# Particulate monitoring, modeling, and management: natural sources, long-range transport, and emission control options: a case study of Cyprus.

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## ABSTRACT

The LIFE+ Project PM$^3$: Particulate Monitoring, Modeling, Management is coordinated by the Department of Labour Inspection in Cyprus and funded in part by LIFE+ Environment Policy & Governance. The project aims at the analysis of dust emissions, transport, and control options for Cyprus, as well as at the identification of “natural” contributions (Directive 2008/50/EC). The ultimate objective is to provide inputs for the design of a dust management plan to improve compliance to EC Directives and minimise impacts to human health and environment.

This paper presents a short analysis of historical monitoring data and their patterns as well as a description of a dynamic dust entrainment model. The pyrogenic $PM_{10}$ emissions combined with the wind driven emissions, are subject to a two phase non-linear multi-criteria emission control optimization procedure. The resulting emission scenarios with an hourly resolution provide input to the Comprehensive Air quality Model with extensions (CAMx) 3D fate and transport model, implemented for the 4,800 km master domain and embedded subdomains (270 km around the island of Cyprus and embedded smaller city domains of up to 30 km down to street canyon modeling). The models test the feasibility of candidate emission control solutions over a range of weather conditions. Model generated patterns of local emissions and long-range transport are discussed compared with the monitoring data, remote sensing (MODIS derived AOT), and the chemical analysis of dust samples.

Keywords: Natural dust, emission modeling, wind erosion, Operational forecasts, Nested grid, Cascading models, Emission control optimization, LIFE+ PM3.

## 1.INTRODUCTION

Particulate Matter ($PM_{10}$) are tinny solid or liquid substances of less than ten micrometers in diameter existing in the atmosphere from natural (desert dust, sea-spray, volcanoes) or anthropogenic (combustion, traffic) sources. They can easily be inhaled by humans causing significant health effects. Such particles are suspected to be major contributors to respiratory diseases, such as asthma and chronic obstructive pulmonary disease, but also to cardio-vascular diseases in sensitive population groups. In addition, they have significant environmental impact on global warming and clouds’ formation, thus influencing the water cycle. Therefore, the interest on PM has widely increased the last years.

Therefore, the Department of Labour Inspection (DLI) has started in January 2011, the implementation of a three-year LIFE project funded by the EU, which aims to assess the $PM_{10}$ contribution between natural and anthropogenic sources regarding the Directive 2008/50/EC. For this purpose, thousand filter samples of $PM_{10}$ were collected from rural, urban and traffic areas all over Cyprus.

**Table 1:** Results of air quality measurements for the years 2008-2010 at DLI's monitoring stations and their comparison with the relevant limit values/target values.

| **Pollutant** | **Period** | **Limit values/ target values Concentration (μg/m$^3$)[i]** | **Allowed excee-dances per year** | **2008** | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Concentration (μg/m$^3$)[ii]** | | | | | | | | | **Exceedances[iii]** | | | | | | | | |
| | | | | **Ay. Mar** | **Nic Tra** | **Nic Res** | **Lim Tra** | **Lim Res** | **Lar Tra** | **Lar Res** | **Paf Tra** | **Zygi Ind** | **Ay. Mar** | **Nic Tra** | **Nic Res** | **Lim Tra** | **Lim Res** | **Lar Tra** | **Lar Res** | **Paf Tra** | **Zygi Ind** |
| Particulate Matter (PM$_{10}$)[iv] | 1 year | 40 | - | 32 | 51 | 53 | 51 | - | 56 | - | 43 | 48 | - | - | - | - | - | - | - | - | - |
| | 24 hours | 50 | 35 | 288 | 255 | 407 | 327 | - | 366 | - | 184 | 753 | 38 | 134 | 131[i] | 124 | - | 178 | - | 67 | 126 |

| **Pollutant** | **Period** | **Limit values/ target values Concentration (μg/m$^3$)[i]** | **Allowed excee-dances per year** | **2009** | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Concentration (μg/m$^3$)[ii]** | | | | | | | | | **Exceedances[iii]** | | | | | | | | |
| | | | | **Ay. Mar** | **Nic Tra** | **Nic Res** | **Lim Tra** | **Lim Res** | **Lar Tra** | **Lar Res** | **Paf Tra** | **Zygi Ind** | **Ay. Mar** | **Nic Tra** | **Nic Res** | **Lim Tra** | **Lim Res** | **Lar Tra** | **Lar Res** | **Paf Tra** | **Zygi Ind** |
| Particulate Matter (PM$_{10}$)[iv] | 1 year | 40 | - | 24 | 50 | 45 | 49 | 49 | 48 | - | 48 | 45 | - | - | - | - | - | - | - | - | - |
| | 24 hours | 50 | 35 | 363 | 435 | 440 | 482 | 458 | 465 | - | 1017 | 1385 | 18 | 112 | 69 | 87 | 62 | 95 | - | 89 | 90 |

| **Pollutant** | **Period** | **Limit values/ target values Concentration (μg/m$^3$)[i]** | **Allowed excee-dences per year** | **2010** | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Concentration (μg/m$^3$)[ii]** | | | | | | | | | **Exceedances[iii]** | | | | | | | | |
| | | | | **Ay. Mar** | **Nic Tra** | **Nic Res** | **Lim Tra** | **Lim Res** | **Lar Tra** | **Lar Res** | **Paf Tra** | **Zygi Ind** | **Ay. Mar** | **Nic Tra** | **Nic Res** | **Lim Tra** | **Lim Res** | **Lar Tra** | **Lar Res** | **Paf Tra** | **Zygi Ind** |
| Particulate Matter (PM$_{10}$)[iv] | 1 year | 40 | - | 30 | 58 | 53 | 51 | 48 | 55 | - | 41 | 45 | - | - | - | - | - | - | - | - | - |
| | 24 hours | 50 | 35 | 210 | 362 | 337 | 448 | 385 | 515 | - | 465 | 852 | 36 | 120[i] | 108 | 118 | 90 | 141 | - | 60 | 71 |

i. Limit value for the protection of human health referred in the Directive 2008/50/EC of the European Parliament and of the Council of the 21st of May 2008
ii. Regarding the hourly and daily values, the maximum value is used
iii. Resulting from the emissions from anthropogenic actions, natural sources and transboundary pollution
iv. Measurements using the gravimetric method

The LIFE+ project CY/000252 under Environment Policy and Governance 2009 PM3: Particulates Monitoring, Modelling, Management, has as one of its core objectives to support the design and implementation of effective and cost efficient approaches to air quality assessment and management, controlling pressures and minimizing impacts, population exposure and public health impacts together with effective public and stakeholder involvement.

## 2. AIR QUALITY MONITORING

The validated data were assessed in accordance to the limits foreseen in the EU Directives/Cypriot legislation.
The results for 2008 to 2010 are shown in **Table 1**. This Table demonstrates the air pollutants monitored and their measured concentrations regarding the DLI monitoring stations Ayia Marina (EMEP), Nicosia Traffic, Nicosia Residential, Limassol Residential, Larnaca Traffic, Larnaca Residential, Pafos Traffic, Zygi Industrial. The Table also contains the number of exceedances of the limit values i.e. the times that the measured concentrations exceeded the concentration limits set by the Directive 2008/50/EC.

### 2.1 Historical monitoring results

Considering the source analysis and the monitoring purposes, it has been decided that a set of sampling units will need to be distributed over the whole island in order to cover the following area attributes:

1. Coastal areas suitable to assess incoming sea salt and other imported PM constituents. These are considered as rural background stations representative for the Cyprus' average altitude (EMEP Ayia Marina).
2. Inland stations in rural areas used as rural background elevations.
3. Inland stations targeting various local natural and anthropogenic sources (industrial, urban background and urban traffic).
4. Inland high elevation areas suitable to act as background stations.

