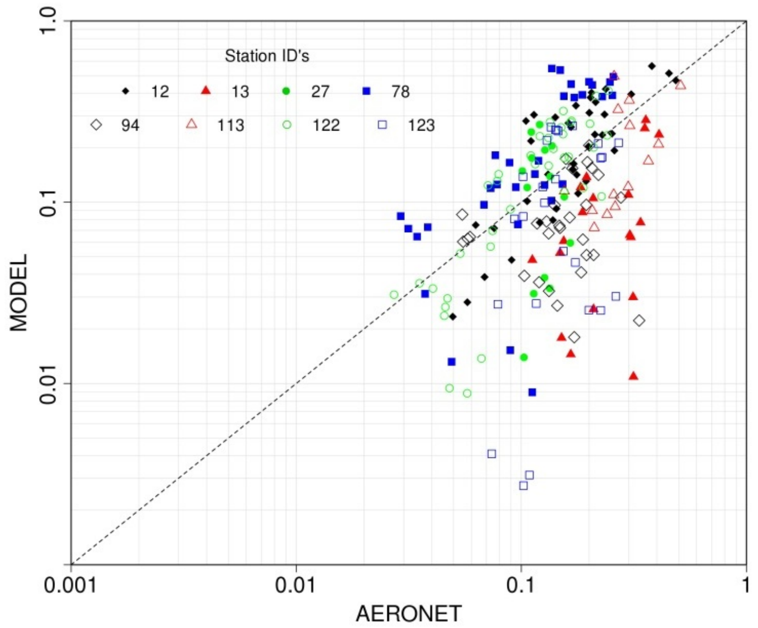

Figure 19. Scatter plot between modeled and observed AOT for different AERONET stations

Furthermore, model AOT estimations have been compared with the available AOT measurements from CUT-TEPAK AERONET site. Figure 20 shows the time evolution of the AOT for the Limassol AERONET station together with the model results. As shown in Figure 20, the model is generally, in agreement with observations in both magnitude and timing for Limassol with respect to the average measured values. The comparison between the modeled and observed AOT indicates the ability of the model to simulate the AOT adequately.

5. Conclusions

An integrated methodology for assessing and studying air pollution in several areas of Cyprus was presented through the AIRSPACE project. Satellite derived aerosol optical thickness data along with LIDAR, sun-photometric and in-situ (PM) measurements were analyzed. The proposed integration of several tools and technologies provides to the user an alternative way for assessing and monitoring air pollution.

First, a new multiple linear regression model for estimating PM_{10} using AOT values and some other auxiliary parameters such as meteorological atmospheric parameters has been developed for the urban area of Limassol in Cyprus. AOT can be retrieved by satellite sensors and

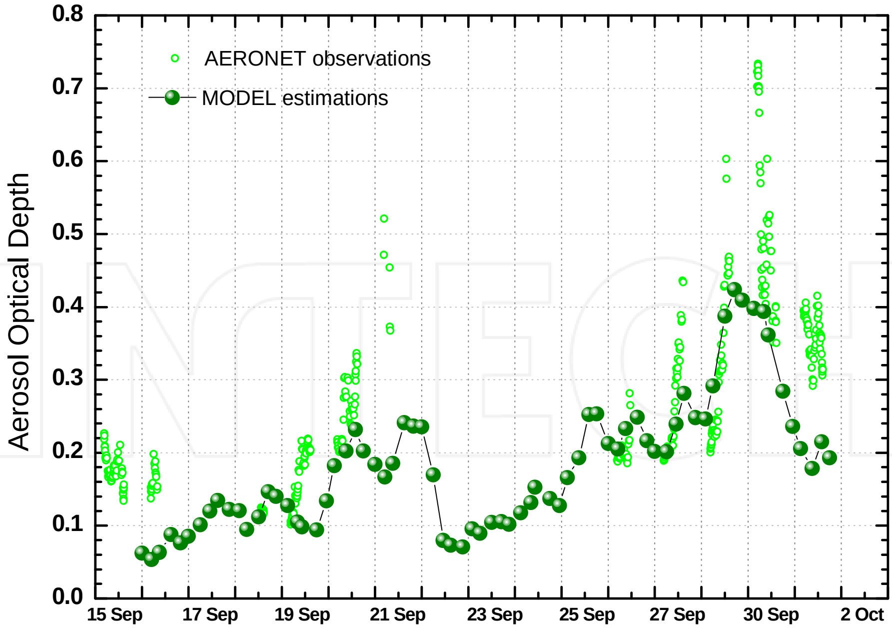

Figure 20. Comparison between the modeled (dark green) and observed (light green) AOT for Limassol AERONET on September 2011

is validated on the ground by using measured values with sunphotometers. Such model can be used for future satellite acquisitions. The integrated use of several resources and technologies such as satellite image data, LIDAR measurements, meteorological data and sunphotometric data lead to the development of new approaches in estimating PM concentrations

Second, an atmospheric chemical simulation model was run for the period September-October 2011. The model results were evaluated using the AOT provided by the NASA AERONET. AOT estimations have been compared with the available AOT measurements from CUT-TEPAK AERONET site. It has been found that the modeled and observed AOT values were in good agreement.

Acknowledgements

The results presented in this Chapter form part of the research project “Air Pollution from Space in Cyprus” - AIRSPACE, funded by the Cyprus Research Promotion Foundation of Cyprus, under contract No. AEIFORIA/ASTI/0609(BE)/12.

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