THE DEVELOPMENT AND VALIDATION OF AN OPERATIONAL AIR QUALITY FORECASTING SYSTEM IN WEST MACEDONIA, GREECE

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ABSTRACT

An environmental data acquisition and dissemination system operates in the area of Kozani-Ptolemais basin in Northwestern Greece since 2002 (http://www.airlab.edu.gr). This has been improved, recently, by extending its ability to provide the public with the next day air quality forecast via the internet and on cell phones. Generally, the development and deployment of a real-time numerical air quality prediction system is technically challenging while even more in complex terrain like the area under consideration. The Air Pollution Model (TAPM) (http://www.csiro.au/tapm) is a hydrostatic prognostic mesoscale model. It has been calibrated for the area in recent studies and used in assessing a variety of cases. TAPM has started operating beginning of 2007 giving in a real-time operational mode next day weather forecast, PM10 daily average concentration and Air Pollution Indexes (API). It is here presented and validated against experimental data the link up between TAPM and SKIRON modelling system (http://forecast.uoa.gr).

ΑΝΑΠΤΥΞΗ, ΕΦΑΡΜΟΓΗ ΚΑΙ ΑΠΟΤΕΛΕΣΜΑΤΑ ΕΠΙΧΕΙΡΗΣΙΑΚΟΥ ΣΥΣΤΗΜΑΤΟΣ ΠΡΟΒΛΕΨΗΣ ΑΤΜΟΣΦΑΙΡΙΚΗΣ ΠΟΙΟΤΗΤΑΣ ΣΤΗ ΔΥΤΙΚΗ ΜΑΚΕΔΟΝΙΑ, ΕΛΛΑΔΑ

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ΠΕΡΙΛΗΨΗ

Σύστημα παρακολούθησης και διάδοσης περιβαλλοντικής πληροφορίας σε πραγματικό χρόνο λειτουργεί στην περιοχή της Κοζάνης-Πτολεμαϊδας από το 2002 (http://www.airlab.edu.gr). Πρόσφατα έχει βελτιωθεί διαθέτοντας την πρόβλεψη ατμοσφαιρικής ποιότητας της επόμενης μέρας στο διαδίκτυο και σε κινητό τηλέφωνο. Γενικά, η ανάπτυξη και εφαρμογή επιχειρησιακού συστήματος πρόβλεψης παρουσιάζει τεχνικές ιδιαιτερότητες, ειδικά σε έντονο ανάγλυφο, όπως η περιοχή μελέτης. Το προγνωστικό υδροστατικό μοντέλο The Air Pollution Model (TAPM) (http://www.csiro.au/tapm) έχει βελτιστοποιηθεί και αξιολογηθεί για τη συγκεκριμένη περιοχή. Η επιχειρησιακή λειτουργία του ξεκίνησε δοκιμαστικά αρχές του 2007 και αξιολογείται υπολογίζοντας τον καιρό της επόμενης μέρας, τις ωριαίες συγκεντρώσεις αιωρούμενων σωματιδίων με διάμετρο <10μm και το δείκτη ρύπανσης (Air Pollution Index API). Στη παρούσα εργασία παρουσιάζεται ο τρόπος λειτουργίας και ο συγχρονισμός του TAPM με το SKIRON (http://forecast.uoa.gr) συστήματος πρόβλεψης, καθώς και σύγκριση με πειραματικά δεδομένα.

1. INTRODUCTION

Fine particles are able to be transferred in long distances even when more sensitive to regional influences and impact at ground level by direct impingement or when deposition is high. Environmental impact assessments and related air pollution studies, to data from site observations around industrial sources, may be adversely affected by complex terrain. These cases can, efficiently, be handled by mathematical modeling that serves as an important tool for the determination of air pollution levels. Coupled prognostic meteorological and air pollution concentration components, eliminate the need to having site-specific meteorological measurements. Instead, a model predicts the flows important to local-scale air pollution such as terrain induced flows, against a background of larger-scale meteorology provided by synoptic analysis.