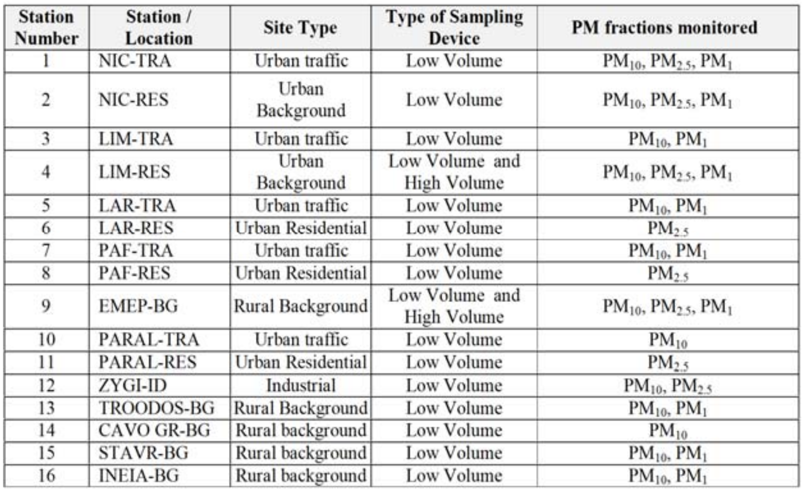
The monitoring plan was based on the existing monitoring activities of DLI. DLI implements a monitoring plan for several years and it was considered useful that a continuity to these results is maintained which will allow for the direct use of the existing historical data, greatly enhancing the monitoring activities of the project. The following plan was drafted:
Fifteen stations are initially selected representing various landuses as follows:

- Nine urban background/traffic stations in Nicosia (2), Paphos (2), Larnaca (2), Limassol (2) and Paralimni (1).
- Three inland background stations, one high elevation (Troodos) and two mid elevation (EMEP Ayia Marina and Stavrovouni).
- Two background stations in coastal areas (Inia, and Cavo Greco)
- One industrial Station located at Zygi

The sampling locations are shown in **Figure 1**. The filter material is quartz. Monitoring details at each station are provided in **Table 2**.

**Figure 1**: DLI's air quality monitoring stations

**Table 2: Monitoring Plan Summary**



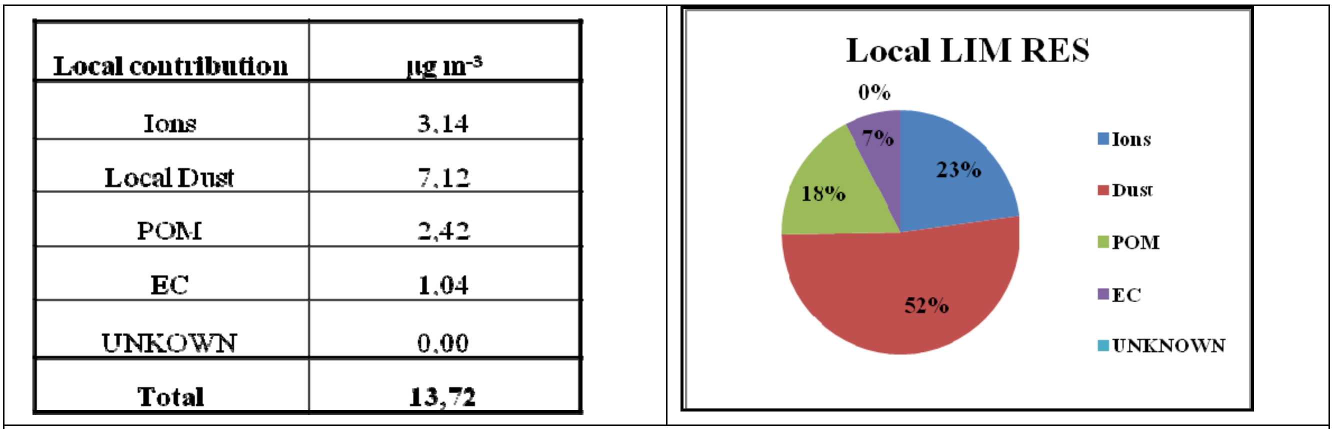
| Station Number | Station / Location | Site Type | Type of Sampling Device | PM fractions monitored |
|---|---|---|---|---|
| 1 | NIC-TRA | Urban traffic | Low Volume | $PM_{10}$, $PM_{2.5}$, $PM_1$ |
| 2 | NIC-RES | Urban Background | Low Volume | $PM_{10}$, $PM_{2.5}$, $PM_1$ |
| 3 | LIM-TRA | Urban traffic | Low Volume | $PM_{10}$, $PM_1$ |
| 4 | LIM-RES | Urban Background | Low Volume and High Volume | $PM_{10}$, $PM_{2.5}$, $PM_1$ |
| 5 | LAR-TRA | Urban traffic | Low Volume | $PM_{10}$, $PM_1$ |
| 6 | LAR-RES | Urban Residential | Low Volume | $PM_{2.5}$ |
| 7 | PAF-TRA | Urban traffic | Low Volume | $PM_{10}$, $PM_1$ |
| 8 | PAF-RES | Urban Residential | Low Volume | $PM_{2.5}$ |
| 9 | EMEP-BG | Rural Background | Low Volume and High Volume | $PM_{10}$, $PM_{2.5}$, $PM_1$ |
| 10 | PARAL-TRA | Urban traffic | Low Volume | $PM_{10}$ |
| 11 | PARAL-RES | Urban Residential | Low Volume | $PM_{2.5}$ |
| 12 | ZYGI-ID | Industrial | Low Volume | $PM_{10}$, $PM_{2.5}$ |
| 13 | TROODOS-BG | Rural Background | Low Volume | $PM_{10}$, $PM_1$ |
| 14 | CAVO GR-BG | Rural background | Low Volume | $PM_{10}$ |
| 15 | STAVR-BG | Rural background | Low Volume | $PM_{10}$, $PM_1$ |
| 16 | INEIA-BG | Rural background | Low Volume | $PM_{10}$, $PM_1$ |

### 2.2 Dust sampling analysis

For chemical composition measurements $PM_{10}$ samples were collected from three different sampling sites in Cyprus (**Figure 1**). One situated in the outskirts of Limassol (the second most important city of Cyprus) and considered as urban-background site (LIMRES), the second at Ayia Marina a natural background site considered as regional background site (EMEP site) and a third in Nicosia (NICTRA), the most important urban center of the island, in close vicinity to traffic emissions and considered as urban traffic site. The idea of the sampling is to follow the Lenschow approach(1). Based on this approach the $PM_{10}$ levels measured at each location is the result of the sum of PM emitted from regional and local sources. By using the Ayia Marina site as a regional site, the relative contribution of local and long-range transport sources can be assessed.

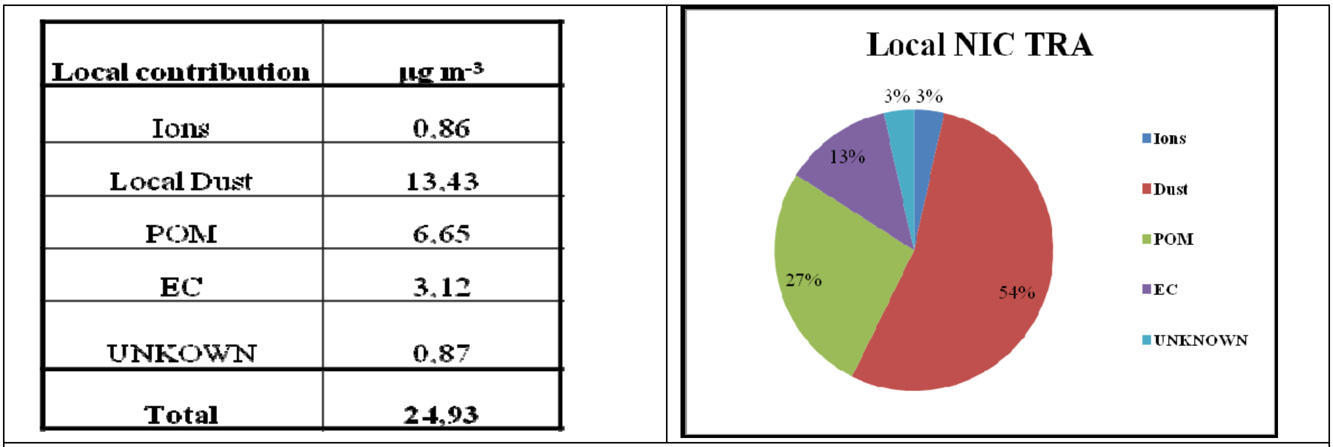
Daily $PM_{10}$ particles were collected from the Department of Labour Inspection on quartz fiber filter using a Seq 47/50 Leckel GmbH sampler. All filters were pre- and post-weighed using a 5-digit microbalance and analysed for main ions, organic (OC) and elemental carbon (EC) and trace metals following the procedure reported by Koulouri(2). As reported above, by using EMEP site as a reference site, the importance of local sources can be assessed for ions, carbonaceous aerosols and dust.

