D13:
MODIS Climatology MAPS

The Moderate-resolution Imaging Spectro-radiometer (MODIS) provides the best long-term aerosol properties from space so far. Data from the two MODIS instruments aboard the TERRA and AQUA satellites are acquired during daytime with overpasses at 10:30 am and 1:30 pm (Local Solar Time) respectively. The retrieving process of MODIS AOT over land and ocean is only performed during daytime and for cloud-free and dark pixels. Hence the AOT retrievals are restricted to the situations over moderately bright surfaces where the measured reflectance at 2.13 μm falls between 0.15 and 0.25.

The MODIS instruments aboard Terra and Aqua satellites both measure spectral radiance in 36 channels (412–14200 nm), in resolutions between 250 m and 1 km. 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 2030 km long. Aerosol products are reported at 10 km resolution. Details of file specification of MODIS L2 aerosol products can be found at the website http://modis-atmos.gsfc.nasa.gov.

In the framework of the WP3, the Level 2, 10x10km, MOD04 aerosol product (Terra satellite, Collection 051) was retrieved for the period 2001-2011 from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS). The AOD fields were extracted from the 'Optical_Depth_Land_And_Ocean' parameter which provides the AOD at 550nm derived via the dark-target algorithms and with best quality data (Remer et al. 2005). According to Remer et al. (2009), the AOD fields for this product have been respectively validated to within the error bounds of (0.04+0.05*AOD) and ±(0.05+0.15*AOD) at 550nm. It should be pointed out though that although the initial work plan presented in WP3, the use of parameters related to aerosol size (i.e. Angstrom Exponent) was foreseen, no such climatology was included in the analysis since according to recent findings the Angstrom Exponent does not exhibit significant correlation with ground truth and thus, should not be used for any geophysical application (data usage disclaimer[1]).

Based on the above AOD 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 AOD measurements ranged approximately from 1000 to 2300 (which amount to 25%-57% time coverage) as shown in Figure 1. 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.

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1 Disclaimer for Dark Target Aerosol Products Collection 5, ftp://ladsweb.nascom.nasa.gov/allData/5/MOD04_L2/README , last accessed Mar 15, 2013

The maps for each month are presented in Figure 2. It is observed that 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 encountered. In Figure 3, the respective monthly average values for the four urban sites Nicosia, Larnaca, Limassol, and Paphos (marked respectively as NI, LI, LA and PA on the maps) and the background site of Ag. Marina, (marked as AGM) are given. In general, the background site is characterised by much lower aerosol loads throughout the year (ranging from 0.1 to 0.28) whereas the load for the urban sites is significant higher. Limassol (the port of the island) 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 and Paphos relatively lower ones. The two distinct maxima associated with dust transport phenomena are observed for 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 AOD levels for Nicosia are higher (~0.45) compared to the other two urban sites (~0.35 for Larnaca and Limassol).

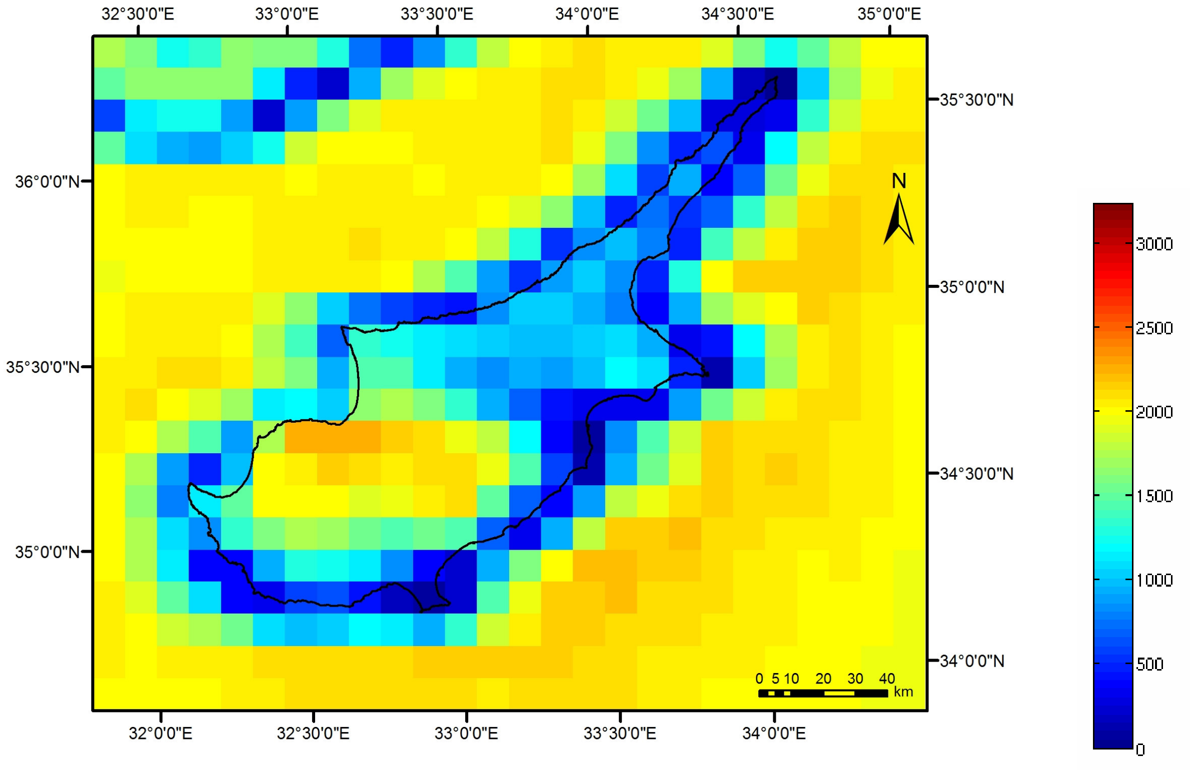
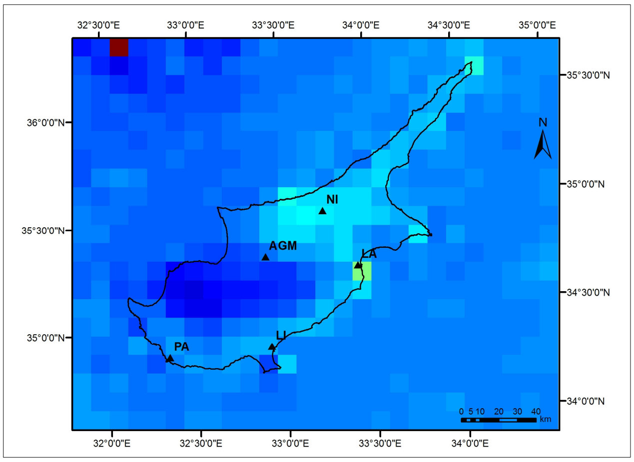