Particulate pollution is of paramount importance in areas with open-pit mines because of its human health related effects. The phenomenon becomes worse when it is combined with raw lignite transfer and combustion in power stations through the resuspension of particles and stack emissions, respectively. The north-western part of Greece is a heavy industrialized area, which is characterized by complex topography. Lignite power stations (PS) operate in the area of West Macedonia with a total installed generating capacity of more than 4 GW. These power stations contribute to about 70% of the total electrical energy produced in Greece. The main industrial activity is developed in the axis Amyntaio- Ptolemais - Kozani, while relatively recently it has been extended northern, in the region of Florina. The power stations use raw lignite as fuel that is mined in the near by open-pit-mines and is transported in the power stations by trucks, wagons and conveyor belts. Since lignite content in sulphur is, generally, low (< 1 %) in the area, the amount of dioxide of sulphur emitted is relatively low. Thus, the more important environmental problem in the region regarding air quality is suspended particulate matter (Triantafyllou, 2003) with the necessity for specialized forecasts (Balseiro et al., 2002).

In order to deal more efficiently with the needs of the area a new web based dynamic ambient air quality data management system given the code name EAP-2 for West Macedonia, Greece, has been designed and developed. This is a new data dissemination approach based on the novel combination of the data processing techniques, software and hardware used for the manipulation of real time environmental information (Triantafyllou et al., 2006b). It has been developed and operated by the lab of Atmospheric Pollution and Environmental Physics.

It is a remote air quality data acquisition and monitoring system for real time data collection from a network of stations, data filtering, analysis and presentation. The system supplies the local community with a better awareness on air quality around the area in a simple and comprehensive way by using environmental indices. The API (EC, 2000) and Discomfort Index (DI) (Thom, 1959) are calculated and provided together with the previous day's values for comparison. The present web based system is designed with no restrictions regarding the area and the number of monitoring stations that can be included in the network. Improvement of the system is carried out continuously by extending its abilities, i.e. the background concentrations, calculation of relative bioclimatic index, next day expected situation and advice for the protection of the public as well as other transmittance techniques. This inevitably employs a modeling procedure in a real-time mode. For example the National Oceanic and Atmospheric Administration (NOAA), in partnership with the United States Environmental Protection Agency (EPA), are developing an operational, nationwide Air

Quality Forecasting (AQF) system. An experimental phase of this program, which couples NOAA's Eta meteorological model with EPA's Community Multiscale Air Quality (CMAQ) model, began operation in June of 2004 and has been providing forecasts over the northeastern United States (Eder et al., 2006).

It is reported here the operational system for air quality forecasts in West Macedonia. This was based on the novel combination of The Air Pollution Model (TAPM) and SKIRON forecasting system. The first results against experimental data after one year of operation are also presented.

2. DATA AND METHODOLOGY

2.1 Study area

The basin axis has a northwest to southeast direction that can be characterized as a broad, relatively flat bottomed basin surrounded by tall mountains with height ranging from 800 to more than 2000 m above sea level. It is approximately 50 km in length and the width ranges from 10 to 25 km. Four lignite PS with stacks of 115 – 200 m in height in the basin are operated by the Greek Public Power Corporation, while recently a new PS (PS5) has been constructed and started operating. The power plants lie at about 650 m above sea level. The cities of Florina, Kastoria and Grevena surround the basin in the west sector. Kozani is located very close to the basin while being protected from the basin's near surface dust by a hill. Figure 1 shows the topography of the region with the monitoring stations (MS) and the PS.

It was reported that places inside the basin appeared to be more polluted than the outer areas (Triantafylou et al., 2006α). This is due to flying ash precipitation emitted from elevated stacks being very close to power stations in combination with stagnant conditions in the basin. Other recent studies have shown that the maximum PM concentrations occur during hot periods in the city of Kozani (Triantafyllou et al., 2006a) while the seasonal maximum of PM concentrations are correlated with stagnant conditions in the basin (Zoras et al., 2006a).

2.2 The models

2.2.1 The Air Pollution Model (TAPM)

TAPM is a PC-based, nestable, prognostic meteorological and air pollution model driven by a Graphical User Interface. Datasets of the important inputs needed for meteorological simulations accompany the model, allowing model setup for any region, although user-defined databases can also be connected to the model if desired. The only user-supplied data required for air pollution applications are emission information.

TAPM solves fundamental fluid dynamics and scalar transport equations to predict meteorology and pollutant concentration for a range of pollutants important for air pollution applications. TAPM consists of coupled prognostic meteorological and air pollution concentration components, eliminating the need to have site-specific meteorological observations. Instead, the model predicts the flows important to local-scale air pollution, such as sea breezes and terrain-induced flows, against a background of larger-scale meteorology provided by synoptic analyses. For computational efficiency, it includes a nested approach for meteorology and air pollution, with the pollution grids optionally being able to be configured for a sub-region and/or at finer grid spacing than the meteorological grid, which allows a user to zoom-in to a local region of interest quite rapidly. The meteorological component of the model is nested within synoptic-scale analyses/forecasts that drive the model at the boundaries of the outer grid. The coupled approach taken in the model, whereby mean meteorological and turbulence fields are passed to the air pollution module every five minutes, allows pollution modelling to be done accurately during rapidly changing conditions such as occur in sea-breeze or frontal situations. The use of integrated plume rise, Lagrangian particle, building wake, and Eulerian grid modules, allows industrial plumes to be modelled accurately at fine resolution for long simulations. Similarly, the use of a condensed chemistry scheme also allows nitrogen dioxide, ozone, and particulates to be modelled for long periods.

