Identification of pollution dispersion patterns in complex terrain using AERMOD modeling system

Despina Deligiorgi, Kostas Philippopoulos, George Karvounis and Magdalini Tzanakou

Abstract**—**The scope of this work is to identify the dispersion patterns of air pollutant emissions in complex topography, using a steady-state dispersion model. The area under investigation is the Chania plain on the island of Crete in Greece and the modeled industrial source is a power generating plant. The meteorological assessment is based on a two year dataset (August 2004 – July 2006) from six automated surface meteorological stations. Case studies of the predicted ground-level distributions of SO_2 are presented for days with commonly observed meteorological phenomena.

Keywords**—**Dispersion modeling, Air quality, AERMOD, Complex topography.

I. Introduction

AIR quality deterioration is related to the capability of the atmosphere to disperse pollutants and to energy production and consumption patterns in the area under investigation. Air pollution modeling is a method for providing information on air quality in a region based on what we know of the emissions, and of the atmospheric processes that lead to pollutant dispersion and transport in the atmosphere [1]-[5]. In most air quality applications the main concern is the dispersion in the Planetary Boundary Layer (PBL), the turbulent air layer next to the earth's surface that is controlled by the surface heating and friction and the overlying stratification. The PBL typically ranges from a few hundred meters in depth at night to 1 - 2km during the day. The key issues to consider in air pollution modeling are the complexity of the dispersion, which is controlled by terrain and meteorology effects along with the scale of the potential effects (e.g. human health) [6].

Manuscript received October 28, 2009: This work was supported by the KAPODISTRIAS research programme of the National and Kapodistrian University of Athens.

D. Deligiorgi is with the Physics Department, Division of Environmental Physics and Meteorology, National and Kapodistrian University of Athens 157-84, Athens, Greece (phone: +30 2107276924; fax: +30 2106018677; e-mail: despo@phys.uoa.gr).

K. Philippopoulos is with the Physics Department, Division of Environmental Physics and Meteorology, National and Kapodistrian University of Athens 157-84, Athens, Greece (e-mail: kostasphilippopoulos@yahoo.com).

G. Karvounis is with the Physics Department, Division of Environmental Physics and Meteorology, National and Kapodistrian University of Athens 157- 84, Athens, Greece (e-mail: gkarv@anadelta.com).

M. Tzanakou is with the Hellenic National Meteorological Service, 167-77, Athens, Greece (e-mail: magdalini.tzanakou@gmail.com).

Air pollution models are classified according to the scales of application. Short-range models apply to space scales up to ten kilometers, while urban and long-range transport models to larger scales. The most widely used models for predicting the impact of relative inert gases, such as sulfur dioxide, which are released from industrial point sources, are based on the Gaussian diffusion [7]. A Gaussian plume model assumes that if a pollutant is emitted from a point source, the resulting concentration in the atmosphere, when averaged over sufficient time, will approximate a Gaussian distribution in vertical and horizontal directions [8]-[11]. The limitations of the simplified Gaussian models are associated with this assumption and they are not suitable for dispersion studies under low wind conditions and in distances less than 100m [12] Furthermore they are not recommended for far field modeling as the required homogeneity of meteorology is not valid [13].

II. Experimental Area and Data

A. Experimental Area

The modeling area is at the Southeastern part of the Chania Plain, located on the island of Crete in Greece. The greater area is constricted by physical boundaries. These are the White Mountains on its Southern side and the Aegean coastline on its Northern and Eastern part. The topography of the region is characterized fairly complex due to the geophysical features of the region. The diesel power generating plant, operated by the Public Power Cooperation S.A. of Greece (PPC), is situated in a suburban area, on the outskirts of the city of Chania (35.59^{o}N and 24.04^{o}E) and is the main source of air pollution in the region (Fig. 1). The region's topography, land-use, along with the existence of a single significant air pollution point source makes the area suitable for identifying the dispersion patterns in complex terrain under various meteorological conditions.

B. Experimental Data

In order to assess the meteorological conditions in the greater region and more specifically in the modeling domain, an experimental meteorological network of six stations is used for two years (August 2004 to September 2006). The location of each station is illustrated in Fig. 1.

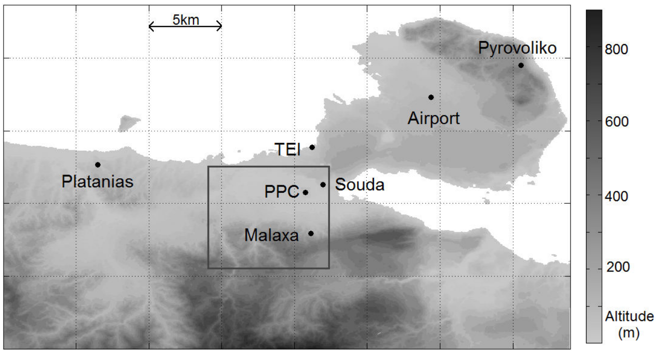

Fig. 1 Area of study, modeling domain and meteorological stations network

The stations of Pyrovoliko (PYR) and Airport (AIR) are situated at the Akrotiri Peninsula and are operated by the Hellenic Meteorological Service and the coastal stations of TEI and Platanias (PLA) by the Technological Educational Institute of Crete. Furthermore, for the study of the dispersion patterns in the region, the suburban station at Souda (SOU) and the inland station at Malaxa (MAL) are used. Upper air measurements are provided from atmospheric soundings at the civil airport of Heraklion. Surface weather maps of Southeastern Mediterranean region at 00UTC and 12UTC are available from the Hellenic Meteorological Service. Table 1 summarizes the available surface meteorological observations in each station.