Figure 1: Map depicting the number of valid TERRA observations for the period under consideration.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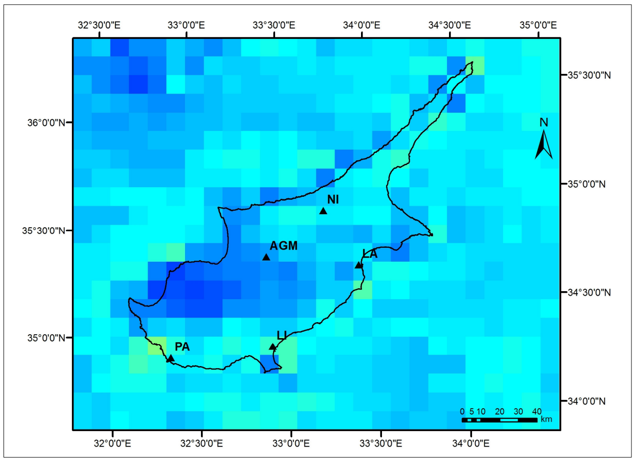
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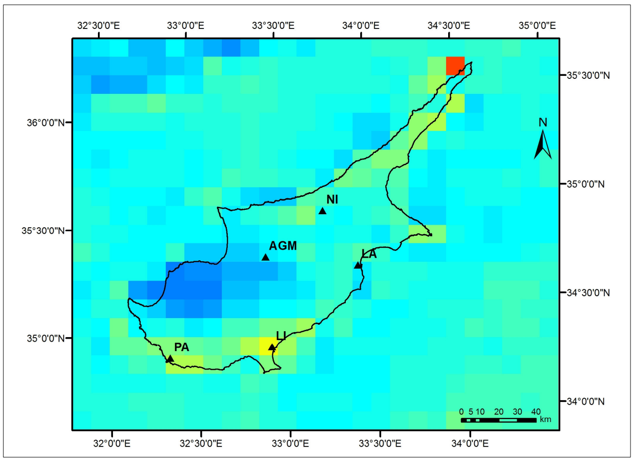
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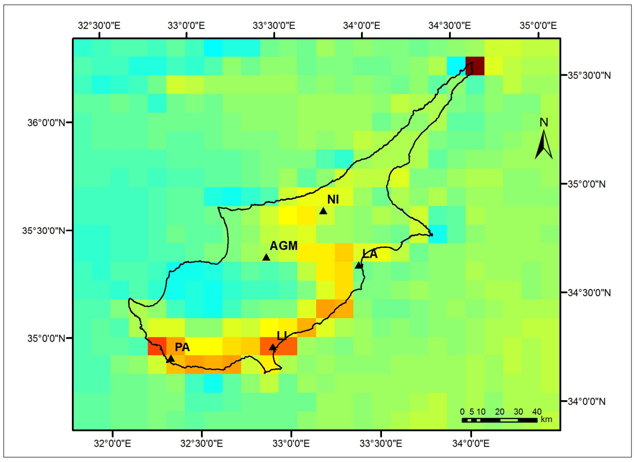
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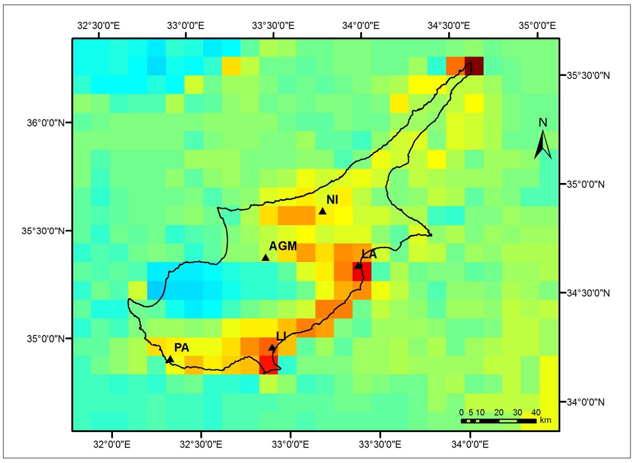
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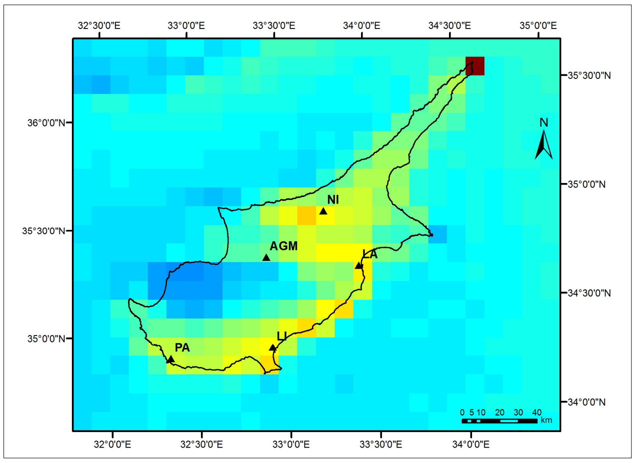
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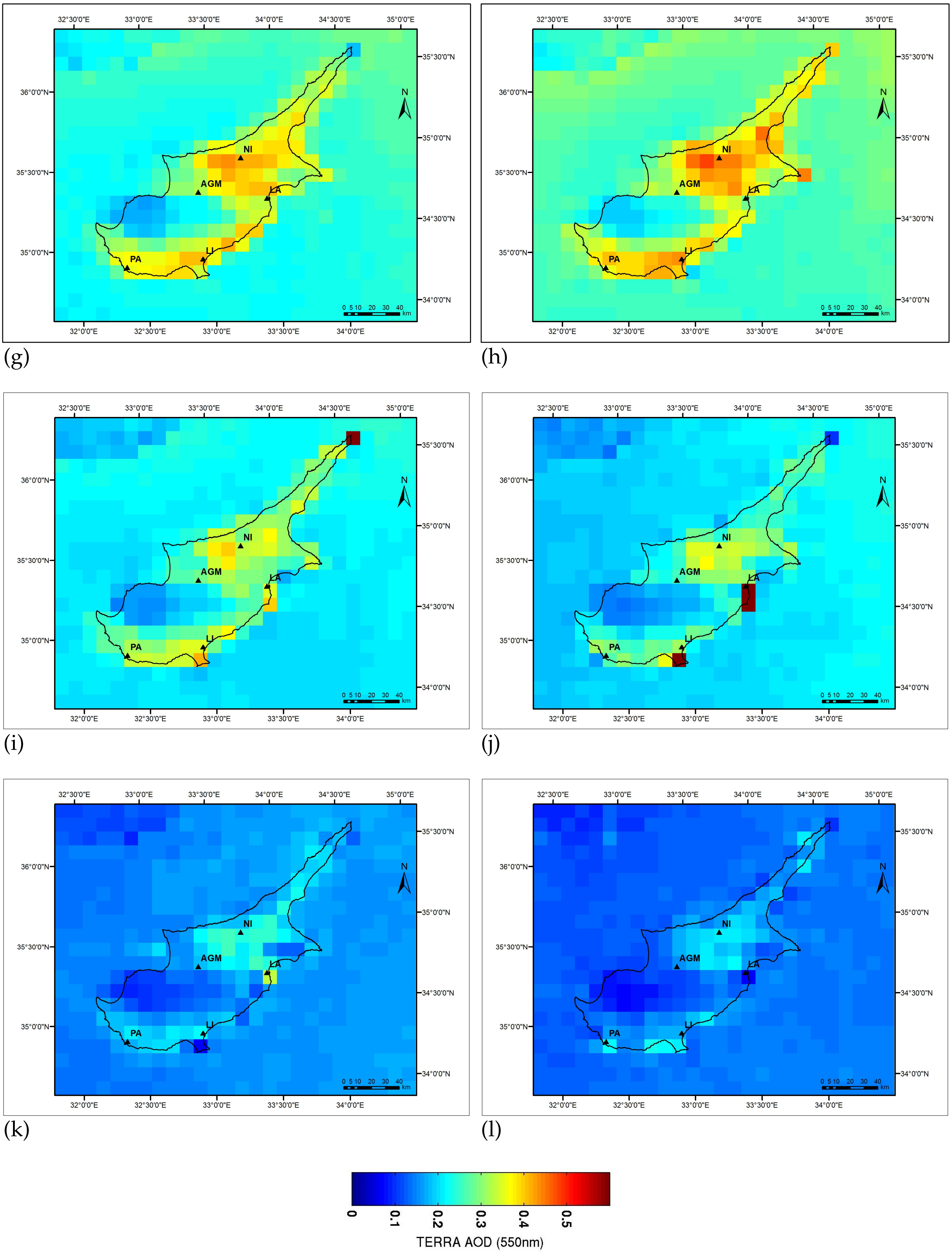