The following **Figures 2 and 3** illustrate the local contribution of ions, local dust, Particulate Organic Matter (POM) and Elemental Carbon (EC) regarding the stations Limassol Residential (LIM RES) and Nicosia Traffic (NIC TRA). The relative local contribution of the ionic mass, dust, POM and EC for NIC TRA and LIM RES varies from 3-23%, 52-54%, 18-27% and 7-13%, respectively. Thus, local dust is a major component of the total mass accounting almost 2/3 of the $PM_{10}$ mass. POM and EC together ascends up to 40% of the total $PM_{10}$ mass. Finally local ionic mass, accounts for a minor part of the $PM_{10}$ mass.



| Local contribution | μg m⁻³ |
|---|---|
| Ions | 3,14 |
| Local Dust | 7,12 |
| POM | 2,42 |
| EC | 1,04 |
| UNKOWN | 0,00 |
| Total | 13,72 |

**Figure 2:** Contribution of local sources to $PM_{10}$ levels in Limassol Residential Station (LIM RES).



| Local contribution | μg m⁻³ |
|---|---|
| Ions | 0,86 |
| Local Dust | 13,43 |
| POM | 6,65 |
| EC | 3,12 |
| UNKOWN | 0,87 |
| Total | 24,93 |

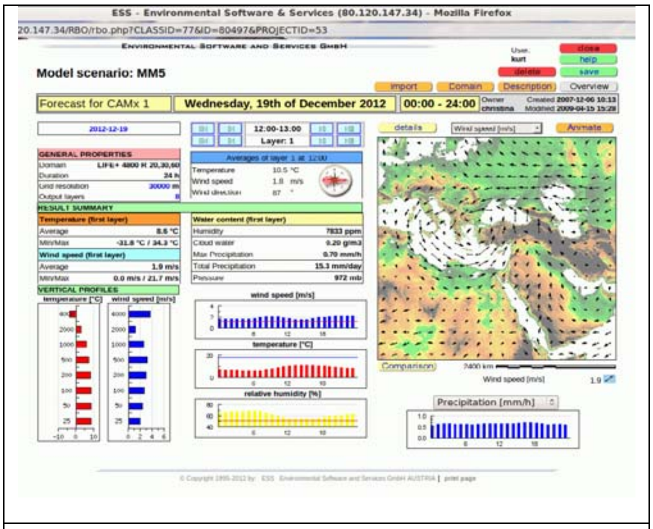
**Figure 3:** Contribution of local sources to $PM_{10}$ levels in Nicosia Traffic Station (NIC TRA).

## 3. MODELING OF DUST EMISSIONS AND DISPERSION

### 3.1 Modeling framework

The objective of the simulation modeling of dust emissions, including natural entrainment, and long-range transport is to determine the possible "natural" and external contribution of dust to the locally observed concentrations, and provide the basis for the development of efficient dust management through emission control. The resulting model framework has a similar structure as the Air Quality Monitoring System (AQMS)(3) in operational use by DLI.

The basic model framework for PM[3] was adapted on the basis of AirWare(4,5), developed mainly in the EUREKA WEBAIR project E!3266 (http://www.ess.co.at/WEBAIR, (6)), into which the DUST emission model was integrated to provide hourly particulate emission matrices as input to the CAMx fate and transport model implementation.


ESS - Environmental Software & Services (80.120.147.34) - Mozilla Firefox

20.147.34/RBO/rbo.php?CLASSID=77&ID=80497&PROJECTID=53

Model scenario: MM5

Forecast for CAMx 1 | Wednesday, 19th of December 2012 | 00:00 - 24:00

2012-12-19 | 12:00-13:00 | Layer: 1

| GENERAL PROPERTIES | |
|---|---|
| Domain | LIFE+ 4800 R 20,30,60 |
| Duration | 24 h |
| Grid resolution | 30000 m |
| Output layers | 8 |

| Averages of layer 1 at 12:00 | |
|---|---|
| Temperature | 10.5 °C |
| Wind speed | 1.8 m/s |
| Wind direction | 87 ° |

RESULT SUMMARY

| Temperature (first layer) | |
|---|---|
| Average | 8.6 °C |
| Min/Max | -31.8 °C / 34.3 °C |

| Wind speed (first layer) | |
|---|---|
| Average | 1.9 m/s |
| Min/Max | 0.0 m/s / 21.7 m/s |

| Water content (first layer) | |
|---|---|
| Humidity | 7833 ppm |
| Cloud water | 0.20 g/m3 |
| Max Precipitation | 0.70 mm/h |
| Total Precipitation | 15.3 mm/day |
| Pressure | 972 mb |

**Figure 4**: MM5 hourly model results for the 4,800 km domain, Southerly winds/cyclone over Cyprus
CAMx master domain (intermediate MM5 domain)

The cascading and nested grid model system combines the prognostic meteorological PSU/NCAR Mesoscale Model (MM5), the DUST entrainment model, emission inventory for pyrogenic emissions, and the 3D transport model CAMx together with a multi-criteria optimization component to design and evaluate emission control strategies.

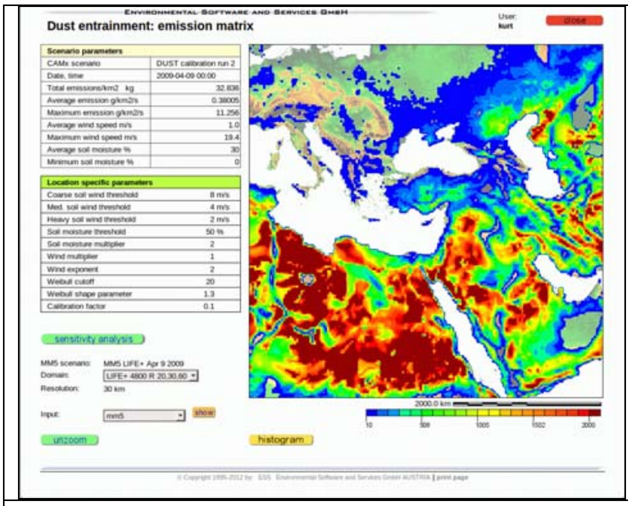
The dust entrainment model is a distributed, (arbitrary resolution) dynamic (hourly time step) model to predict the wind erosion and entrainment of particles from natural surfaces. It produces dynamic emission matrices that together with any anthropogenic emission data for point, line and area sources provide input to the respective transport, dispersion, and deposition model used. In addition to the threshold friction velocity approach(7) that uses geomorphology and soil properties, it also considers vegetation coverage and soil moisture as estimated by the MM5 (**Figure 4**) prognostic meteorological model used to forecast wind velocities, and a Weibull function to generate distributed wind speeds around the predicted hourly mean. The dust entrainment model estimates non-pyrogenic dust emission from natural surfaces as a function of primarily wind speed, land cover/vegetation, soil characteristics, and soil moisture,

The total Dust $PM_{10}$ emission [g/s/ha or km2] is calculated for each of three soil classes, and subject to a soil moisture constraint, as the product of

1. WindFactor, based on soil specific friction velocity thresholds;
2. ErosionFactor (erodibility)

The DUST model developed for $PM^3$ is quite complex, using highly non-linear constructs based on an exponential threshold function of wind speed (for three different soil fraction), erodibility defined by land use, land cover or a vegetation index (NDVI), and dynamic soil moisture. The DUST model generates an hourly emission matrix that provides input to the 3D nested grid transport model CAMx, where it can be simulated either as a conservative species, or part of the photochemical aerosol modelling. On-line manual pages for the DUST entrainment model can be found at http://80.120.147.34/MANUALS/AIRWARE/dustent.html The model and its operational implementation for regular (daily) forecasts with hourly resolution is described.

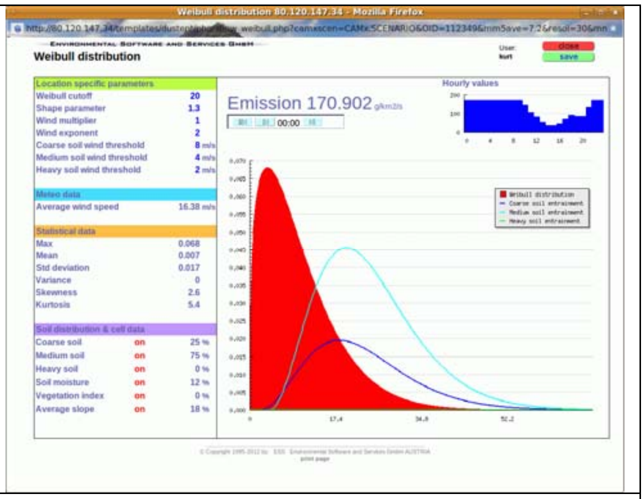
**Figures 5 and 6** show the emission estimates generated by the model for the overall domain (hourly total), as well as the Weibull function and related data for a $1km^2$ cell of the emission matrix.