Table 1 Measured Meteorological Parameters

	PLA	SOU	MAL	TEI	AIR	PYR
Temperature(^{o}C)	✓	✓	✓	✓	✓	✓
Relat. Hum. (%)	✓	✓	✓	✓	✓	✓
Atm. Pres (hPa)	--	✓	--	✓	--	✓
W. Speed(m/sec)	✓	✓	✓	✓	✓	✓
W. Direction (^{o})	✓	✓	✓	✓	✓	✓
Rainfall (mm)	--	✓	✓	✓	✓	✓
Soil Temp (^{o}C)	✓	✓	--	✓	--	--
Cloud Cover (%)	--	--	--	--	✓	--
Sol. Rad (W/m^2)	--	--	--	✓	--	--
Net Rad. (W/m^2)	--	--	--	✓	--	--
Ceiling Hgt (ft)	--	--	--	--	✓	--
Sun.Duration(hr)	--	--	--	--	✓	--

The station sites cover the main topographical and land-use characteristics of the study area (Table 2).

Table 2 Characteristics of the meteorological stations

Station	Altitude (m)	Characterization
Souda	118	Suburban
Platanias	23	Rural – Coastal
Malaxa	556	Rural – Inland
TEI	38	Urban – Coastal
Airport	140	Rural
Pyrovoliko	422	Rural

III. AERMOD MODELING SYSTEM

AERMOD modeling system is developed by the American Meteorology Society (AMS) and the U.S. Environmental Protection Agency (EPA) [14]. It consists of two pre-processors (AERMET and AERMAP) and the AERMOD dispersion model. The overall modeling system structure is presented in Fig. 2.

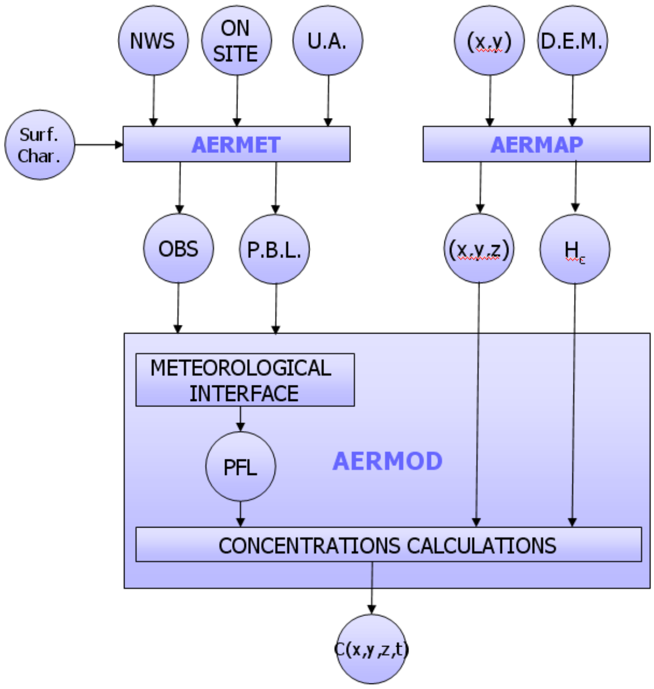

Fig 2 Data Flow and structure of the AERMOD modeling system

AERMET, AERMOD modeling system's meteorological pre-processor, provides the dispersion model with the meteorological information it needs to characterize the PBL. AERMET uses routinely measured meteorological data (i.e. wind speed and direction, ambient temperature and cloud cover), surface characteristics (i.e. Albedo, Bowen ratio and Surface Roughness Length) and upper air sounding data, to calculate boundary layer parameters (i.e. mixing height zi, friction velocity u*, Monin-Obukhov length L, convective velocity scale w^*, temperature scale θ^* and surface heat flux H). This data, whether measured off-site or on-site, must be spatial and temporal representative of the meteorology in the modeling domain. AERMAP, the terrain pre-processor, characterizes the terrain, using a Digital Elevation Model (DEM) and generates the receptor grids for the dispersion model. Furthermore, for each receptor grid (x,y) it generates a representative terrain-influence height H_c. This information along with the receptor's location and height above mean sea level (x,y,z), are forwarded to the dispersion model.

The dispersion model in the Stable Boundary Layer (SBL) assumes both vertical and horizontal distributions to be Gaussian. In the Convective Boundary Layer (CBL) the horizontal distribution is also assumed to be Gaussian, but the vertical distribution is described by a bi-Gaussian probability density function. AERMOD modeling system may be used for flat and complex terrain as it incorporates the concept of a critical dividing streamline [15]. Where appropriate the plume is modeled as a combination of a horizontal plume (terrain impacting) and a terrain-following (terrain responding) plume. Therefore, AERMOD handles the computation of pollutant impacts in both flat and complex terrain within the same modeling framework.

IV. METHODOLOGY

This study is focused on the impact of a single air pollution point source at the Chania plain under the various meteorological conditions, which are observed at the area under investigation. The surface pressure maps of the Southeastern Mediterranean region at 00UTC along with the meteorological measurements from the stations network are used for the selection of days and to characterize the weather conditions in the region. In detail, the identification of the distinct meteorological conditions with well established wind flows in the region is performed by analyzing the daily evolution of wind speed and direction from the experimental measurements, with increased significance the measurements from the station of Souda, due to its proximity to the modeled power plant.

Once the representative days are selected, surface daily averaged concentrations of sulfur dioxide are estimated using AERMOD modeling system. Sulfur dioxide is selected as the pollutant of reference because due to its rather inert nature it is suitable to estimate the dispersion patterns in the region.