Figure 2: Mean monthly climatology maps for the area of Cyprus derived from TERRA AOT (550 nm) for the period 2001-2011. Nicosia, Larnaca, Limassol, and Paphos (marked respectively as NI, LI, LA and PA on the maps)

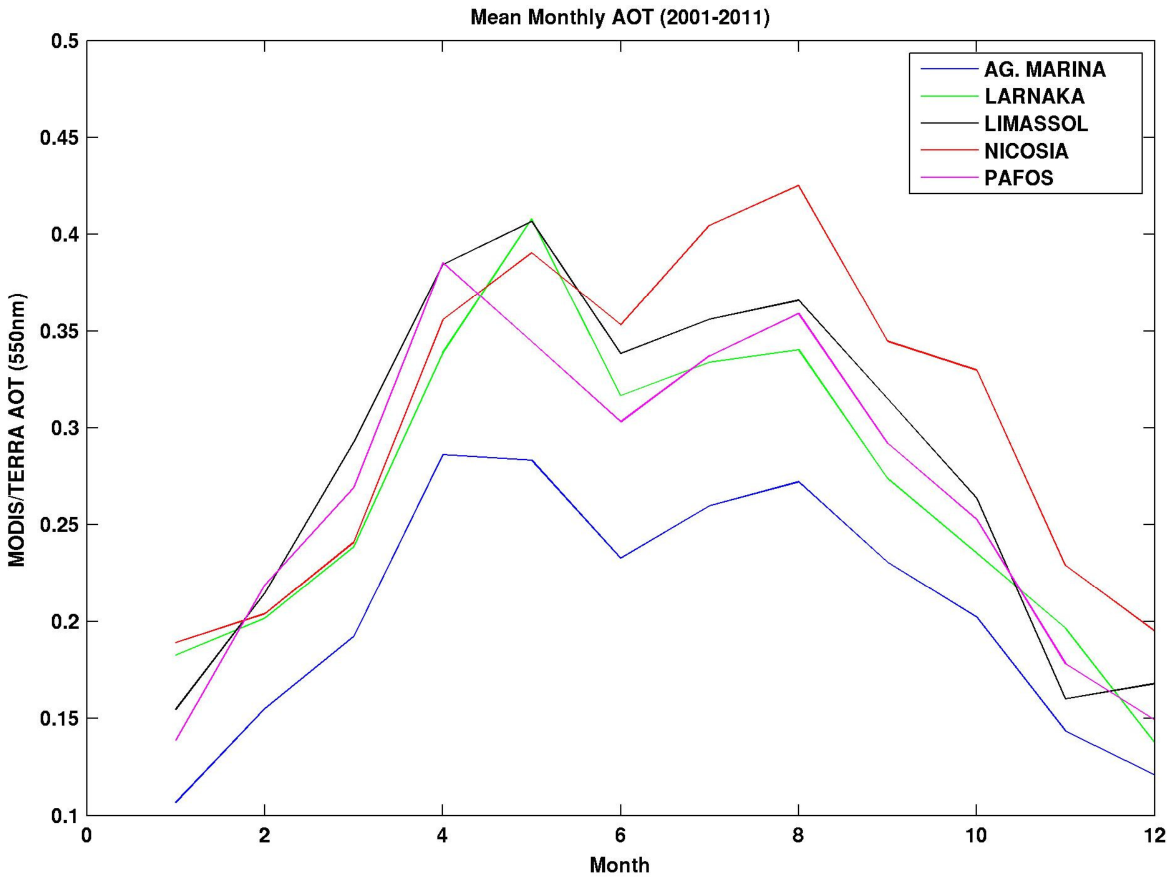

Figure 3: Monthly TERRA AOT averages for the sites of Nicosia, Limassol, Larnaca and Paphos for the period 2001-2011.

REFERENCES

Remer, Tanre, Kaufman, Levy, & Mattoo, 2006: Algorithm for Remote Sensing of Tropospheric Aerosol from MODIS for Collection 005 Products: 04_L2, ATML2, 08_D3, 08_E3, 08_M3

Remer, Tanre, Kaufman, Levy, & Mattoo, 2009: Algorithm for Remote Sensing of Tropospheric Aerosol from MODIS for Collection 005: Revision 2 Products: 04_L2, ATML2, 08_D3, 08_E3, 08_M3

D14:
Methodology for PM retrievals over Cyprus from statistical models using MODIS AOT, Lidar data and RH measurements.

Introduction

Limassol is an Eastern Mediterranean seaside city located in Southern coast of Cyprus. Under favourable meteorological conditions (sea breeze and calms) and due to the trans-boundary pollution (forest/biomass burning fires, dust from Saharan region, etc.), the concentration of air pollutants may exceed the air quality standards of the European Union and the World Health Organization (WHO). Thus, the satellite remote sensing is certainly a valuable tool for assessing and mapping air pollution due to their major benefit of providing complete and synoptic views of large areas due to the good temporal resolution of various satellite sensors. AOD is considered as the main parameter that is used to assess air pollution. MODIS on board the Earth Observing System (EOS) Terra and Aqua satellites is a sensor with the ability to measure the total solar radiance scattered by the atmosphere as well as the sunlight reflected by the Earth's surface and attenuated by atmospheric transmission.

The C005 Level 2 MODIS aerosol products concerning Limassol, Cyprus (34. 67oN, 33.04oE) have been used in our study (see D13). Validation of satellite aerosol retrieval is commonly performed by means of direct comparison with a reference AOD retrieved by AERONET Sun photometers. In this study, the quality assurance of the MODIS optical parameters was established from a ground based continuously operating scientific instrument. Under the aegis of the CUT, the ground based Remote Sensing Station is operating continuously to monitor atmospheric pollution levels over the city of Limassol in Cyprus. This station is equipped with a CIMEL sunphotometer (fully operating since April 2010), which is part of the global network AERONET (hhtp://aeronet.gsfc.nasa.gov). The availability of AERONET Level 1.5 AOD data in the years 2010 and 2012 is about 650 days of observations for each year, with the exclusion of one season due to the calibration of the instrument. The AERONET data are available between morning and afternoon observations. The mean daily Level 1.5 AOD values obtained from the CIMEL used in this study. For the validation approach, we considered all pixels from satellite data within 25km from the Sun photometer location.

The correlation coefficient between the CIMEL (500nm) and MODIS AOD (550nm) data over the city of Limassol is presented in Figure 1, which demonstrates a sufficiently good agreement between the values obtained by two instruments. The MODIS data on board in Aqua satellite shows a better agreement than Terra data for the 2 years period.