Dust entrainment: emission matrix

| Scenario parameters | |
|---|---|
| CAMx scenario | DUST calibration run 2 |
| Date, time | 2009-04-09 00:00 |
| Total emissions/km2 kg | 32.636 |
| Average emission g/km2/s | 0.38005 |
| Maximum emission g/km2/s | 11.256 |
| Average wind speed m/s | 1.0 |
| Maximum wind speed m/s | 19.4 |
| Average soil moisture % | 30 |
| Minimum soil moisture % | 0 |

| Location specific parameters | |
|---|---|
| Coarse soil wind threshold | 8 m/s |
| Med. soil wind threshold | 4 m/s |
| Heavy soil wind threshold | 2 m/s |
| Soil moisture threshold | 50 % |
| Soil moisture multiplier | 2 |
| Wind multiplier | 1 |
| Wind exponent | 2 |
| Weibull cutoff | 20 |
| Weibull shape parameter | 1.3 |
| Calibration factor | 0.1 |

MM5 scenario: MM5 LIFE+ Apr 9 2009
Domain: LIFE+ 4800 R 20,30,60
Resolution: 30 km
Input: mm5


Weibull distribution

| Location specific parameters | | |
|---|---|---|
| Weibull cutoff | | 20 |
| Shape parameter | | 1.3 |
| Wind multiplier | | 1 |
| Wind exponent | | 2 |
| Coarse soil wind threshold | | 8 m/s |
| Medium soil wind threshold | | 4 m/s |
| Heavy soil wind threshold | | 2 m/s |
| **Meteo data** | | |
| Average wind speed | | 16.38 m/s |
| **Statistical data** | | |
| Max | | 0.068 |
| Mean | | 0.007 |
| Std deviation | | 0.017 |
| Variance | | 0 |
| Skewness | | 2.6 |
| Kurtosis | | 5.4 |
| **Soil distribution & cell data** | | |
| Coarse soil | on | 25 % |
| Medium soil | on | 75 % |
| Heavy soil | on | 0 % |
| Soil moisture | on | 12 % |
| Vegetation index | on | 0 % |
| Average slope | on | 18 % |

Emission 170.902 g/km2/s

**Figure 5**: Emission matrix for the 4,800 km CAMx master domain

**Figure 6**: Weibull function and source details for a 1 km emission grid cell

### 3.2 Meteorological drivers

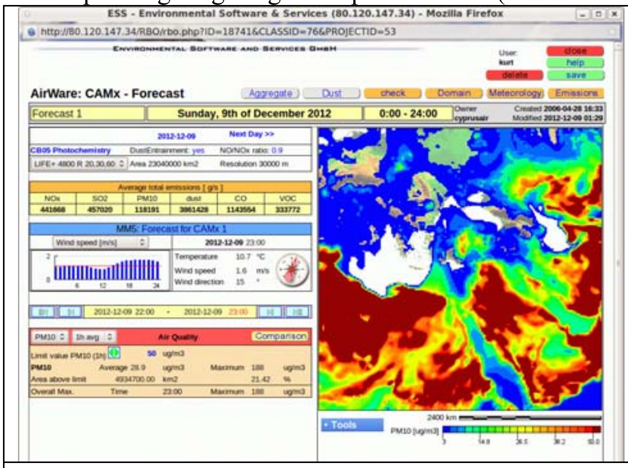
The starting level of the cascading model system is the prognostic meteorology. This is based on either daily forecast from the NOAA GFS servers (one degree and 6 hourly resolution) or NCEP re-analysis for historical data. The system uses either the

Weather Research and Forecasting (WRF) or the MM5 3D nested grid non-hydrostatic meteorological forecasting models in three levels of nesting for the dynamic downscaling of the GFS data to a 1 km hourly resolution (**Figure 4**). This is used to drive the DUST emission model and the 3D Eulerian model CAMx with 3D meteorological data fields.

MM5 is run in daily forecast mode, dynamic downscaling of NCEP-GFS global weather forecasts, or for historical episode using the NCEP-FLN re-analysis data as the dynamic forcings and boundary conditions. For the DUST entrainment model MM5 generates the wind field and soil moisture estimates.

### 3.3 Dispersion modeling: nested domains

The central model used for the simulation of local and long-range transport of particulates is CAMx (latest release R 5.40) which uses the CBM 05 chemistry mechanism. The model describes both conservative pollutants, particulates with diameter specific (PM 10/2.5) net settling velocity, and the contribution to photochemical processes and ozone formation. CAMx is used with the 3D dynamic inputs from the meteorological models, and is set up in a three level nesting with two-way coupling. Model domains cover 4,800 km, 270 km around the island of Cyprus, and several local domain of 30 km for the major cities (Nicosia, Larnaca, Limasssol, and Pafos) with their associated monitoring locations. CAMx uses 8 or more vertical layers, and the model resolution ranges from several km to a minimum of 500 meters. **Figures 7 and 8** illustrate the nested model domains and give examples of computed particulate concentrations for a predominantly Southerly wind over Cyprus and a corresponding long-range transport scenario (for the corresponding wind field see **Figure 4**).



AirWare: CAMx - Forecast

Forecast 1 | Sunday, 9th of December 2012 | 0:00 - 24:00

User: kurt

2012-12-09

CB05 Photochemistry DustEntrainment: yes NO/NOx ratio: 0.9

LIFE+ 4800 R 20,30,60 Area 23040000 km2 Resolution 30000 m

Average total emissions [ g/s ]

| NOx | SO2 | PM10 | dust | CO | VOC |
|---|---|---|---|---|---|
| 441668 | 457020 | 118191 | 3861428 | 1143554 | 333772 |

MM5: Forecast for CAMx 1

Wind speed [m/s] 2012-12-09 23:00

Temperature 10.7 °C

Wind speed 1.6 m/s

Wind direction 15 °

2012-12-09 22:00 - 2012-12-09 23:00

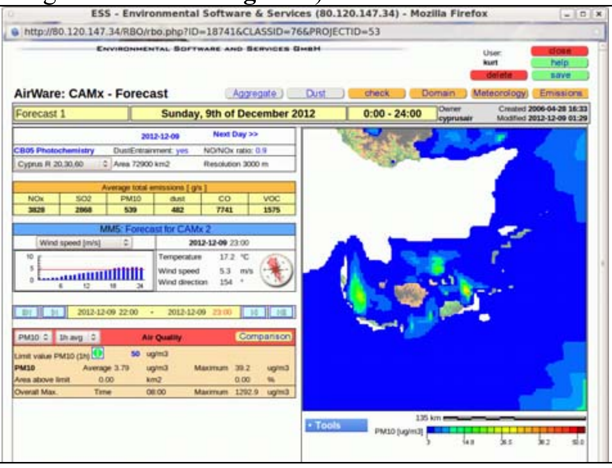
PM10 1h avg Air Quality Comparison

Limit value PM10 (1h) 50 ug/m3

PM10 Average 28.9 ug/m3 Maximum 188 ug/m3

Area above limit 4934700.00 km2 21.42 %

Overall Max. Time 23:00 Maximum 188 ug/m3



AirWare: CAMx - Forecast

Forecast 1 | Sunday, 9th of December 2012 | 0:00 - 24:00

User: kurt

2012-12-09

CB05 Photochemistry DustEntrainment: yes NO/NOx ratio: 0.9

Cyprus R 20,30,60 Area 72900 km2 Resolution 3000 m

Average total emissions [ g/s ]

| NOx | SO2 | PM10 | dust | CO | VOC |
|---|---|---|---|---|---|
| 3828 | 2868 | 539 | 482 | 7741 | 1575 |

MM5: Forecast for CAMx 2

Wind speed [m/s] 2012-12-09 23:00

Temperature 17.2 °C

Wind speed 5.3 m/s

Wind direction 154 °

2012-12-09 22:00 - 2012-12-09 23:00

PM10 1h avg Air Quality Comparison

Limit value PM10 (1h) 50 ug/m3

PM10 Average 3.79 ug/m3 Maximum 39.2 ug/m3

Area above limit 0.00 km2 0.00 %

Overall Max. Time 08:00 Maximum 1292.9 ug/m3

| **Figure 7**: dust from North Africa reaching Cyprus, 4,800 km domain in a cyclone with predominantly Southerly winds over Cyprus (see the wind field in Figure 1) | **Figure 8**: 270 km domain around Cyprus (center of map) Note the compass (Southerly local average) as compared to the master domain average, which is Northerly. |
|---|---|

## 4. STREET SCALE MODELLING

### 4.1. Modelling tool.

In the framework of PM$^3$, several pilot street scale applications were carried out. For this purpose, **O**perational **S**treet **P**ollution **M**odel$^{(8)}$ was utilized by performing a series of test runs, in order to describe the processes that govern the distribution of the pollutants inside a typical street canyon in Cyprus, as well as to assess the sensitivity of the input data.