V. RESULTS – CASE STUDIES

A. AERMOD Input

The modeled industrial source (PPT), which is situated Chania plain (Fig. 1), has a total maximum power capacity 349.3MW and uses diesel as a fuel with 0.035% w/w sulfur concentration. Its seven buoyant sources have different operational characteristics (Table 3). The high variability of consumption patterns in the region [16], leads to multiple operational patterns for each substation.

Table 3: Characteristics of the buoyant sources

Source	Height (m)	Exit Speed (m/sec)	Exit Temp (^oC)	Emission Rate (m^3/sec)
Stack1	12	27	322	0.0099
Stack2	14	15	462	0.0097
Stack3	17	15	478	0.0199
Stack4	40	35	515	0.0555
Stack5	40	30	505	0.0461
Stack6	60	21	170	0.0619
Stack7	60	25	174	0.0703

The selected modeling domain covers an area of $51km^2$ (Fig. 1) and a Cartesian grid is used containing 20,541 receptors with spatial resolution 50m. The power plant is situated at the Northeastern part of the modeling domain.

AERMOD is found to be highly sensitive on the selection of land use parameters and especially to surface roughness length, with an error reaching up to 20%, when inappropriate values are used [17],[18]. In our case field measurements were not available and their representative selection was based on observational-qualitative criteria in conjunction with the proposed tables by EPA. These tables provide typical values of Surface Roughness Length, Albedo and Bower Ratio for each season and land use type.

Gaussian type models and therefore AERMOD require spatial and temporal representative meteorological data for the application area. Representativeness is the extent to which a set of measurements taken in a space-time domain reflects the actual conditions in the same or different space-time domain taken on a scale appropriate for a specific application [19],[20]. For this purpose, the two year experimental dataset is compared with the 50-year climatological data series provided by the Hellenic Meteorological Society. The dataset was found to be a statistical representative sample of the meteorological conditions that occur in the application area. The temporal meteorological representativeness for the mean monthly time-series of temperature and relative humidity is presented in Fig 3 and 4.

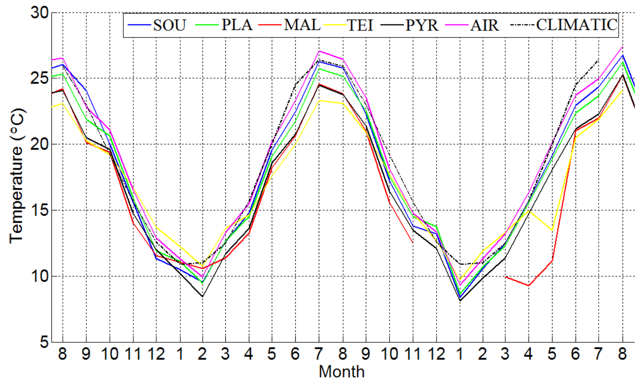

Fig 3 Comparison of experimental and climatological temperature time-series

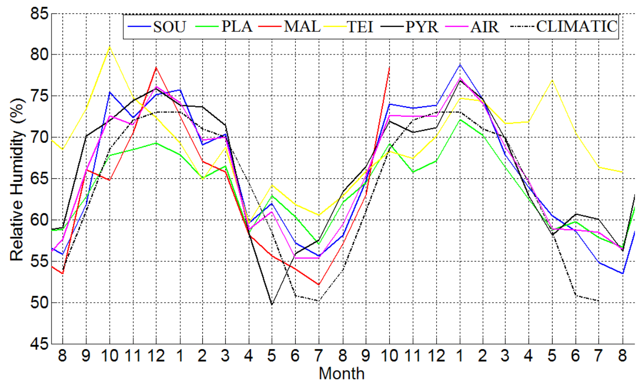

Fig 4 Comparison of experimental and climatological relative humidity time-series

Furthermore, after a qualitative spatial meteorological assessment, Souda measurements are found to be spatial representative for the modeling domain due to the proximity of the Souda site and to the resemblance in land use characteristics with the modeled area. Hourly values of wind speed, wind direction and ambient temperature are used as a meteorological input in AERMOD from Souda station. Cloud cover observations have greater spatial representativeness and therefore are acquired from the Airport Station. The required upper air observations are obtained from Heraklion airport which is the only station at the island of Crete that performs atmospheric soundings.

B. *Case Studies*

The following eight case studies correspond to cases with commonly observed meteorological conditions, leading to the typical dispersion patterns in the region. For each case the surface pressure map along with the daily wind evolution at the station of Souda is illustrated. The ground level, daily averaged SO_2 concentrations are presented for each case study. In order to study the lower concentrations in more detail, the logarithmic scale of the relative quantity C/C_{max} is used.

The first case corresponds to the 27th of August 2004. This day is characterized by combination of a relatively high pressure system in the central Mediterranean and Greece with a relative shallow low system in the Southeastern Turkey. Such a system is mainly observed during the warm period of the year. This synoptic condition leads to a background West-northwestern flow, which is enhanced during midday hours under the influence of the sea breeze circulation cell (Fig. 5). This case corresponds to a group of days where air pollution concentrations are strongly influenced by the interaction of mesoscale flow (i.e. sea-breeze) with synoptic gradient winds.