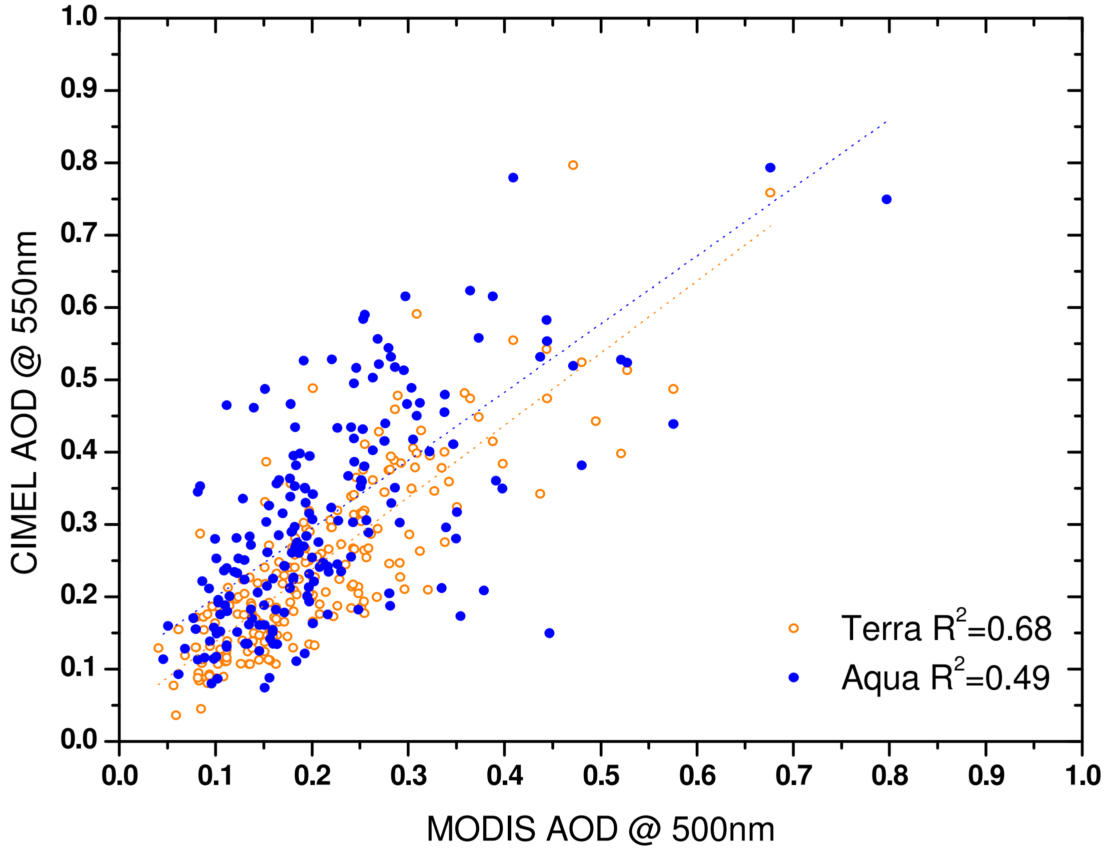

Figure 1: Correlation coefficient between AOD values obtained by MODIS (550 nm) and CIMEL (500 nm).

In Figure 2 we present the temporal variability of AOD at UV, Vis and IR as well as the Ångström exponent at 380/500nm over Limassol, retrieved from AERONET data. The seasonal variability of the aerosol optical properties is strongly related to the seasonal characteristics of aerosol production and transportation processes, over specific regions. As can be seen from Figure 2, the AOD reach maximum values during spring (0.30 at 500nm) and summer (0.5 at 500nm), and more specifically during the months June and July. Lower AOD values appeared during winter months mostly because of the aerosol washout by rain, but also due to the absence of Saharan dust transport events, forest fires or polluted air mass transportation coming from anthropogenic sources from Asian Continent.

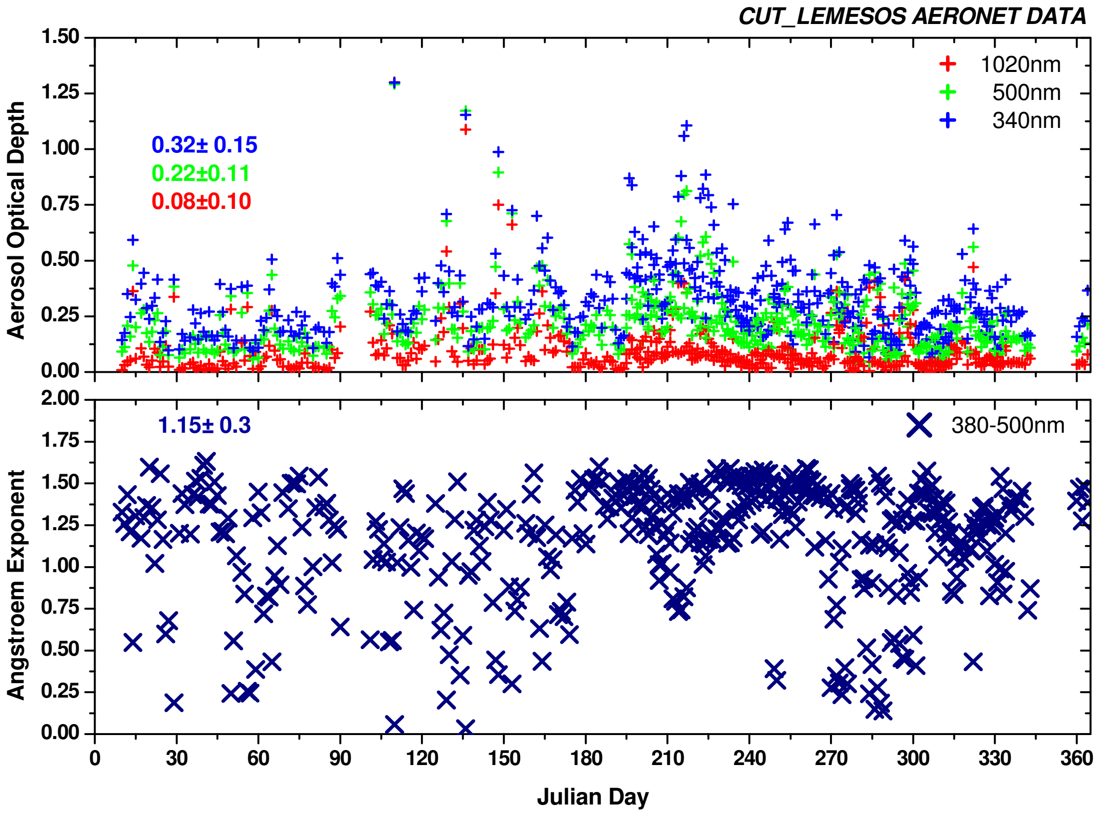

Figure 2: Temporal variability of AOD at 30, 500 and 1020nm and Ångström exponent at 380/500nm, as retrieved by CIMEL data.

The strong variability of the AOD over Limassol is also demonstrated by the aerosol integrated mass concentration variability from MODIS data (not shown here). In addition, the Ångström exponent which had a mean value of 1.15, varied from 0.2 up to 1.7. This large variability is directly related to the aerosol size (big up to small particles), during the studied period. Low values of Ångström exponent (accompanied with high AOD value) is linked with coarse particles suspended in the atmosphere, usually dust particles from Saharan desert. On the other hand, the high Ångström values are linked with fine particles, mainly of anthropogenic origin. The higher AOD values measured during spring and summer months are due to Saharan dust events over the greater Mediterranean region; very high AOD values measured in some specific days of extreme dust events could then affect the mean AOD monthly value, as well (Papayannis et al., 2005). At this point we would like to comment on the great importance of the geolocation of Cyprus, which is on the crossroad of three continents, thus it is affected from air masses coming from Europe, Asia, as well as from dust particles coming from Saharan region.