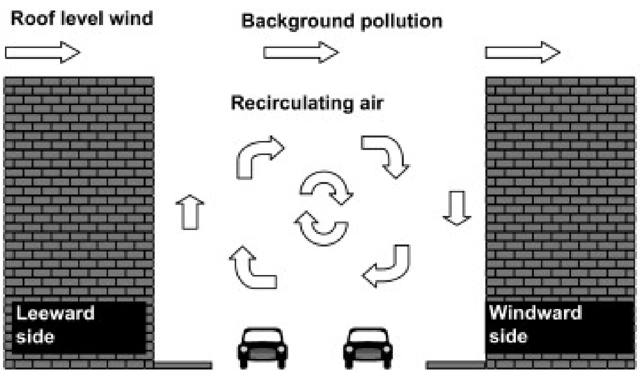


**Figure** ... urring
inside

For the direct contribution of vehicle emitted pollutants the model makes use of a plume model and an empirical algorithm based on a revised street canyon algorithm. The total concentration is made up of the direct and the resuspension contribution. The model accounts for resuspension in the street using a box model approach, in which the concentration in the recirculation zone is calculated assuming that the inflow rate of the pollutants into the zone is equal to the outflow rate and that the pollutants are well mixed inside the zone. The distribution pattern of concentrations along both sides of the canyon when an intersection is present is computed with the implementation of a simplified empirical formula. **Figure 9** presents the main air flow and pollutant dispersion characteristics occurring inside a street canyon which are simulated by OSPM.

### 4.2. Long term applications in Nicosia and Larnaca

In the frame of the street scale application, air quality calculations were performed for two typical hotspots of Cyprus, one in Nicosia and one in Larnaca. For this purpose, OSPM model was utilized for a full calendar year (2011).

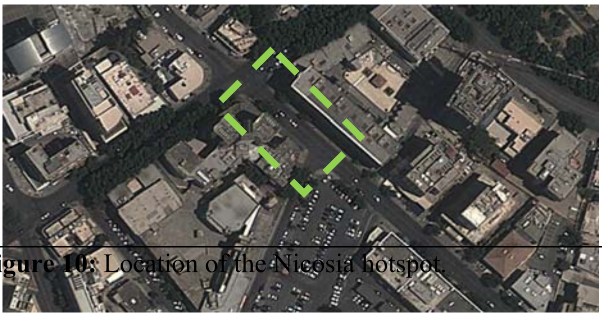


**Figure 10:** Location of the Nicosia hotspot.

Regarding the Nicosia case study, the area of the calculations is situated on Makariou Ave. The average height of the buildings along the street generally approaches 20 m, the width of the street is approximately 19 m, while the street length from the receptor point to the eastern and western intersection is 17 m and 14 m, respectively. **Figures 10 and 11** present the location and the geometric characteristics of the hot spot.

The street canyon, where the Larnaca case study was performed, is located at Grigoriou Afxediou St. close to the intersection of Vyronos street. The average height of the structures along the street approaches 20 m, the width of the street is about 16 m, while the street length from the receptor point to the eastern and western intersection is 40 m in both cases. **Figures 12 and 13** show the location and the geometric characteristics of this street canyon.

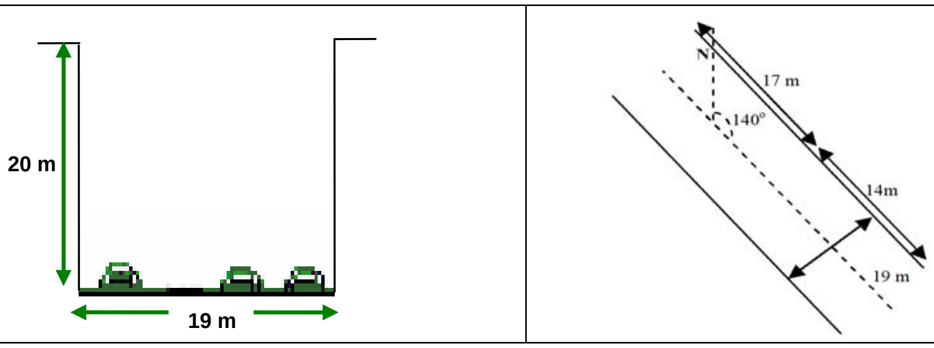


**Figure 11:** Street geometry of the Nicosia hotspot.

Regarding the input data which were used for the application of OSPM, the composition of the vehicle fleet in Cyprus came from the use of the relevant data base of the project FLEETS(9). In addition, the used emission factors for the final calculation of the emissions came from the last version of COPERT methodology(10). Besides, meteorological data originated from observed timeseries at the DLI's urban background measurement stations of Nicosia and Larnaca. This is also the case with respect to the urban background concentrations which were derived from measured concentrations of the species of interest at the same stations.

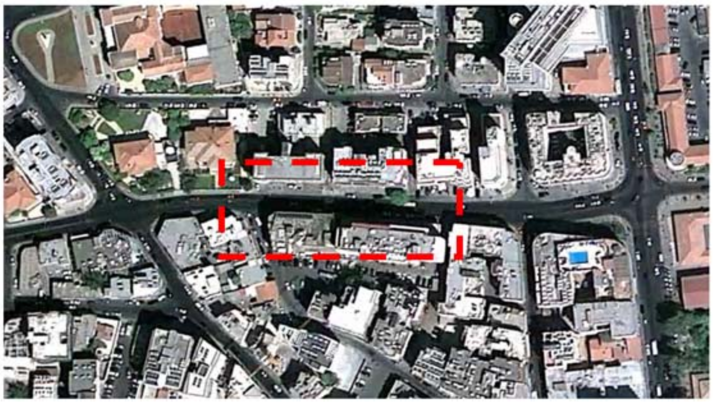


**Figure 12:** Location of the Larnaca hotspot.

The results (**Figure 14**) indicate that street level concentrations both in Nicosia and in Larnaca are significantly affected by local factors, such as traffic emissions. More specifically, the average computed street scale increments for Nicosia for $PM_{10}$ and $PM_{2.5}$ approach 20% and 26% of the urban background concentrations. On the other hand, the aforementioned percentages for the case of Larnaca for $PM_{10}$ and $PM_{2.5}$ are 33% and 36%, respectively.