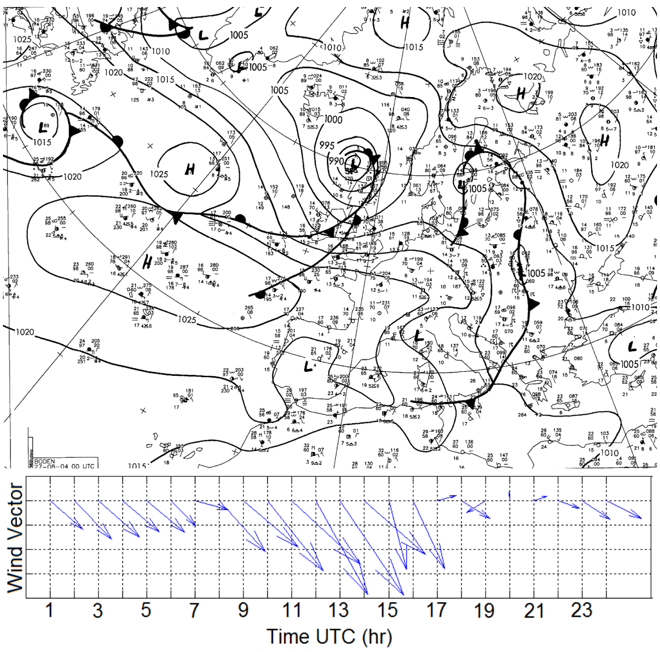

Fig.5 Surface pressure map at 00UTC and daily wind evolution at Souda station for 27/08/2004

The relatively strong flow, especially during the midday hours, results to the transfer of the plume along the prevalent direction with relatively low horizontal dispersion. The flat terrain at the eastern part of the power plant contributes to the above mentioned dispersion pattern (Fig. 6).

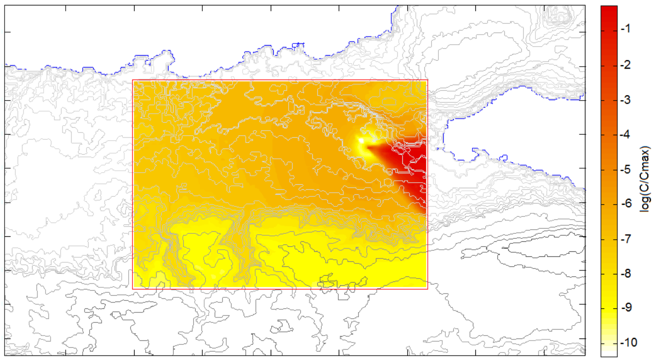

Fig.6 AERMOD's ground level predicted SO_2 concentrations for 27/08/2004

The main synoptic characteristic of the second case (31st August 2004) is the normal field of high pressures in central Mediterranean and Greece, in combination with the relative shallow low system in South Turkey and Cyprus. This weak combination preserves the Northwesterly flow throughout the day and it is enhanced by the sea breeze flow during midday hours (Fig. 7). This case has some common characteristics with the previous case, but differs substantially in the intensity of the background synoptic flow.

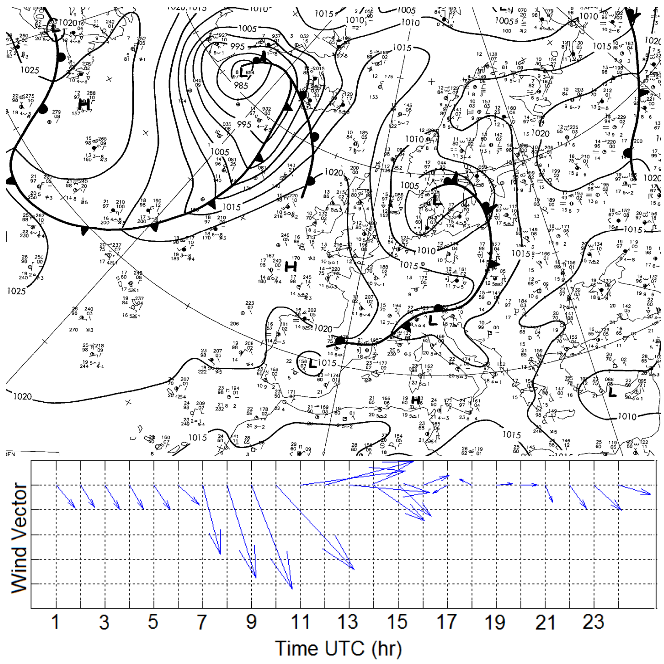

Fig. 7 Surface pressure maps at 00UTC and daily wind evolution at Souda station for 31/08/2004

The combination of the above meteorological conditions in conjunction with the topography of the modeled area leads to increased concentrations at the South of the power plant, at the roots of the White Mountains. Additionally, relatively high concentrations are predicted at the South of the power plant, at the roots of the Akrotiri Peninsula (Fig, 8).

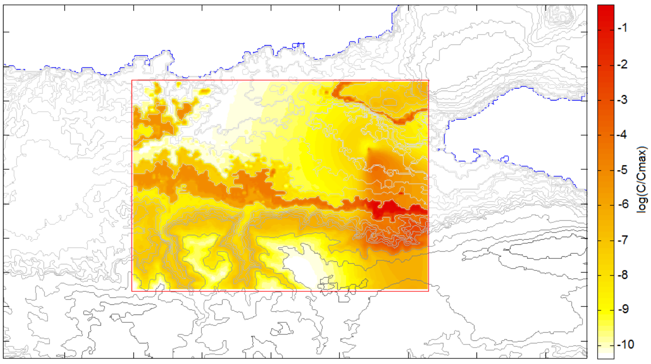

Fig.8 AERMOD's ground level predicted SO_2 concentrations for 31/08/2004

The third case corresponds to the 1st of April 2005, where a strong Nothernly flow is observed at the station of Souda. The main synoptic characteristic is the passage of of a cold front, which moves Southwards. Furthermore, the Northerly flow results from the combination of an anticyclone in central Europe with a low system in East Turkey and is enhanced during the evening (Fig 9).