Statistical Model

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

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

$$Ln(PM_{10}) = \beta 0 + \beta 1\ (logAOT)+\beta 2(logAE)\ +\beta 3(WVdep)+\ \beta 4\ ln(T)+\ \beta 5\ ln(RH)\ +\ \beta 6\ ln(WS)\ +\ \beta 7(Wd)+\ \beta 8(P)+\ +\ \beta 9(PBL)$$

Where βi are the regression coefficients, AOT is the Aerosol Optical Thickness, AE is the Angstroem Exponent, WV is the Water Vapour, T is the surface temperature, WS is the wind speed, Wd the wind direction, , P is the pressure at surface level and PBL is the Planetary boundary layer height.

The available data set in AIRSPACE project are given in Table 2 :

Table 1: AIRSPACE dataset used for the statistical model

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)

Based on the proposed methodology, the performance of the multi-regression model was examined by introducing one predictor (Xi) at α 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

For 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.

The results of the above sensitivity analysis are presented below. In Figure 3 the correlation coefficient between the predicted and measured PM_{10} is presented for 8 different models. It was observed that the maximum performance of the model is reached by using the following predictors (in strength order), having a correlation coefficient of the order of CC=0.85

Table 2: Best correlation coefficients and regression coefficients derived

	CC= 0.853 *βi*	CC=0.850 *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

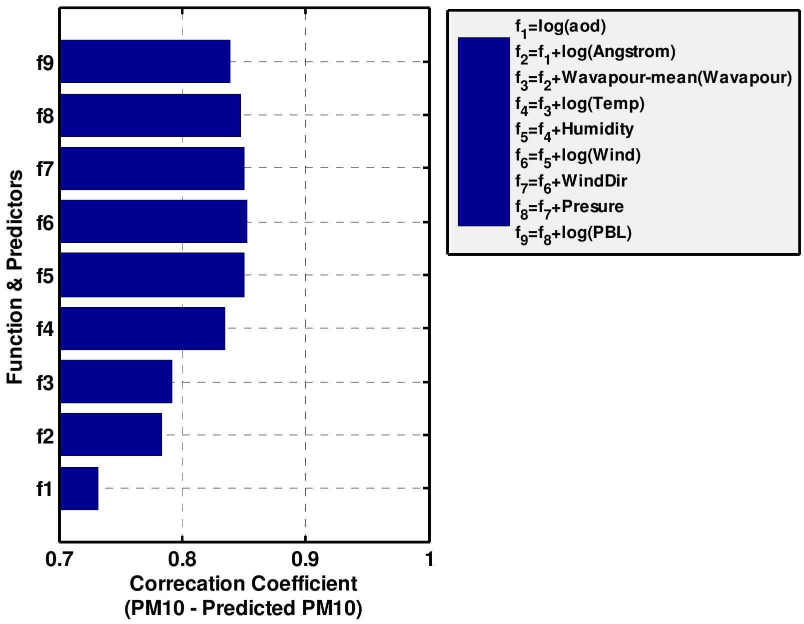

Figure 3: Correlation coefficient between the predicted and measured PM10 is presented for 8 different models.

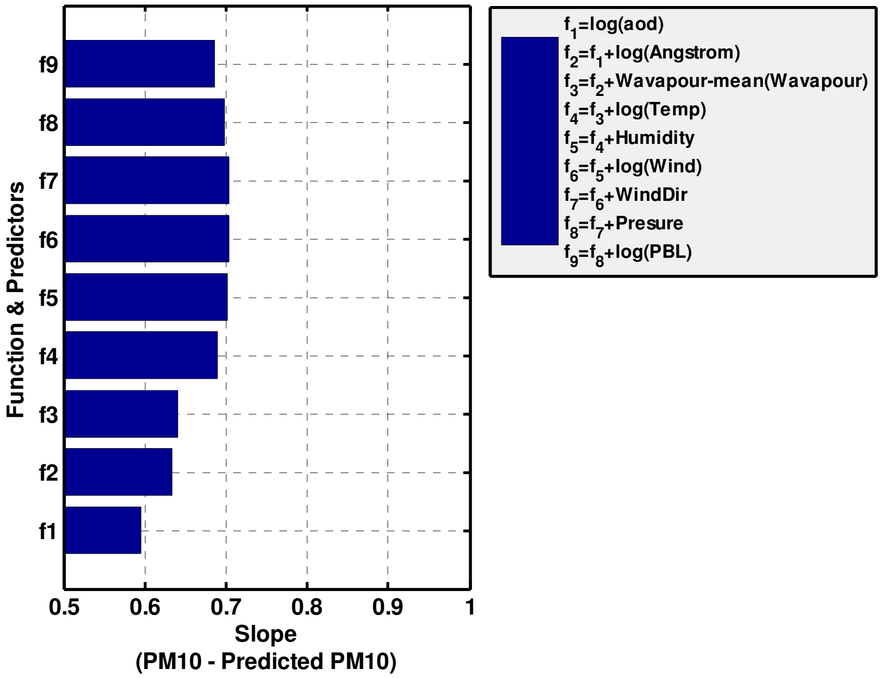

Figure 4: Slope of linear fit between the measured PM_{10} and predicted with 8 different models.

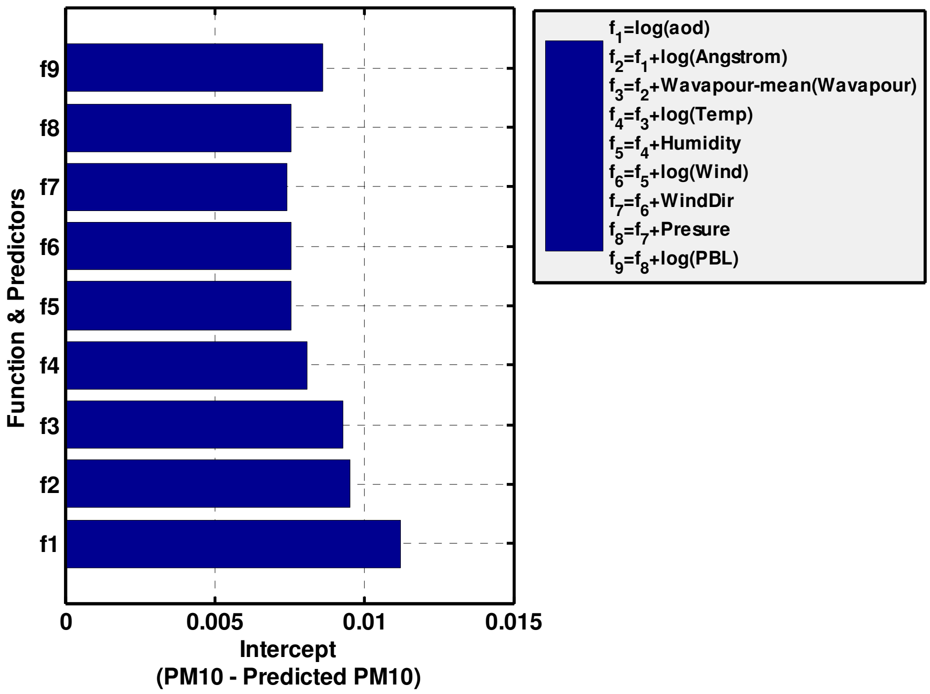

Figure 5: Intercept of linear fit between the measured PM_{10} and predicted with 8 different models.