The meteorological component of TAPM Version 3.0 has been used in this study. Some detail on the TAPM approach and verification studies can be found elsewhere (Hurley, 2005).

Lagrange particle modelling LPM of turbulence and particles has been used in the present study that accounts for non-terrain-following vertical velocity and turbulence that would, possibly, give an indication of recirculation. Stack emissions from power plants are handled as point sources in LPM mode, with a simulated particle travelling time of 12 hours, which will allow mean meteorology and turbulence to be included in the calculated trajectories and get, generally, accurate particle positions.

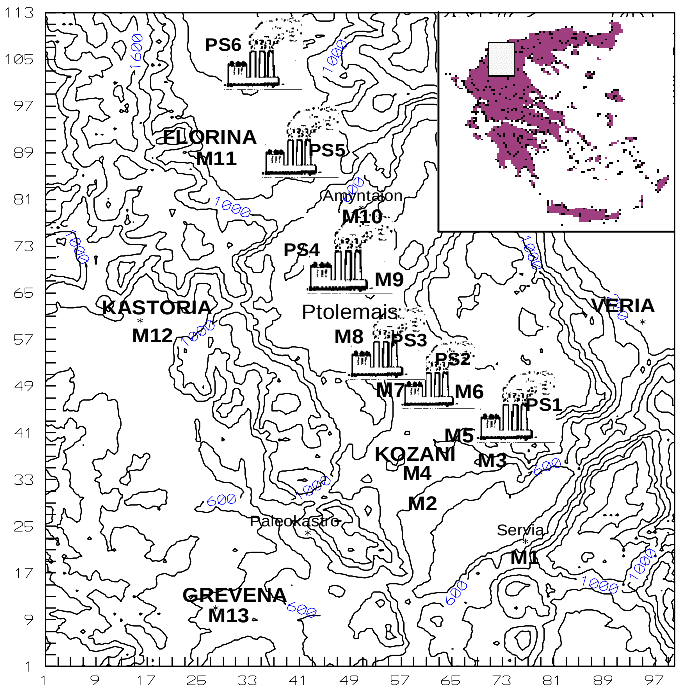

FIGURE 1. Topography of the cities of West Makedonia. PS (PS1,…6), monitoring stations (M1,…13).

2.2.2 SKIRON

The SKIRON modeling system has been developed by the Atmospheric Modeling and Weather Forecasting Group (AM&WFG) of the University of Athens (http://forecast.uoa.gr). It consists of various modules for pre and post-processing together with a version of the model appropriately coded to run on any parallel computer platform utilizing any number of processors. The SKIRON system is based on the NCEP/Eta model (Janjic 1994). This model runs in operational and research mode in a large number of meteorological centers and institutes such as the University of Athens, the Hellenic National Meteorological Service, the Hellenic Centre for Marine Research, the Atmospheric Sciences Research Centre of the University of Albany, and others. Detailed description of its characteristics and configurations is to be found in Kallos (1997) and Papadopoulos et al. (2002).

SKIRON is a full physics atmospheric model with several unique capabilities that make it appropriate for regional/mesoscale simulations in regions with varying physiographic characteristics. It has the unique capability to use the "step-mountain" Eta vertical coordinate and it includes the option to use nonhydrostatic dynamics. The nonhydrostatic model appears to be computationally robust at all resolutions and efficient in NWP applications (Janjic et al. 2001). Sophisticated parameterizations are utilized in order to represent the various physical processes such as radiation, convection, grid-scale precipitation and clouds, boundary layer and soil processes.