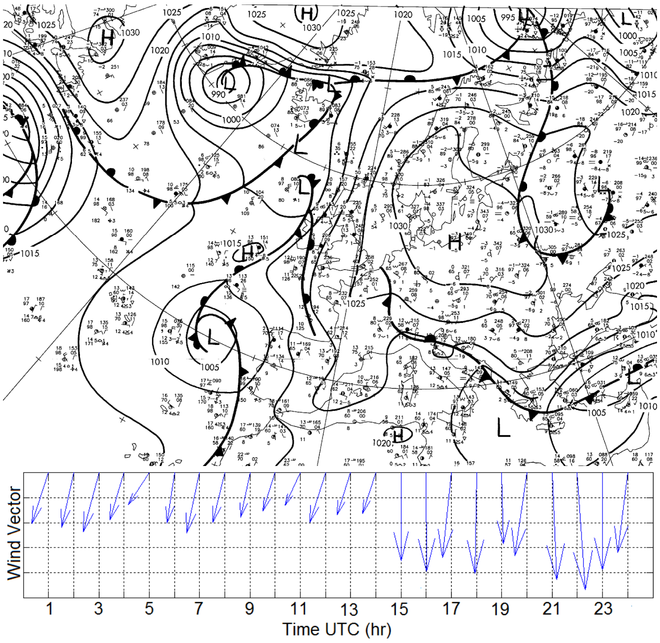

Fig. 9 Surface pressure maps at 00UTC and daily wind evolution at Souda station for 01/04/2005

The plume, as a result of the strong flow, is transferred to the wind direction, following the terrain. Due to its high kinetic energy, the plume is concentrated around the main transfer axis, without being trapped in the valley of Chania (Fig. 10).

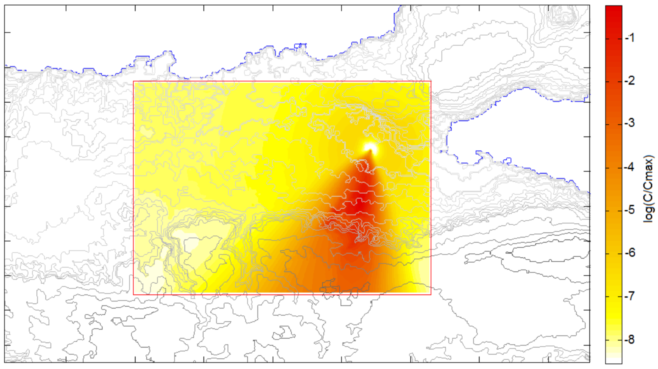

Fig. 10 AERMOD's ground level predicted SO_2 concentrations for 01/04/2005

The synoptic condition for the forth case study (20th October 2005) is infrequently observed in the region, but important in terms of pollution dispersion. An extensive anticyclone in the Balkans is combined with relative low pressure systems at Eastern Turkey, resulting a Easterly-northeasterly surface flow at the Chania valley (Fig. 11).

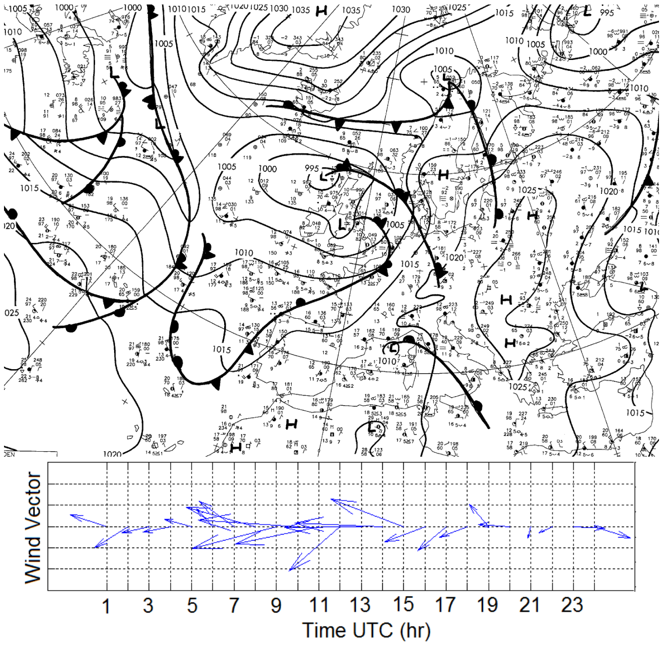

Fig.11 Surface pressure maps at 00UTC and daily wind evolution at Souda station for 20/10/2005

In the entire modeled domain, a background pollution concentration is observed. The plume, under the influence of the wind is transferred to the West of the power plant. The top-end concentrations are observed at the roots of the White Mountains, as a result of the topography and of the moderate intensity surface flow. In every case where the plume is trapped inside the Chania valley, increased concentrations are predicted at the two narrow passages of the White Mountains at the Southeastern part of the modeling domain (Fig. 12).

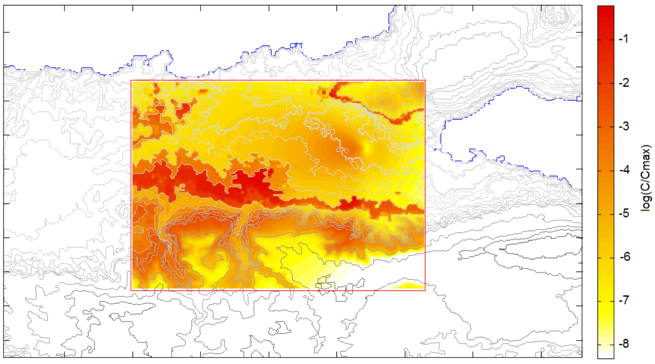

Fig. 12 AERMOD's ground level predicted SO_2 concentrations for 20/10/2005

The synoptic gradient at the 13th of October 2005 is moderate and the modeled area is under the influence of an anticyclone. During midday hours, the flow is Southeastern, with a gradually decreasing intensity and becomes Northwestern during the night (Fig. 13).