The results of the above sensitivity analysis indicate the maximum performance of the model of the order of CC=0.85 for the following formula 2:

$$Ln(PM_{10}) =-4.11+0.952(logAOT)+0.299(logAE)-0.393(WVdep)+0.643ln(T)+0.008RH-0.096ln(WS)$$

Finally, using formula 2 as the best model and the coefficients derived and shown in Table 2, the correlation between the models prediction and the measured PM_{10} concentrations are given in Figure 6. The respectively differences between the measured and the predicted value of the PM concentration is given in Figure 7 . The points in the residual plot in Figure 7 are randomly dispersed around the horizontal axis, thus, a linear regression model is appropriate for our statistical model.

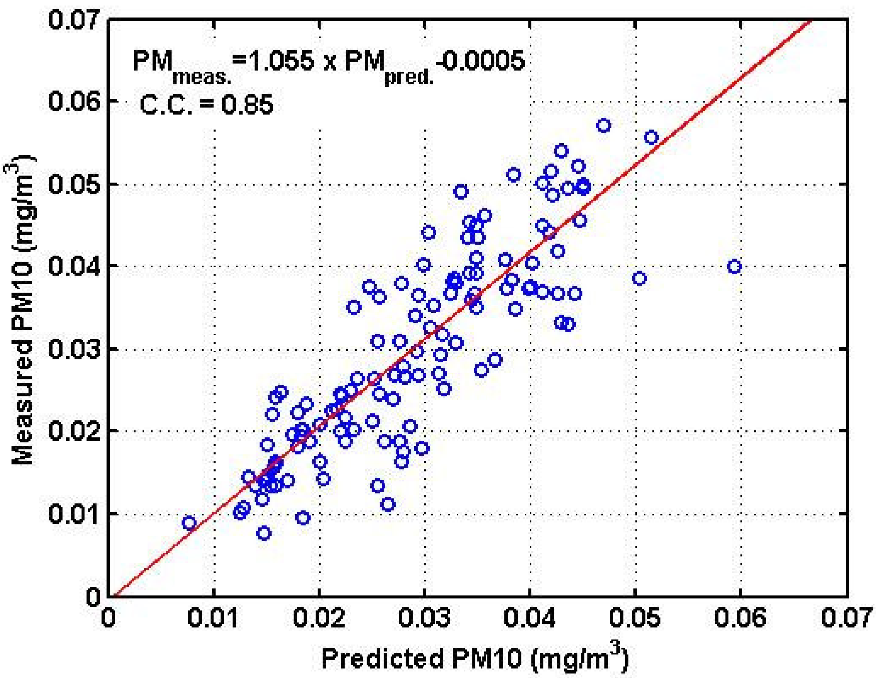

Figure 6: Comparison between predicted and measured PM_{10} by TSI DUST Track at Limassol (Red line : linear fit)

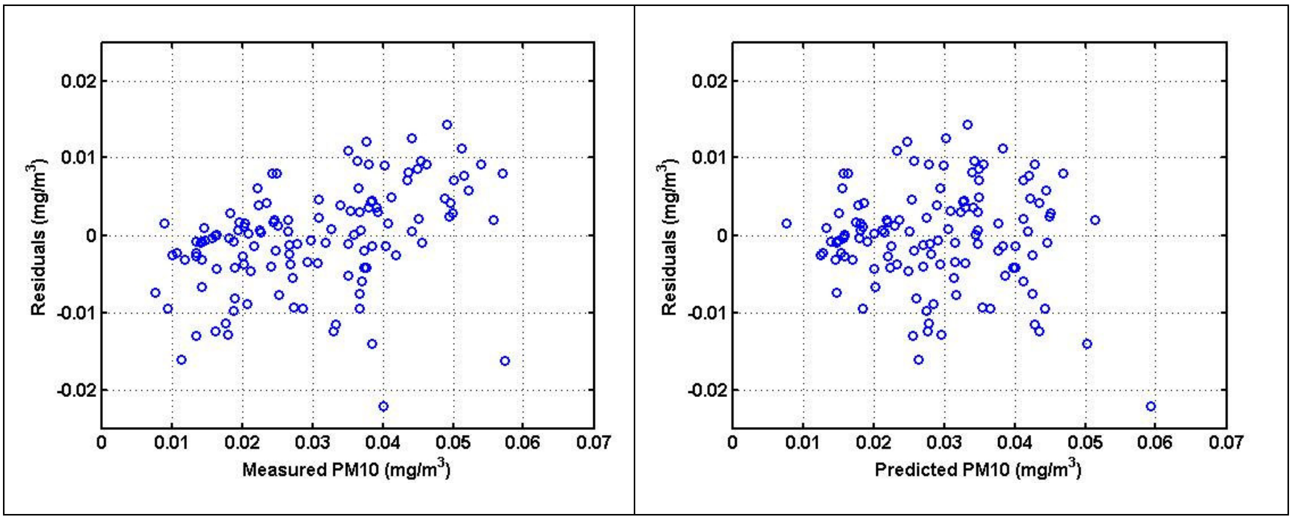

Figure 7: Differences between the measured and the predicted value of the PM concentration (Residual plots)

In order to verify the water vapor data derived from the CIMEL instrument and used in this study, we have compared them with the Total Column ECWMF water vapor product.

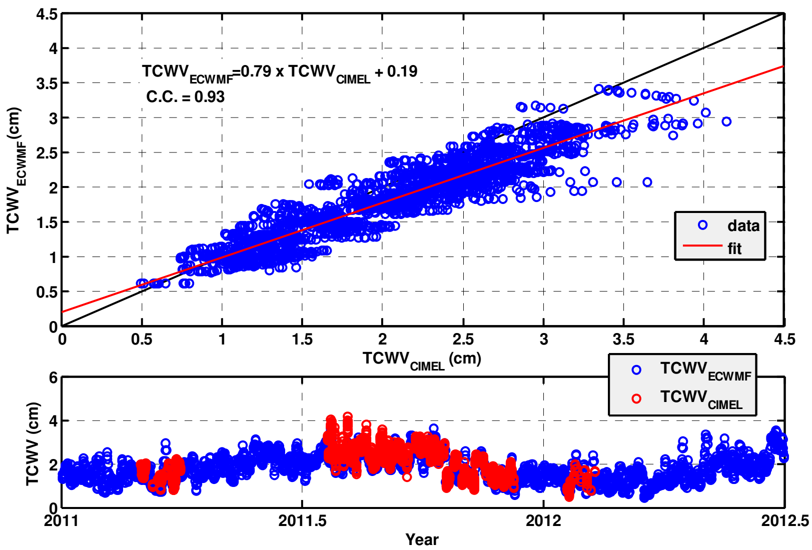

Figure 8: Comparison of ECWMF and CIMEL total column of water vapour (TCWV) (upper panel). Time series for the examined period of both TCWV datasets (lower pannel).