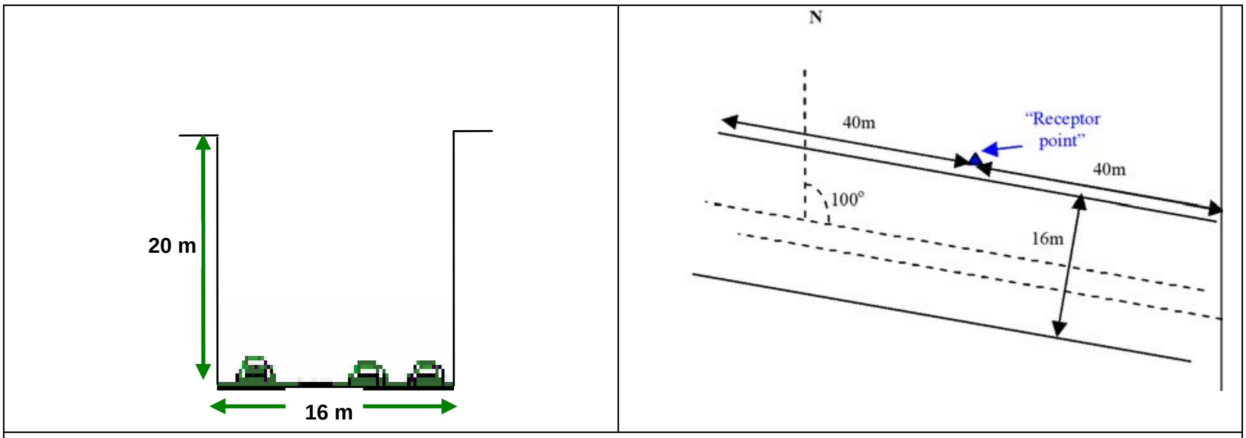


**Figure 13:** Street geometry of the Larnaca hotspot.

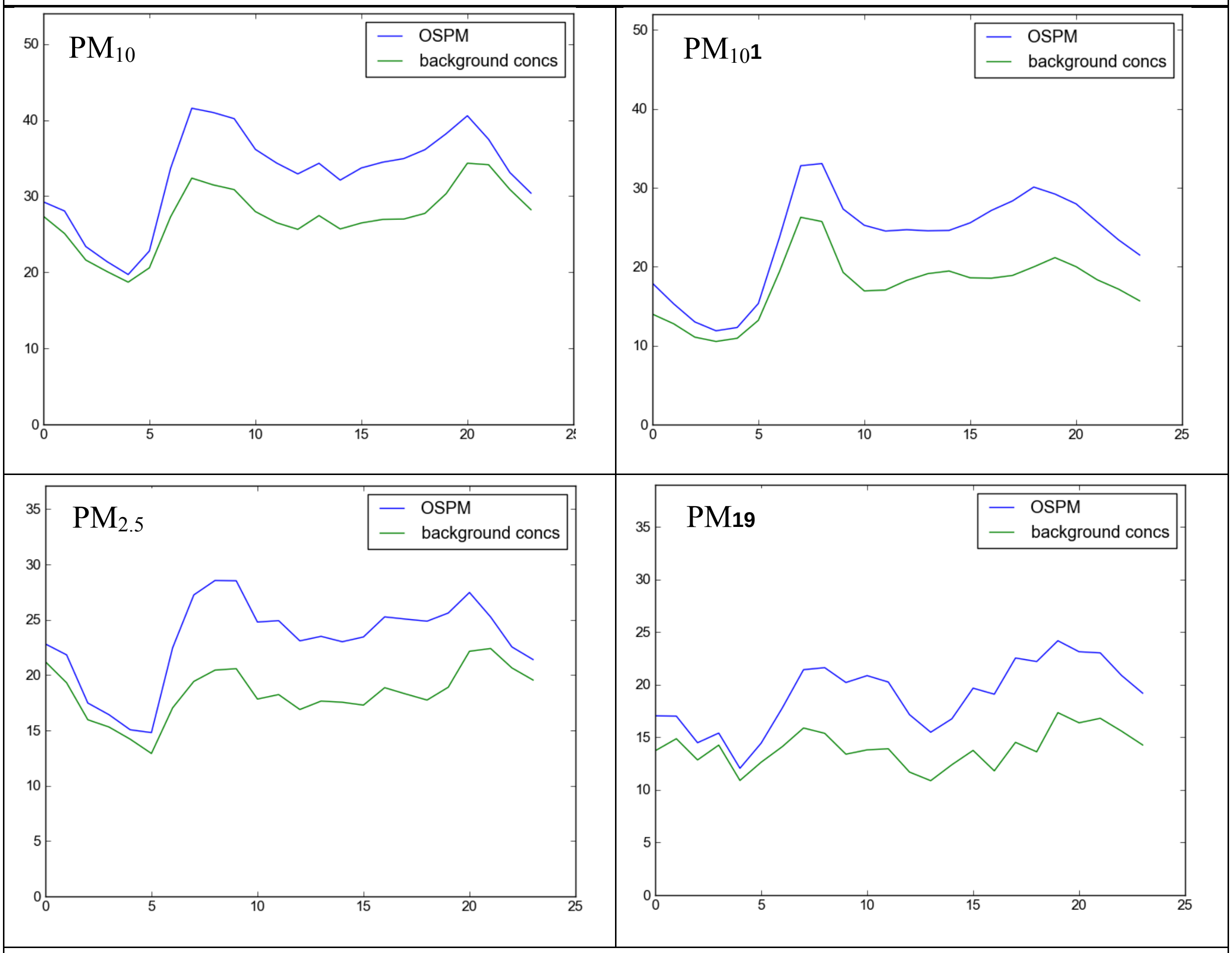


**Figure 14:** Annual average diurnal pattern for $PM_{10}$ and $PM_{2.5}$ as regards Makariou Ave. (Nicosia – left) and Gr.Afxendiou street (Larnaca - right).

Despite the fact that the geometric characteristics of the location in Larnaca, where the street scale calculations were performed, indicate that it can be more strictly characterized as a street canyon than the corresponding location in Nicosia and that the emissions from road traffic in the Larnaca case are higher than those in the Nicosia case, the absolute values of the computed street level concentrations are higher in Makariou Ave. than in Grigoriou Afxediou. This is due to the elevated urban background concentrations occurring in Nicosia than those in Larnaca.

# 5. REMOTE SENSING

## 5.1. Synoptic observation: remote sensing data results and interpretation

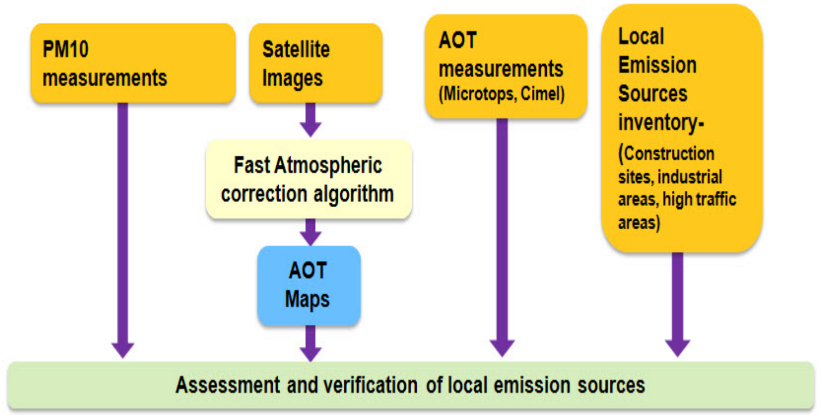


**Figure 15**: Overall Methodology adopted in this study

The overall methodology of synoptic observation is shown in **Figure 15**. Aerosol Optical Thickness (AOT) values derived from satellite images were used to identify sources of air pollution. AOT is the wavelength dependent measure of the total extinction of sunlight due to scattering and absorption by aerosols. In order to retrieve AOT from satellite images, the fast atmospheric correction algorithm developed by Themistocleous**(11,12)** was used. This algorithm is an effective image-based atmospheric correction method based on the radiative transfer equation and the improved darkest pixel method of atmospheric correction using non-variant targets**(12,13)**. In the fast atmospheric correction algorithm, the in-situ reflectance data of the non-variant targets established as calibration targets in the Limassol area were used in order to atmospherically correct the image with the improved darkest pixel method**(11,12)**. The radiative transfer equations are then used to solve for AOT**(11)**.

GIS maps were created using the Kriging algorithm to identify areas which have air pollution levels above the acceptable threshold, based on the methodology developed by Themistocleous**(12,14)**. AOT values derived from Landsat TM/ETM imagery were regressed again $PM_{10}$ levels. GIS maps were used to assess air pollution levels and verify local emission sources**(14)**. By using the AOT values retrieved from satellite, a thematic map was developed through the application of Krigging algorithm to indicate high-polluted areas, according to the methodology outlined by Themistocleous**(12,14)**. The Krigging method of interpolation was used to estimate the AOT values on the GIS map. Using the AOT values derived from the fast atmospheric correction algorithm and interpolation, thematic maps were generated showing the levels of the AOT**(12,14)**. The thematic map was overlaid with GIS vector data which included roads, plots and municipality boundaries, to make it easier to identify sources of AOT values within the city and the local municipalities. Following, AOT values and $PM_{10}$ measurements were assessed. The AOT values derived from the fast atmospheric correction algorithm were assessed with the in-situ AOT values from the Microtops and Cimel sun photometers. The $PM_{10}$ levels were determined from the air quality monitoring stations from the Department of Labor Inspection. Following, a comparison was conducted of the AOT measurements from the air quality monitoring stations with the $PM_{10}$ measurements recorded by the air quality monitoring stations. The AOT measurements were compared with the $PM_{10}$ measurements that corresponded to the time of the satellite overpass.

