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ASSESSMENT OF THE PERFORMANCE OF THE UoWM MM5-SMOKE-CMAQ OPERATIONAL SYSTEM FOR WEST MACEDONIA

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Abstract: This paper presents evaluation results in terms of statistical metrics (bias, correlation coefficient, NMSE, factor of 2) for an MM5-SMOKE-CMAQ operational forecasting system for the region of West Macedonia, Greece. The evaluation period is 15 October 2009 – 15 February 2010 and the focus is on particulate matter. West Macedonia is a region of northern Greece where many lignite power plants and mines are located, and where the majority of the electrical power of Greece is produced. The plants and mines are located in a mountainous basin where occasional exceedences of the allowable limits for particulate matter concentrations are observed. The operational system has been set up by the University of Western Macedonia on behalf of the Greek Public Power Corporation (PPC) and performs three-day air quality forecasts every day. Separate evaluations were performed for each day of the forecast (first, second, and third), with no significant difference in the results being observed. This shows that the quality of the forecasts is mostly affected by other factors rather than the elapsed time of the forecast, for forecast durations up to 3 days.

***Key words:** MM5, CMAQ, particulate matter,PM10, PM2.5, model evaluation.*

INTRODUCTION

The region of West Macedonia, in the north of Greece, shown in Figure 1, is a mountainous relatively sparsely populated area. In the north east of this region there is the Eordea basin which is rich in lignite deposits, and this has caused the construction of several lignite-fired power plants by the Greek Public Power Corporation (PPC). The basin extends into the F.Y.R.O.M. where another power plant is installed near Bitola. All the power plants are fed by open cast mines, and the power plants of the PPC produce 70% of the total electrical energy output of Greece.

The Eordea basin is oriented from NW to SE, is around 50 km long and 10-25 km wide, and relatively flat at 650 m above sea level surrounded by mountains which reach 2000 m (Figure 1). The largest cities of West Macedonia, Kozani and Ptolemais, as well as the city of Florina, are located within the basin. The prevailing winds are weak, and directed along the axis of the basin. Environmental concerns due to the intense industrial activity have led the PPC to install a network of air quality monitoring stations, the locations of which are indicated in Figure 1, and which measure continuously PM_{10} and $PM_{2.5}$ concentrations. The situation with respect to particulate matter in West Macedonia is described in more detail by Triantafyllou *et al*, 2006.

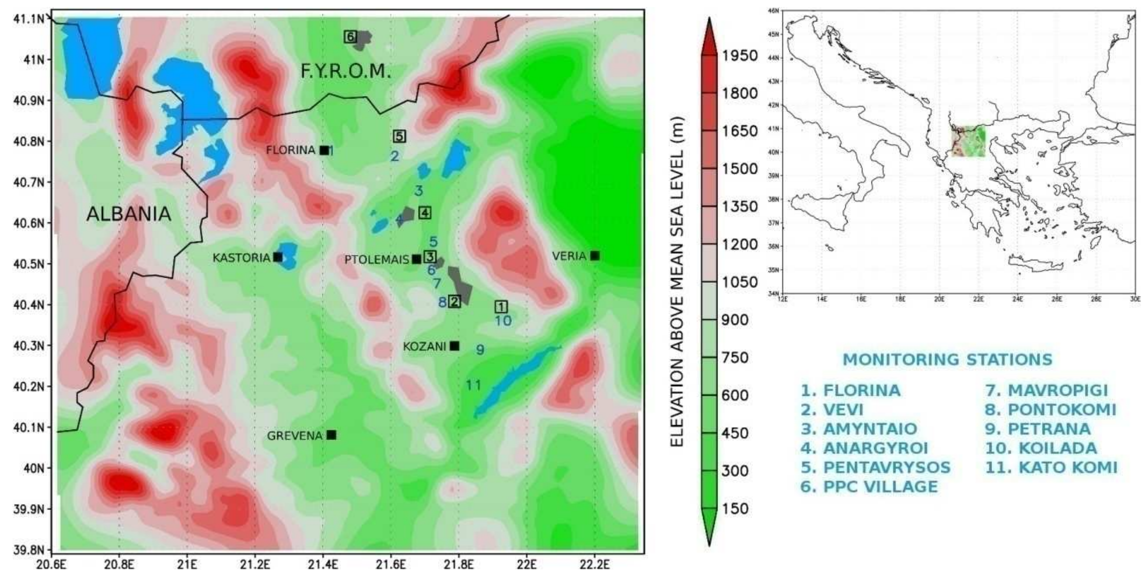

Figure 1. The topography of West Macedonia. Black numbered squares indicate power plants and grey areas mark the lignite mines. The blue numbers indicate the locations of the air quality monitoring stations whose names appear in the legend on the right.