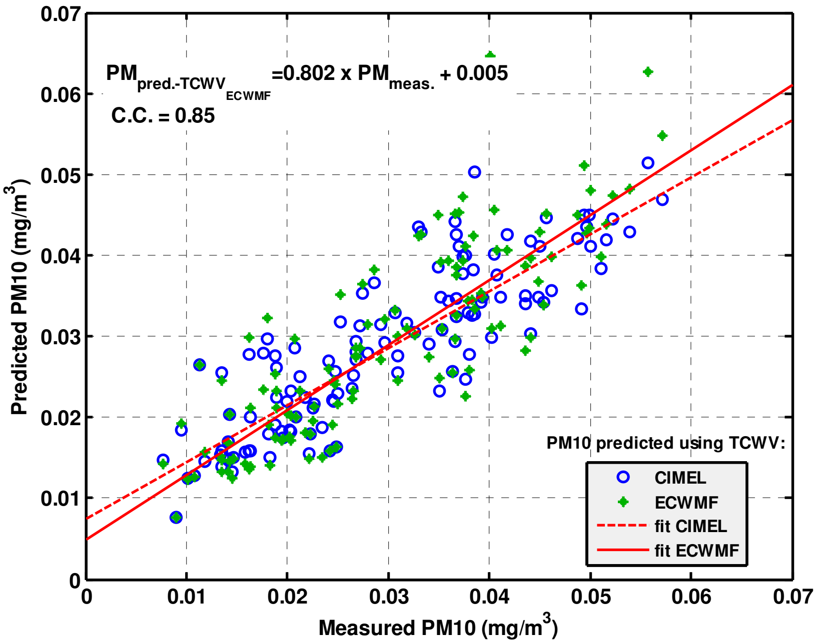

Figure 9: Comparison between predicted and measured PM_{10} at Limassol (period Mar 2011 – Feb 2012). Blue symbols (o) and red dashed line refer to the comparison for PM_{10} predicted using CIMEL – TCWV while the green symbols (*) and solid line refer to the comparison for PM10 predicted using the ECWMF – TCWV.

Comparison of MODIS-MAPSS and CIMEL data

MODIS aerosol optical depth at 550nm, Ångström exponent (AE) where downloaded from the MAPSS/MODIS web site. The MAPSS data are constructed by the MODIS team as the most representative for ground based CIMEL and MODIS AOD comparisons. The comparison between MODIS and CIMEL at CUT-TEPAK data is presented in the following graphs.

The comparison shows that MODIS overestimates the AOT at 550nm and is unable to follow the day-to-day variability of Angstrom exponent as given by the CIMEL sun-photometer.

- Using MODIS AOT as input to the MLR model would lead to deviations of the order of 20%
- The Ångström exponent cannot be used
- Should try the comparison with different MODIS dataset

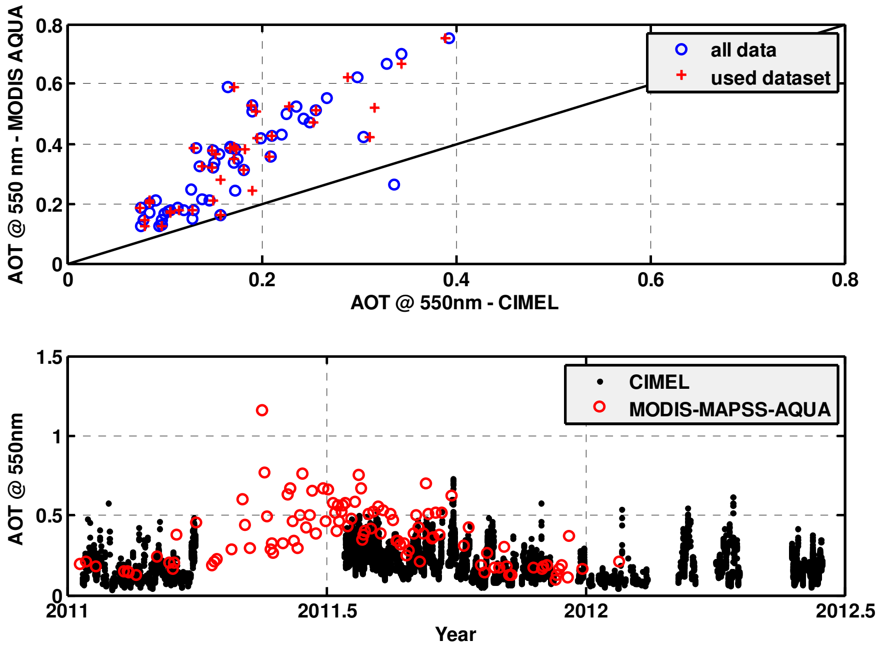

Figure 10: Comparison of aerosol optical depth at 550 nm between CIMEL (AOT500nm, Ångström Exponent 440-675nm) and MODIS – AQUA (MAPSS 051) (upper panel). Time series of AOT for the two instruments (lower panel).

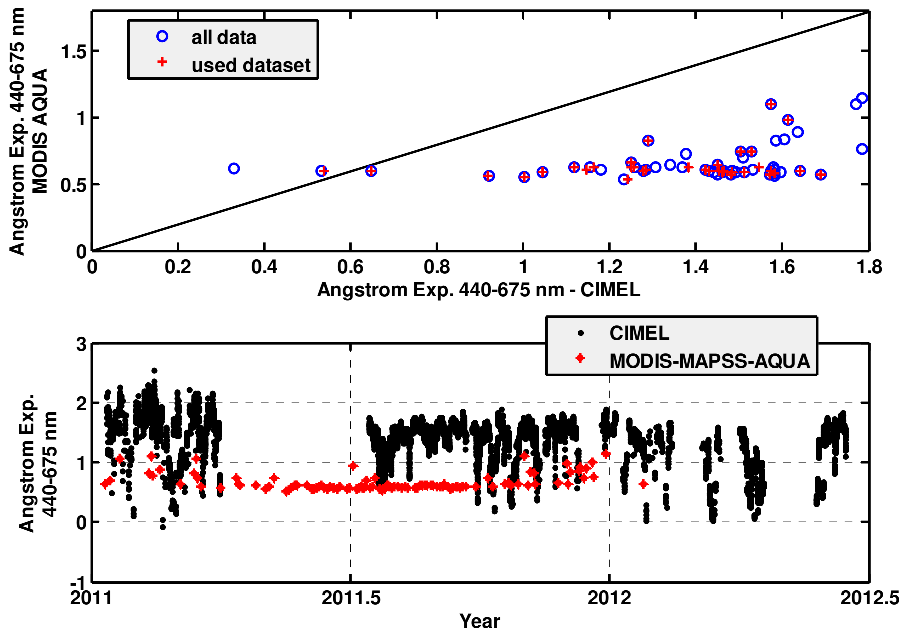

Figure 11: Comparison of aerosol Angstrom exponent 440-675 nm between CIMEL and MODIS – AQUA (MAPSS 051) (upper panel). Time series of AOT for the two instruments (lower panel).

Ground Based Measurements in other test cases

The measurements of aerosol optical parameters, total column water vapour (Microtops) and PM_{10} (TSI) at two different sites (Larnaka and Lefkosia) were used for the validation of the MLR model.

Meteorological data were obtained from the closest available weather station (LCLK-Larnaka, INCOSIA2-Lefkosia).

The TSI data were averaged in a time frame of 2h from AOT measurements. PM_{10} values that exceed the maximum of the PM_{10} training dataset were deleted.

In generally the result show satisfactory results taking into account that AOT measurements are not performed within the stabilized PM_{10} measurement time frame and the limited dataset for Larnaka.