The hydrostatic version of the system was successfully used operationally in the University of Athens since 1997. It has also been successfully applied to a large number of different regions and for long forecasting periods (e.g. Papadopoulos et al. 2002). The modeling system has been prepared to utilize initial and lateral boundary conditions from different forecasting centers such as NCEP, ECMWF and Meteo-France. The nonhydrostatic SKIRON is in operational use since January 2003 utilizing NCEP/GFS global analyses and forecasts, at a resolution of 1°x1° until Autumn 2007 and at a resolution of 0.5°x0.5° since then, on a daily basis and producing 5-day forecasts. The model domain covers the entire Mediterranean region and most of Europe. SKIRON was integrated with a horizontal increment of about 10 km and 38 vertical Eta levels from January 2003 to Autumn 2007, while a horizontal increment of about 5-6 km and 45 vertical Eta levels up to 25 hPa are used since then.

The operational forecasts of the various configurations of SKIRON model integrated in the premises of the AM&WFG are freely available in the Internet (http://forecast.uoa.gr). The web page of AM&WFG is very popular with approximately 7000 visitors daily from whom only 45% are from Greece.

2.3 Methodology and data

The development and deployment of a real-time numerical air quality prediction system is technically challenging (McHenry et al., 2004). This is even more challenging in complex terrain (Vaughan et al., 2004) like the area under consideration. In order to develop a modeling system, simulation tools must first be used in the assessment of case studies. Air quality tools must be evaluated in meteorology prediction, back ground concentration and emission sources performance. Other mesoscale studies have proved this way of approach useful when a modeling system is to be used in operational mode (Garcia et al., 2003).

The problem is more complicated for urban areas due to additional contribution from the urban pollution sources. The Air Pollution Model (TAPM) has been calibrated by means of sensitivity analysis techniques (Zoras et al., 2007) in order to handle more efficiently the area and the specified periods by the approximation of particles' positions, trajectories and wind fields. Moreover, seasonal concentrations and episodes of particulate matter with an aerodynamic diameter less than 2.5 μm (PM2.5) have been modeled (Zoras, et al., 2006b) by TAPM in order to verify and evaluate its performance.

The area model predicted influence from stack emission in the city of Kozani under a governing system of meteorological conditions and topographic complexities that modulates the transferable particulate pollution. However, it mostly remains a qualitative approximation due to the absence of detailed emission inventories in the area.

TAPM has been employed in a real-time operational mode to give next day weather forecast, PM10 daily average concentration and API. This has been achieved in collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and The Atmospheric Modeling and Weather Forecasting Group (AM and WFG).

Four day forecast of synoptic data are downloaded every morning on a PC hard drive from SKIRON modeling system. The downloaded forecasts are then read by a FORTRAN code and converted to the format required by TAPM. The model runs and finally, a few batch files upload results to the server. The whole process is integrated into a visual basic executable file. Note that, the current real-time operational modeling system is novel in terms of the combination of the tools used.

Building blocks of two main cities in the area (i.e. Kozani and Ptolemais) are imported into TAPM to accommodate urban emission sources. Traffic emissions were calculated from the experimental number and type of vehicles according to the European Guidelines (EEA, 2003). GPS measurements have been carried out of the urban street canyon locations and imported into TAPM as area pollution sources. From particulate matter measurements in the area (Triantafyllou et al., 2006a) it has been found that the ratio PM2.5/PM10 has a mean value of 0.25 and therefore, that was the value set for stack dust emissions. The rest of stack emissions (i.e. SO2, NOx and smog) were mostly indicative to represent a real case but very helpful in the approach attempted in the present study. This was due to the absence of detailed emission inventories while sources from the open mines have been handled qualitatively. Details on stack characteristics can be found elsewhere (Triantafyllou et al., 2003).

3. OPERATION AND RESULTS

The model's high level of reliability was proved by Table 1 and Figure 2. This is a first result since the system has started working operationally (about ten months) with a reasonable degree of reliability. The root mean square error between the next day forecasts and measurements of the mean daily PM10 concentrations was about 16 $\mu g/m^3$ with a correlation coefficient of 0.63. Whilst, the API index has been predicted more accurately with a correlation coefficient of 0.69. Obviously, this was due to the nature of this kind of indexes that range in relatively wide intervals. However, this still remains of paramount importance in regional environmental data dissemination, decision making systems, public awareness and protection. Meteorological parameters were also predicted with a high degree of accuracy, mostly, due to model's calibration and the very fine and accurate synoptic and mesoscale data provided by SKIRON forecast system. In addition, all input data were derived from real experiments in the area e.g. number of vehicles, building blocks. It was also, of paramount importance, the knowledge acquired from past experimental data to set the background values of pollution (Triantafyllou et al., 2006a). Note that, wind data were provided from TEI station outside the city. The period's coverage percentage of the presented PM10 and API data was about 60% due to instrumentation or connectivity malfunctions.