To aid in the environmental management, the Environmental Technology Laboratory (ETL) of the University of Western Macedonia, located in Kozani, has set up on behalf of the PPC an operational system which includes a component which produces 3-day air quality forecasts on a daily basis, based on MM5 (Grell *et al*, 1994) and CMAQ (Byun and Ching, 1999, Byun and Schere, 2006). Some aspects of this operational system were described in a previous work (Sfetsos *et al*, 2009). In this paper, the prognostic ability of the system is assessed against the PM_{10} and $PM_{2.5}$ measurements of the PPC stations, over a winter period of four months (15 Oct. 2009 – 15 Feb. 2010). The complex topography, the lack of detailed emissions inventories for the neighbouring countries (F.Y.R.O.M., Albania), and the high grid resolution (2 x 2 km) are factors which may adversely affect the quality of the forecasts. The evaluation is performed separately for the first, second, and third day of each forecast to investigate the evolution of the forecast accuracy in time.

SYSTEM SET-UP

The initial and boundary conditions for MM5 are obtained from the output of the GFS model stored in the daily global repository of the National Center for Environmental Prediction (NCEP), USA. A series of four nests reduces the resolution from the original 1 x 1 deg. (approx 100 x 100 km) resolution of the GFS to the 2 x 2 km resolution of the grid which covers West Macedonia (the region shown in Figure 1). Two-way nesting is used. The number of vertical levels is 30, with the first layer having a height of approx. 35 m.

The MM5 parameterization used is as follows: Reisner Graupel (Reisner2) explicit moisture scheme, Kain-Fritsch 2 cumulus parameterization, MRF planetary boundary layer scheme, RRTM radiation scheme, and five-layer soil model.

Because the original initial condition information is on a 100 x 100 km grid (the GFS grid) and this is interpolated to a 2 x 2 km grid, a start-up period is used to quench the errors introduced by the interpolation. Therefore, each forecast is made to use yesterday's start as its starting time. That is, the first 24 hours of each forecast are not really a forecast, but a simulation of a period that has already elapsed, and so observation data are available. In fact the initial and boundary conditions for this initial 24 hour period are obtained from the NCEP "FNL Global Tropospheric Analyses" product available from http://dss.ucar.edu/datasets/ds083.2/. This product is in the form of GRIB files containing data covering the entire globe at 1×1 degree resolution (approx. 100 km), at 6-hour intervals, obtained by correcting the GFS model predictions using available observations. These data are not only used as initial and boundary conditions, but they are also used to nudge the MM5 simulation in the interior of the coarsest domain, using the "three-dimensional analysis nudging (FDDAGD)" option of MM5. This initial start-up period gives a good starting point for the actual forecast, which extends for four days into the future. During the actual forecast, the GFS model predictions are used as boundary conditions.

CMAQ on the other hand uses only one domain, the 140 x 140 km domain shown in Figure 1, which is also the finest domain used by MM5. The same grid is used as with MM5, with a resolution of 2 x 2 km and 30 vertical layers. The reason why only the finest domain is used is that any larger domain would cover parts of the F.Y.R.O.M. and Albania, for which detailed emissions inventories are not available at such high resolution. Of course this may significantly limit the prognostic ability of the system because only local emission sources are taken into account. The present evaluation attempts to investigate the effect of this limitation. For the interior of the domain, a detailed emissions inventory has been prepared by the Environmental Technology Laboratory of the UoWM and NCSR Demokritos, Athens (Vlachogiannis *et al*, 2007), which includes sources such as the traffic network, domestic heating, industry, and biogenic sources, and of course the power generation-related sources (plants and mines).

The emissions inventory is processed by the UNC SMOKE model (http://www.smoke-model.org/) to produce hourly emissions for each of the species of the Carbon Bond IV mechanism selected for CMAQ. The power plant stacks emissions are spread among several layers, according to the plume rise prediction performed by SMOKE which uses the meteorological prediction provided by MM5. All other emissions are assumed to occur within the grid cells which are adjacent to the ground (i.e. within layer 1). The particulate matter is represented in CMAQ using the "aero3" aerosol module.