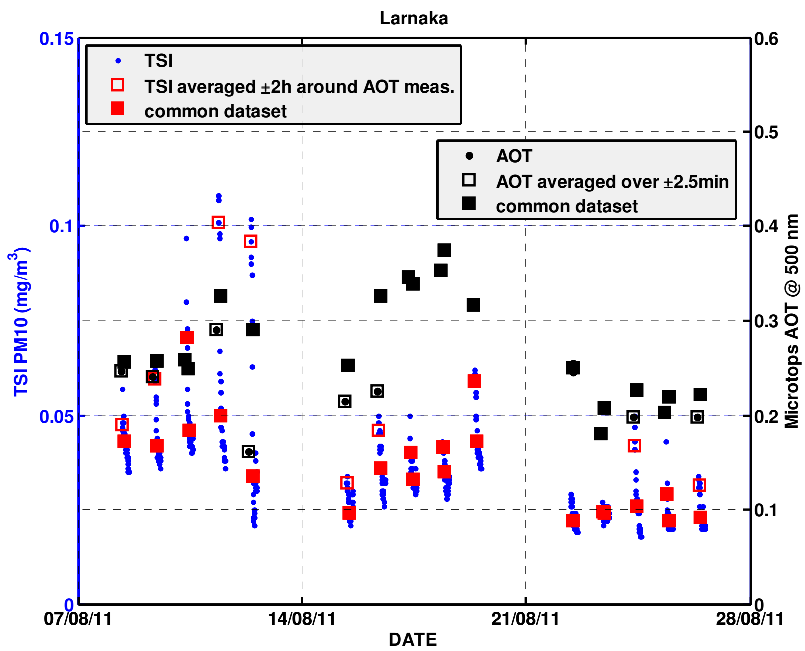

Figure 12: Time series of PM_{10} (TSI) (left axis) and aerosol optical depth (Microtops) (right axis) performed at Larnaka. With blue dots the available PM_{10} measurements are denoted while with red squares, the averaged PM_{10} data over the time window ±2h from the Microtops measurements. With black dots the available Microtops measurements are denoted while with black squares, the ±2min averaged values. Filled squares show the data used as input to the MLR model.

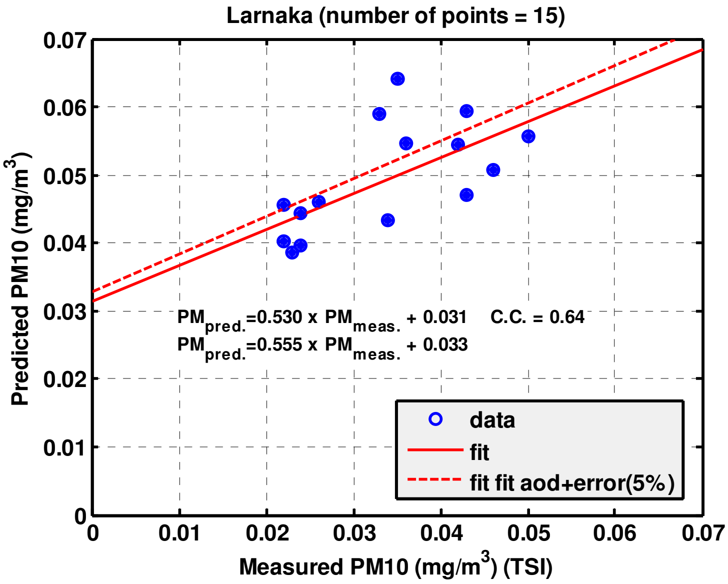

Figure 13: Comparison between predicted and measured PM_{10} at Larnaka. Blue circles and red solid line refer to the comparison for PM_{10} predicted using Microtops and LCLK_METAR. Assuming 5% underestimation error in measured aod at 500nm the slope and intercept of the comparison fit are also changed by ~5% (Dashed red line).

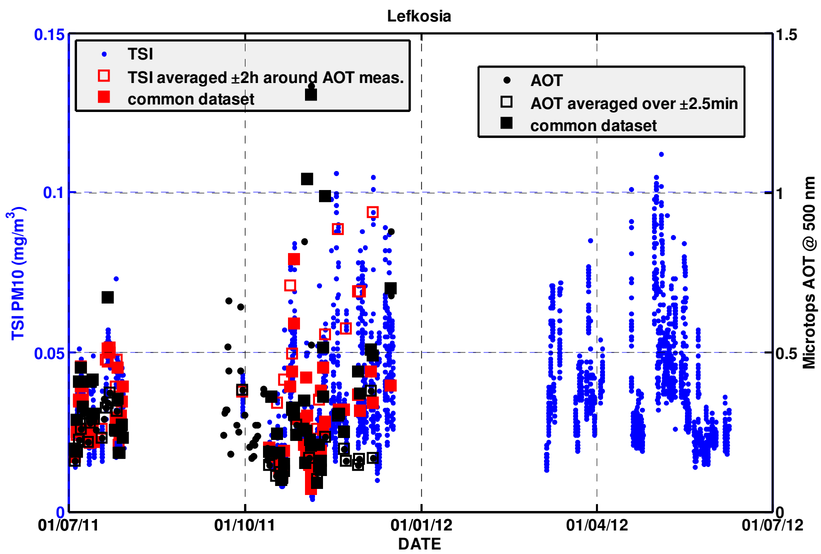

Figure 14: Time series of PM_{10} (TSI) (left axis) and aerosol optical depth (Microtops) (right axis) performed at Lefkosia. With blue dots the available PM_{10} measurements are denoted while with red squares, the averaged PM_{10} data over the time window ±2h from the Microtops measurements. With black dots the available Microtops measurements are denoted while with black squares, the ±2min averaged values. Filled squares show the data used as input to the MLR model.

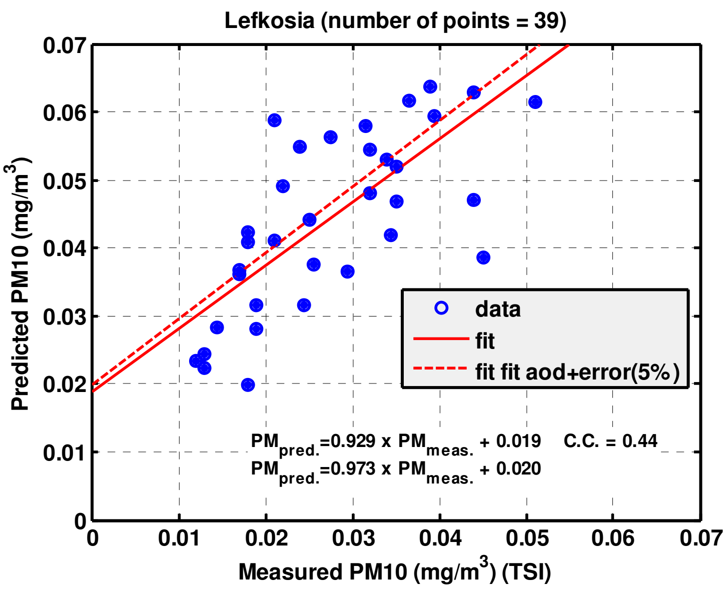

Figure 15: Comparison between predicted and measured PM_{10} at Lefkosia. Blue circles and red solid line refer to the comparison for PM_{10} predicted using Microtops and LCLK_METAR. Assuming 5% underestimation error in measured aod at 500nm the slope and intercept of the comparison fit are also changed by ~5% (Dashed red line).

REFERENCES

Liu, Y, Franklin, M, Kahn, R, & Koutrakis, P. Using aerosol optical thickness to predict ground-level PM2.5 concentrations in the St. Louis area: A comparison between MISR and MODIS. *Remote sensing of Environment*, 107(1), 33-44, (2007).

Papayannis A., Balis D., Amiridis V., Chourdakis G., Tsaknakis G., Zerefos C., A. Castanho D. A., Nickovic S., Kazadzis S., and Grabowski J., "Measurements of Saharan dust aerosols over the Eastern Mediterranean using elastic backscatter-Raman lidar, spectrophotometric and satellite observations in the frame of the EARLINET project", *Atmospheric Chemistry and Physics*, 5, 2065-2079, 2005.