TABLE 1. Performance indices of TAPM prediction results against experimental data from Kozani ground station

WS10=Wind speed at 10m from ground surface U10 and V10=wind components RH=Relative humidity Temp=Temperature PM10=Pariculate matter mean daily concentration API=Air pollution index OBS=Observations MOD=Model Predictions MEAN=Arithmetic mean CORR=Pearson Correlation Coefficient (0=no correlation,1=exact correlation) STD=Standard Deviation RMSE=Root Mean Square Error RMSE_S=Systematic Root Mean Square Error RMSE_U=Unsystematic Root Mean Square Error IOA=Index of Agreement (0=no agreement, 1=perfect agreement) SKILL_E=(RMSE_U)/(STD_OBS) (<1 shows skill) SKILL_V=(STD_MOD)/(STD_OBS) (near to 1 shows skill) SKILL_R=(RMSE)/(STD_OBS) (<1 shows skill)

HOURLY DATA

SITE	NUM_OBS	MEA_OBS	MEA_MOD	STD_OBS	STD_MOD	CORR	RMSE	RMSE_S	RMSE_U	IOA	SKILL_E	SKILL_V	SKILL_R
TEMP	6818.00	16.78	15.38	8.47	8.64	0.94	6.99	1.58	6.37	0.85	0.75	1.02	0.83
RH	5203.00	63.82	49.91	22.51	16.99	0.75	37.77	17.11	26.61	0.51	1.18	0.76	1.68
WS10	7303.00	2.57	3.11	2.10	1.47	0.38	2.39	1.53	1.58	0.57	0.75	0.70	1.14
U10	6875.00	-0.41	0.56	2.25	1.86	0.32	2.60	1.93	1.75	0.57	0.78	0.83	1.16
V10	6875.00	0.17	-1.26	2.45	2.01	0.33	2.97	2.29	1.90	0.54	0.78	0.82	1.22
MEAN DAILY DATA													
PM10	189.00	42.99	39.17	15.23	16.73	0.63	16.42	5.94	14.90	0.73	0.98	1.10	1.08
API	184	3.3	3.1	1.3	1.4	0.69	1.08	0.39	1.01	0.82	0.78	1.08	0.84

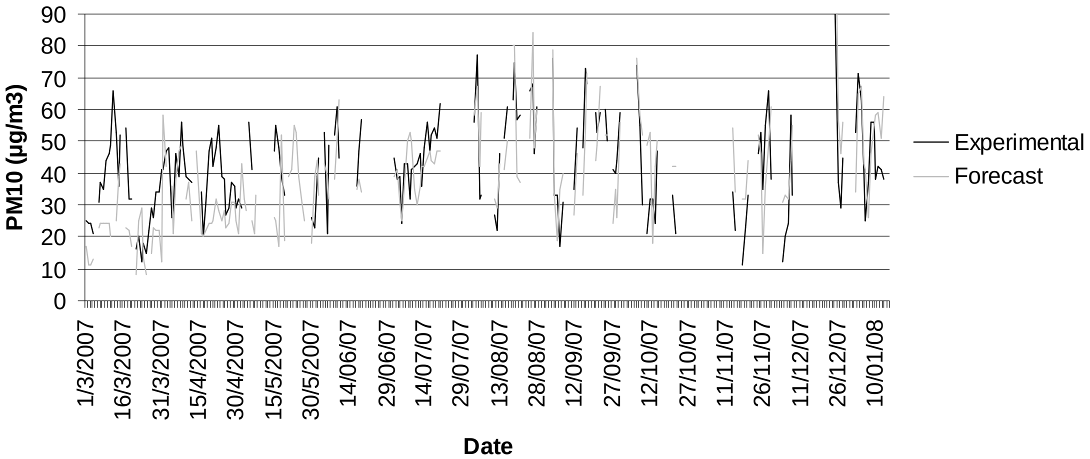

FIGURE 2. Experimental vs predicted PM10 mean daily concentrations

4. CONCLUSIONS

The forecasting system has been integrated into EAP-2 to deal more efficiently with air pollution management. Therefore, EAP-2 employs a novel combination of simulation tools for air quality assessment and next day forecast. The degree of accuracy is reasonable for a system of this kind, especially, in API index forecast being of increased priority in air quality management systems. The system has been developed for online use, giving the pollutant's concentrations and, recently, employed Air Pollution Index (API) in real-time.

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