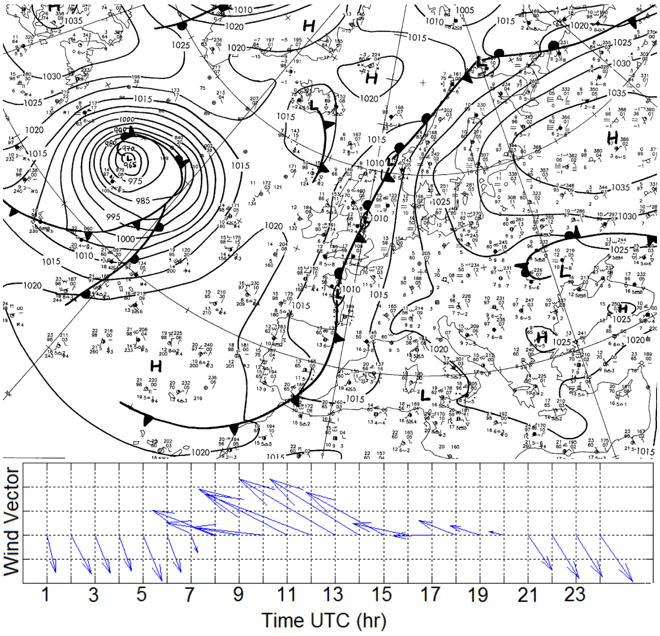

Fig. 13 Surface pressure map at 00UTC and daily wind evolution at Souda station for 13/10/2005

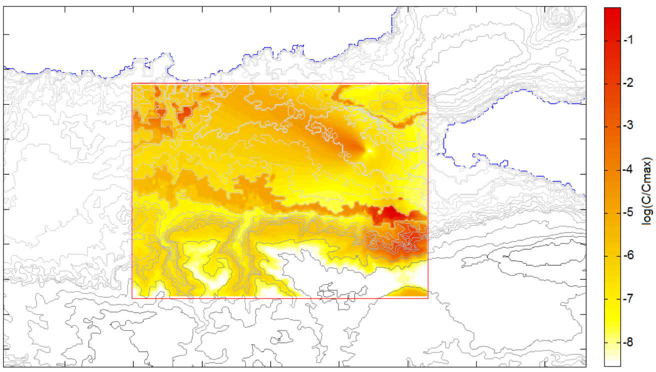

Fig. 14 AERMOD's ground level predicted SO_2 concentrations for 13/10/2005

At the whole area under study, a background pollution concentration is observed. The higher concentrations are observed at the western roots of the White Mountains, at the valley of Chania. The Southeasterly winds, which prevail during midday hours, transfer the plume towards the city of Chania (Fig. 14).

The 6th of May 2005 corresponds to a complex synoptic case and its main characteristic is the relative shallow low system in the North Aegean with a cold front at the western part of the Peloponnese. The flow during the day is weak with an Easterly direction, but after the front passage the flow is enhanced. The direction varies from Easterly to Northeasterly components, following a clockwise rotation (Fig. 15).

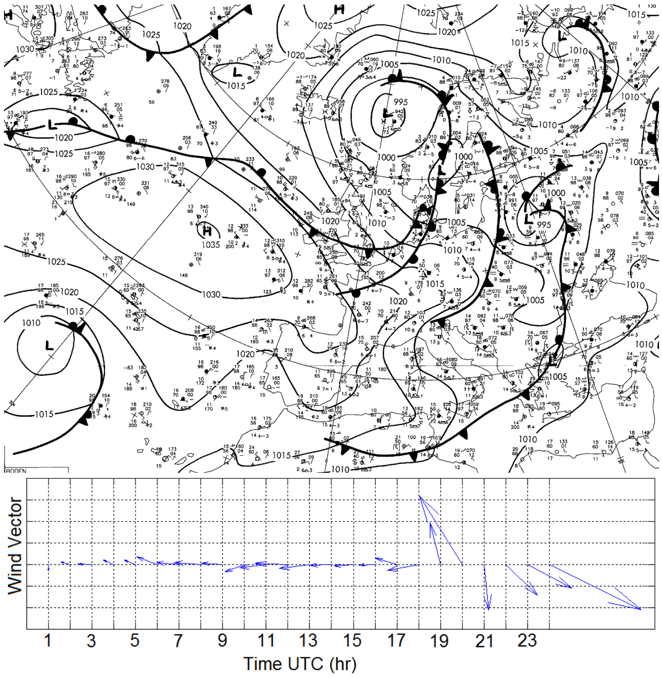

Fig.15 Surface pressure maps at 00UTC and daily wind evolution at Souda station for 06/05/2005

The weak wind regime results to a relative high concentration background in the plain of Chania. The five distinct concentration components observed at Fig. 16 are the result of the wind fluctuations.

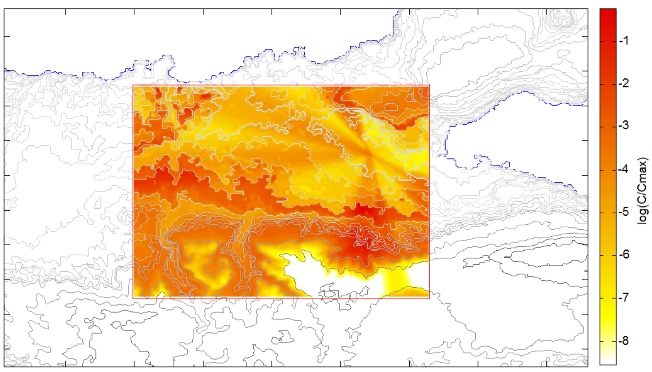

Fig. 16 AERMOD's ground level predicted SO_2 concentrations for 06/05/2005

The synoptic condition of the seventh case (6th July 2005) is characterized by a normal field of relative high pressure in Greece, which favors local flow development. The land-sea temperature contrast leads to the development of the sea breeze circulation cell. At the station of Souda, during midday hours a Northwesterly flow is observed (Fig. 17).