Thematic GIS maps indicating the AOT levels in Limassol were created (**Figures 16 and 17**). In the thematic maps, AOT levels were verified for several local emission sources, such as construction sites, industrial areas and high traffic areas. The in-situ AOT levels and the AOT levels from the satellite (derived from the fast atmospheric correction algorithm) were compared. The AOT measurements were compared with the $PM_{10}$ measurements that corresponded to the time of the satellite overpass.

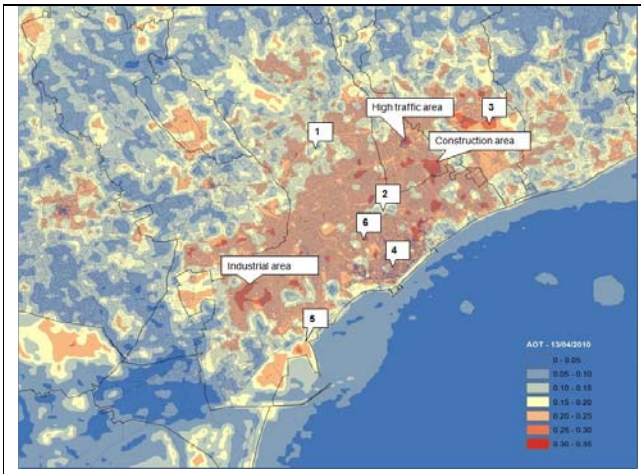


**Figure 16**: GIS map with AOT levels for 13 April 2010.

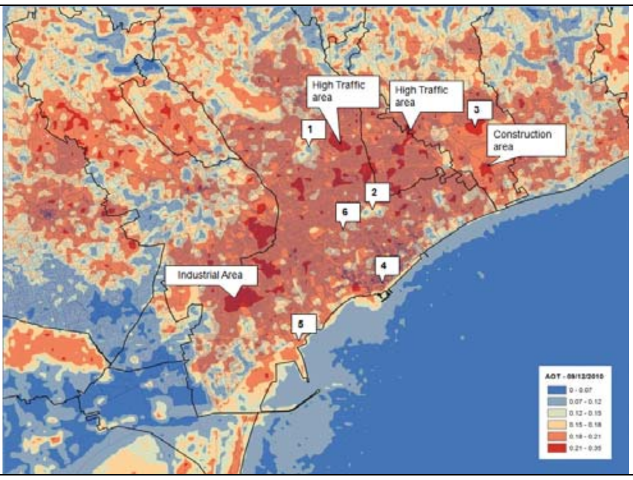


**Figure 17**: GIS map with AOT levels for 9 December 2010.

For April 13, 2010 (**Figure 16**), the lowest levels of AOT were found at the stadium (#1) and the school complex (#2). Moderate levels of AOT were found at the Limassol Port (#5) and the Cyprus University of Technology (#4) in the center of Limassol. This was supported by moderate levels of AOT at the Department of Labor Inspection air quality monitoring site (#6), which reported $PM_{10}$ of 35.96 μg/$m^3$. High AOT levels were found in the Linopetra Industrial area (#3). The highest AOT levels were found in industrial areas, high traffic areas and construction sites.

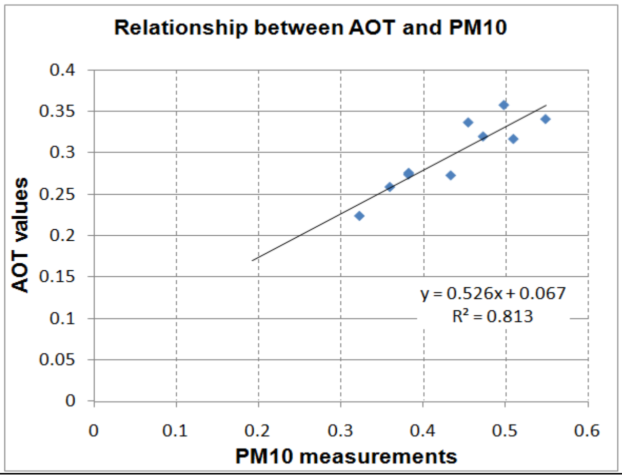


**Figure 18**: Graphical representation of the linear regression model found between the AOT values retrieved from Landsat TM/ETM+ and PM10 values obtained from ground stations.

For December 9, 2010 (**Figure 17**), the lowest levels of AOT were found at the stadium and the school complex. Moderate levels of AOT were found at the Limassol Port (#5) and the Cyprus University of Technology (#4) in the center of Limassol. High AOT levels were found in the Linopetra Industrial area (#3). This was supported by high levels of AOT at the Department of Labor Inspection air quality monitoring site (#6), which reported $PM_{10}$ 47.31 μg/$m^3$. The highest AOT levels were found in industrial areas, high traffic areas and construction sites.

The results found that the larger the blue area, the lower the AOT levels. The lowest levels of AOT were found at stadium (#1) and the school complex (#2), both of which are characterized by low congestion and large blue spaces. The highest levels of AOT were found at the Linopetra Industrial Estate (#3), the Cyprus University of Technology (#4) and the Limassol Port (#5). This is not surprising, as all three of these areas are characterized by high levels of traffic congestion and air pollution. The $PM_{10}$ levels at the Department of Labor Inspection air quality monitoring site (#6) were consistent with the AOT levels, indicating a positive correlation between $PM_{10}$ and AOT, as indicated in **Figure 18**. The AOT derived from the satellite images was consistent with the identified local emission sources, including construction sites, industrial areas and high traffic areas.

In conclusion, the larger blue areas correspond with lower levels of AOT. The AOT derived from the satellite images was consistent with the identified local emission sources, including construction sites, industrial areas and high traffic areas. It was found that the highest levels of AOT and $PM_{10}$ were found in areas with high traffic congestion, such as road intersections, industrial sites and construction sites.

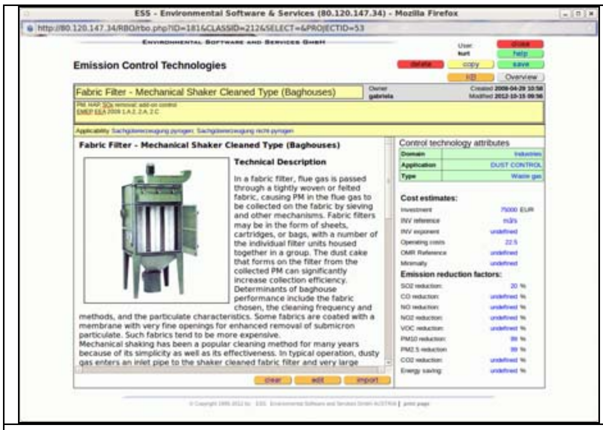
## 6. EMISSION CONTROL OPTIMIZATION

### 6.1 Optimization methodology

The multi-criteria optimization methodology is based on a two phase optimization procedure developed in the EUREKA project E!3266 WEBAIR, using the 3D nested grid dispersion code (CAMx) but with low spatial resolution if necessary. A first naïve Monte Carlo (MC) method is used to generate a large set of alternatives; analysis of alternatives (inverse solution mapping the *pareto*-optimal alternatives back into the decisions space; subsequent series of numerical experiments are based on the analysis of the decision space structures, using adaptive heuristics, genetic algorithms, and machine learning concepts.

A discrete multi-criteria (DMC) DSS tool is used to define the "best" strategy (non-dominated solution nearest to UTOPIA or a user defined reference point. The basic constraints and assumptions for the task include the availability of a realistic emission inventory; and the definition of realistic emission control policies and techno-economic data (costs and efficiency of emission control measures), so that sufficient and realistic data for the optimization can be based on expert assessment and literature sources. Results consist primarily of a set of pareto optimal solutions (effective and cost-efficient emission control strategies) that demonstrate measurable improvement (better compliance) compared to the baseline (assuming a complete and realistic baseline emission scenario). A primary indicator of success is demonstrated improvement of compliance *vis a vis* the baseline scenarios and observation time series.

Emission control technologies or policies (**Figures 19 and 20)** for the optimization are stored in a data base open for users' contributions, currently holding more than 320 entries, more than half with PM10/2.5 reduction efficiencies. These technologies can be assigned to any one of the above source classes, but also individual member of these classes, in particular to large point sources.