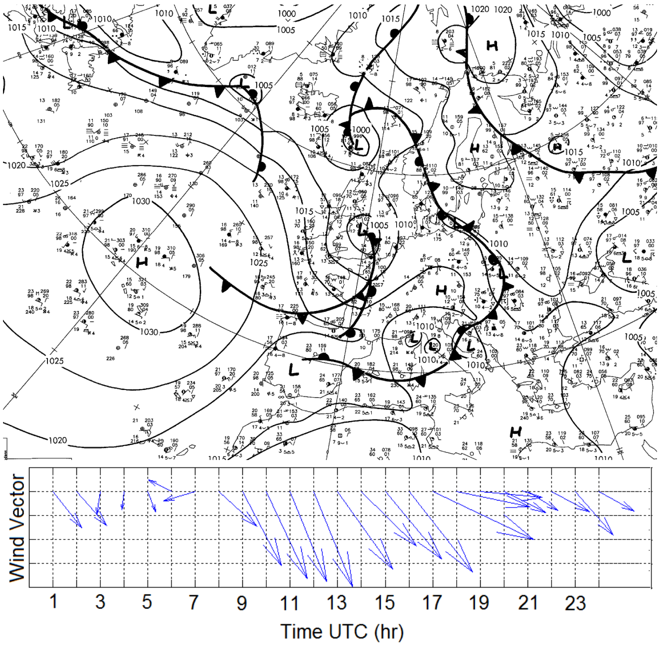

Fig. 17 Surface pressure map at 00UTC and daily wind evolution at Souda station for 06/07/2005

The weak and moderate winds that are observed during the day, lead to the entrapment of the plume in the valley of Chania. The increased intensity sea breeze flow which is observed at midday, gives the plume enough kinetic energy to follow the terrain at the Southwest of the power plant (Fig. 18).

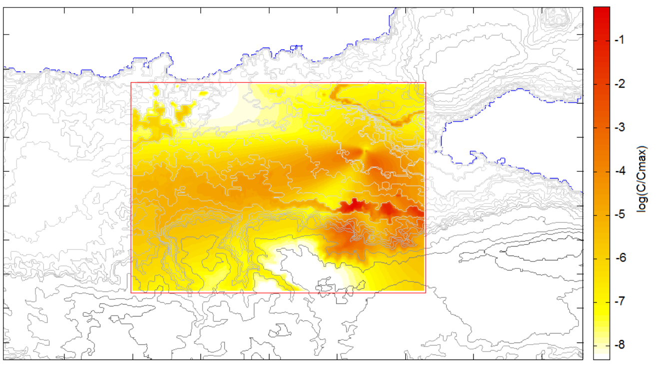

Fig. 18 AERMOD's ground level predicted SO_2 concentrations for 06/07/2005

During the 25th of January 2005, Crete is at the warm sector of an occluded cyclone, which advances slowly towards the East. Its combination with an anticyclone at Turkey leads to Northeasterly wind components until midday. For the rest of the day a swift of the wind vector is observed (Fig. 19).

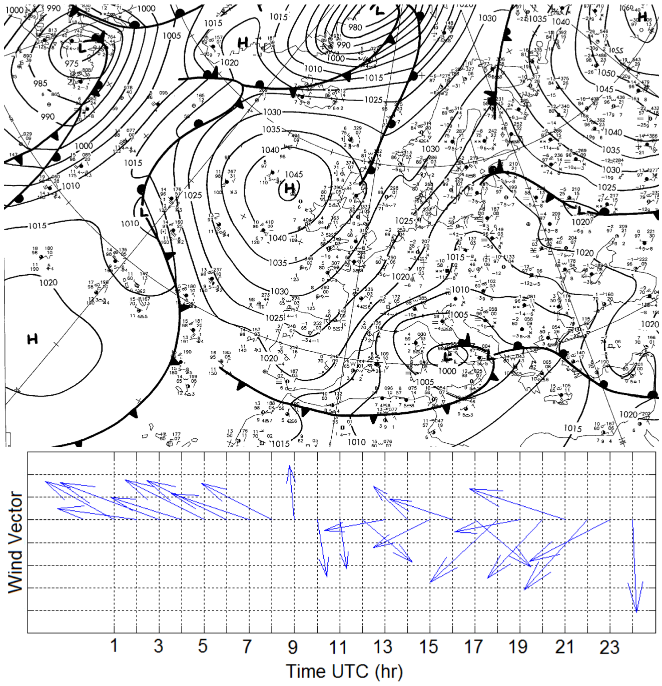

Fig. 19 Surface pressure map at 00UTC and daily wind evolution at Souda station for 25/01/2005

The predicted concentrations have two distinct spatial components. The primary component is related with the Northeasterly flow, while the secondary with the morning southeasterly flow, which leads the plume towards the city of Chania (Fig. 20).