ESS - Environmental Software & Services (80.120.147.34) - Mozilla Firefox

http://80.120.147.34/RBO/rbo.php?ID=181&CLASSID=212&SELECT=&PROJECTID=53

ENVIRONMENTAL SOFTWARE AND SERVICES GMBH

User: kurt

Emission Control Technologies

Fabric Filter - Mechanical Shaker Cleaned Type (Baghouses)

Owner: gabriela

Fabric Filter - Mechanical Shaker Cleaned Type (Baghouses)

Technical Description

In a fabric filter, flue gas is passed through a tightly woven or felted fabric, causing PM in the flue gas to be collected on the fabric by sieving and other mechanisms. Fabric filters may be in the form of sheets, cartridges, or bags, with a number of the individual filter units housed together in a group. The dust cake that forms on the filter from the collected PM can significantly increase collection efficiency. Determinants of baghouse performance include the fabric chosen, the cleaning frequency and methods, and the particulate characteristics. Some fabrics are coated with a membrane with very fine openings for enhanced removal of submicron particulate. Such fabrics tend to be more expensive.
Mechanical shaking has been a popular cleaning method for many years because of its simplicity as well as its effectiveness. In typical operation, dusty gas enters an inlet pipe to the shaker cleaned fabric filter and very large

Control technology attributes

| Domain | Industries |
|---|---|
| Application | DUST CONTROL |
| Type | Waste gas |

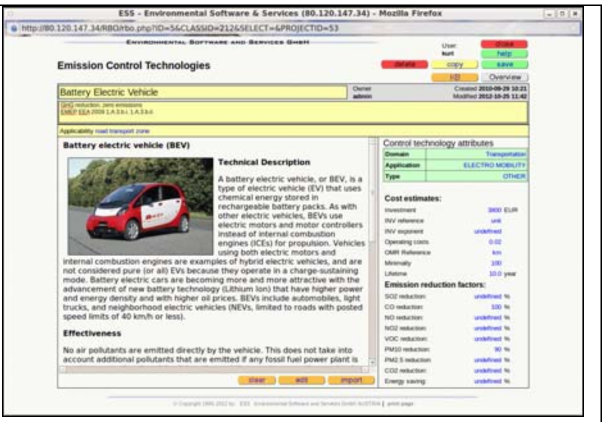
Cost estimates:

| | |
|---|---|
| Investment | 75000 EUR |
| INV reference | m3/s |
| INV exponent | undefined |
| Operating costs | 22.5 |
| OMR Reference | undefined |
| Minimality | undefined |

Emission reduction factors:

| | |
|---|---|
| SO2 reduction: | 20 % |
| CO reduction: | undefined % |
| NO reduction: | undefined % |
| NO2 reduction: | undefined % |
| VOC reduction: | undefined % |
| PM10 reduction: | 99 % |
| PM2.5 reduction: | 99 % |
| CO2 reduction: | undefined % |
| Energy saving: | undefined % |

**Figure 19**: Emission control technology example, end of stack dust filter



ESS - Environmental Software & Services (80.120.147.34) - Mozilla Firefox

http://80.120.147.34/RBO/rbo.php?ID=5&CLASSID=212&SELECT=&PROJECTID=53

ENVIRONMENTAL SOFTWARE AND SERVICES GMBH

User: kurt

Emission Control Technologies

Battery Electric Vehicle

Owner: admin

Applicability road transport zone

Battery electric vehicle (BEV)

Technical Description

A battery electric vehicle, or BEV, is a type of electric vehicle (EV) that uses chemical energy stored in rechargeable battery packs. As with other electric vehicles, BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion. Vehicles using both electric motors and internal combustion engines are examples of hybrid electric vehicles, and are not considered pure (or all) EVs because they operate in a charge-sustaining mode. Battery electric cars are becoming more and more attractive with the advancement of new battery technology (Lithium Ion) that have higher power and energy density and with higher oil prices. BEVs include automobiles, light trucks, and neighborhood electric vehicles (NEVs, limited to roads with posted speed limits of 40 km/h or less).

Effectiveness

No air pollutants are emitted directly by the vehicle. This does not take into account additional pollutants that are emitted if any fossil fuel power plant is

Control technology attributes

| Domain | Transportation |
|---|---|
| Application | ELECTRO MOBILITY |
| Type | OTHER |

Cost estimates:

| | |
|---|---|
| Investment | 3800 EUR |
| INV reference | unit |
| INV exponent | undefined |
| Operating costs | 0.02 |
| OMR Reference | km |
| Minimality | 100 |
| Lifetime | 10.0 year |

Emission reduction factors:

| | |
|---|---|
| SO2 reduction: | undefined % |
| CO reduction: | 100 % |
| NO reduction: | undefined % |
| NO2 reduction: | undefined % |
| VOC reduction: | undefined % |
| PM10 reduction: | 90 % |
| PM2.5 reduction: | undefined % |
| CO2 reduction: | undefined % |
| Energy saving: | undefined % |

**Figure 20**: Emission control technology example: electro mobility

### 6.2 Discrete multi-criteria DSS

The set of feasible alternatives is then processed with the DMC (discrete multi-criteria) interactive DSS to filter candidates for the use with the dispersion model.

The non-dominated sub-set of alternatives is, *a priori*, defined by treating all criteria with the same importance or weight, measuring the distance from UTOPIA, and comparing all criteria along these normalized distances or level of achievement, i.e. the relative distance between NADIR and UTOPIA.
In the participation phase of stakeholders, the relative importance of the individual criteria can be adjusted in two ways:

- introducing ex post constraints (new constraints or tightening of existing constraints)
- moving of the target reference that expresses the decision makers preference, i.e., UTOPIA.

This process is based on the interaction of one or more decision makers with the system. The resulting set of non-dominated alternatives is then subjected to the full model resolution test of its feasibility after processing of the emission scenario with the dispersion model for selected (worst case) meteorological scenarios. For a description of the underlying ideas of reference point optimization, see Wierzbicki(15).

## 7. DISCUSSION AND CONCLUSIONS

The ultimate objective of air quality assessment and management must be the improvement of air quality. The improvement of air quality is based on emission control i.e., emission reductions.

Before the model results are used for public information and as the basis for emission control, the quality of results against observational data is analyzed. Model validation measures the agreement between model generated and observed concentration values. The new consolidated air quality framework Directive 2008/50/EC (replacing 1999/30/EC) defines acceptable model performance as within 50% plus or minus hourly observation data.

However, the comparison of model results and monitoring data is difficult due to the every different nature if not incommensurability of these data: continuous point measurements of a highly dynamic process involving turbulent mixing and high spatial variability, and the hourly average over a large volume of air. The direct comparison of model results and monitoring data therefore requires careful consideration of sampling statistics. Alternative monitoring data for model validation can be derived from large scale synoptic observations, such as aerosol optical density or aerosol optical thickness (AOT) from satellite imagery. While covering large areas in space, they are comparably infrequent, and describe the entire vertical atmosphere, while the monitoring data only sample the bottom layer.

A GIS map was created using the Kriging algorithm to identify areas which have air pollution levels above the acceptable threshold. AOT values derived from Landsat TM/ETM imagery have been regressed again $PM_{10}$ levels. It was found that larger blue areas correspond with lower levels of AOT and $PM_{10}$. The AOT derived from the satellite images was consistent with the identified local emission sources, including construction sites, industrial areas and high traffic areas. It was found that the highest levels of AOT and $PM_{10}$ were found in areas with high traffic congestion, such as road intersections, industrial sites and construction sites.

The results of the pilot street scale applications both in Nicosia and Larnaca indicate that street level concentrations are significantly affected by local factors. This fact is more or less expected for these hot spots which are influenced at a very high level from road traffic emissions.

The non-linearity of the underlying air quality processes together with the non-linear cost functions for emission control poses special requirements for an optimization approach that has to represent this non-linearity as well as the dynamic and distributed nature of the fate and transport system.

The optimization approach is therefore based on the full resolution non-linear dynamic model CAMx, and adaptive heuristics and genetic algorithms for the generation of feasible alternatives in an iterative implementation. The challenge is to improve the efficiency of the iterative search strategy to generate likely candidate solutions in the absence of simple gradients.

For each emission source or class of sources, one or more possible mechanisms, strategies or technologies are selected for possible applications with rules for their combination or mutual exclusion. These measures are described in terms of their costs (annualized investment and operations) and their efficiency in reducing individual pollutants from the source's emissions.

## Acknowledgements

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