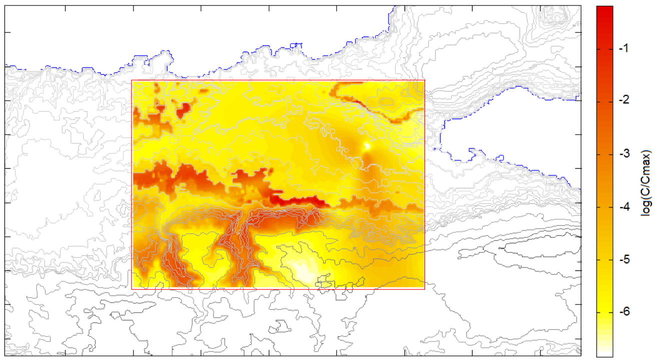

Fig. 20 AERMOD's ground level predicted SO_2 concentrations for 25/01/2005

VI. Conclusion

AERMOD modeling system was applied for the Southeastern part of the Chania plain and for days with well established wind flows. The ground level daily averaged sulfur dioxide concentrations were obtained. The selection of days was based on the analysis of the surface pressure maps at 0000 UTC and the wind measurements at the six experimental sites. Case studies are presented, which reveal the dispersion patterns of atmospheric pollutants in the region. The effect of topography and the complexity of wind circulation patterns lead to a number of dispersion patterns in the region. Under weak wind regimes the higher concentrations are predicted at the roots of the White Mountains, while under strong wind regimes the top-end concentrations are found along the plume centerline.

REFERENCES

[1] N. Moussiopoulos, S. Papagrigoriou, J.G. Bartzis, K. Nester, H. van den Bergh and G. Theodoridis, "Forecasting air quality in the Greater Athens area for the year 2004: an intercomparison of the results of four different dispersion models", *Int. J. of Env. and Pollution,* vol. 14, pp. 343-353, 2000.

[2] C. Borrego, O. Tchepel, A. M. Costa, J. H. Amorim and A.I.Miranda, "Emission and dispersion modelling of Lisbon air quality at local scale," *Atm. Env*., vol. 37, no. 37, pp. 5197-5205, Oct. 2003.

[3] T. Davitashvili, "Mathematical Modeling Pollution From Heavy Traffic in Tbilisi Streets," *WSEAS Trans. on Env. and Development*, vol. 5, pp. 498-507, Jul. 2009.

[4] G. Gualtieri, C. Busillo and F. Calastrini, "Modelling emission scenarios variations: an inert-mode CALGRID long-term application over the Florence metropolitan area to improve PM10–related air quality standards," *WSEAS Trans. on Env. and Development,* vol. 4, pp. 970-981, Nov. 2008.

[5] R. San Jose, J. L. Perez and R. M. Gonzalez, "Air Quality CFD and Mesoscale Modelling Simulations: Madrid Case Study," *WSEAS Trans. on Env. and Development,* vol. 2, pp. 1291-1296, Oct. 2006.

[6] J. Bluett, N. Gimson, G. Fisher, C. Heydenrych, T. Freeman and J. Godfrey, "Good Practice Guide for Atmospheric Dispersion Modelling," Ministry for the Environment, Wellington, New Zealand, 2004.

[7] A.Venkatram, "Challenges of Air Pollution Modeling and its Application in the Next Millennium ," *Air Pollution Modeling and Its Application,* vol. XIV, pp. 613-630, 2001.

[8] D.B. Turner, "A diffusion model for an urban area," *J. Appl. Meteor.* vol.3, pp. 83-91, 1964.

[9] *Handbook on Atmospheric Diffusion*, 1st ed., Technical Information Center U.S. Department of Energy, Springfield, Virginia, 1982, pp.11-36.

[10] G.A. Briggs, "Some recent analyses of plume rise observation," in *Proc. 2nd Int. Clean Air Congress*, New York, 1971.

[11] G.A. Briggs, "Discussion: chimney plumes in neutral and stable surroundings," *Atm. Env.*, vol. 6, pp. 507-510, 1972.

[12] N.S. Holmes and L. Morawska, "A review of dispersion modeling and its application to the dispersion of particles: An overview of different dispersion models available," Atm. Env. vol. 40, pp. 5902-5928, 2006.

[13] M. Caputo, M. Gimenez and M. Schlamp, "Intercomparison of atmospheric dispersion models," Atm. Env., vol 37, pp. 2435-2449, June 2003.

[14] AERMOD Description of Model Formulation, U.S. Environmental Protection Agency, Research Triangle Park, NC, 2004, pp. 40-66.

[15] W. H. Snyder, R. S. Thompson, R. E. Eskridge, R. E. Lawson, I. P. Castro, J. T. Lee, J. C. R. Hunt and Y. Ogawa, "The structure of strongly stratified flow over hills: dividing-streamline concept," *J. of Fluid Mech.*, vol.152, pp.249-288, March 1985.

[16] G.Karvounis., D.Deligiorgi, and K. Philippopoulos,, "On the Sensitivity of AERMOD to Surface Parameters under Various Meteorological Conditions," in *Proc. 11th Int. Conf. on Harmonization within Atm. Dispersion Modelling for Regulatory Purposes*, Cambridge, 2007, pp. 43-47.

[17] T.G. Grosch T.G. and R.F. Lee R.F., "Sensitivity of the AERMOD air quality model to the selection of land use parameters," Trans. on Ecol. and the Env., vol.37, 1999.

[18] G. P. Giatrakos, T. D. Tsoutsos and N. Zografakis, "Sustainable power planning for the island of Crete," *Energy Policy*, vol. 37, no. 4, pp. 1222-1238, Apr. 2009.

[19] C.J. Nappo, J.Y. Caneill, R.W.Furman, F.A.Gifford, J.C. Kaimal, M.L.Kramer, T.J. Lockhart, M.M. Pendergas, R.A. Pielke , D. Randerson, J.H. Shreffler and J.C. Wyngaard J.C., "The Workshop on the Representativeness of Meteorological Observations", *Bull. Am. Meteorol. Soc.*, vol. 63, pp.761-764, 1982.

[20] G.R. Latini, G. Cocci and G. Passerini , "The Optimal Choice of AERMOD Input Data in Complex Areas," *Air Pollution Modeling and Its Application*, vol. XV, pp. 513-514, 2002.