For each 3-day CMAQ forecast there is no initial start-up period like MM5, but the initial conditions are obtained from yesterday's CMAQ forecast.

MODEL EVALUATION

This paper presents evaluation results for the system for the four-month period 15 Oct 2009 – 15 Feb 2010. For each of the PPC monitoring stations we have one time series of daily average values for the four month period from the recorded observations, and three model time series: one obtained from the first day of each forecast, one from the second day, and one from the third day. Although the stations record hourly concentrations, and so do the models, yet for the present work we have used daily averages. Also, the model predictions have not been interpolated to the station locations, but the observations of each station have been directly compared to the model results at the grid cell which contains the station.

Figure 2 shows time series of hourly PM10 concentrations for two rather random 4-day periods, at Kozani, the largest town of West Macedonia, where the Environmental Technology Laboratory is based. The observations are from ETL's own monitoring station (black lines). In each diagram the coloured lines indicate different MM5/CMAQ forecasts. A different forecast starts every 24 hours. The only input which is different in every forecast is the initial and boundary meteorological conditions which come from the GFS model. The emissions are exactly the same in each forecast (except maybe the plume rise from the stacks which is calculated by SMOKE according to the meteorology). Usually this difference in initial / boundary conditions causes a small deviation between successive forecasts, as can be seen from the left diagram of Figure 2, where the coloured lines are not much different from each other. However, there are cases when successive forecasts give substantially different results, such as in the case shown on the right diagram of Figure 2, in the right part of the diagram. To investigate this, in this work we have assembled three time series, one consisting of the first day of each forecast, one consisting of the second day of each forecast, and one consisting of the third day of each forecast, and have performed separate evaluations for each time series. One would expect that the quality of each forecast deteriorates as time passes.

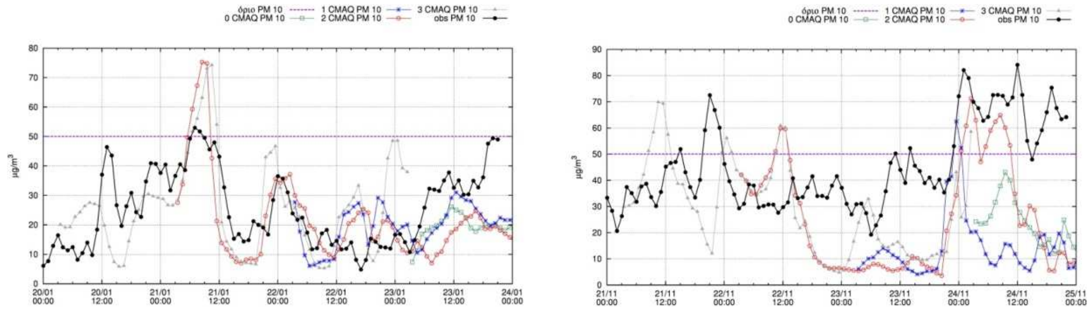

Figure 2. Time series of hourly PM_{10} concentrations for Kozani for two 4-day periods (left: 20-23 Jan 2010, right: 21-24 Nov 2009). The black lines indicate the concentrations measured by the UoWM station, and the coloured lines indicate the MM5/CMAQ predictions.

Table 1. Performance statistics for each monitoring station (the locations of the stations are shown in Figure 1).

STATION	DAY	$PM_{2.5}$					PM_{10}				
		MB	FB	NMSE	FAC2	R	MB	FB	NMSE	FAC2	R
1. Florina	1	21.1	1.29	3.76	0.06	0.13	38.0	1.47	6.71	0.01	-0.12
	2	21.6	1.33	3.95	0.08	0.21	38.3	1.49	6.94	0.05	-0.07
	3	21.4	1.34	4.15	0.06	0.19	39.0	1.51	7.22	0.02	-0.04
2. Vevi	1	11.8	0.86	1.78	0.38	0.17	14.0	0.76	1.65	0.43	0.07
	2	11.7	0.84	1.81	0.40	0.08	14.6	0.79	1.57	0.41	0.22
	3	11.8	0.87	1.73	0.38	0.38	14.8	0.80	1.62	0.43	0.22
3. Amyntaio	1	9.0	0.65	1.09	0.43	0.33	10.5	0.52	0.83	0.48	0.48
	2	9.8	0.72	1.21	0.41	0.34	11.3	0.56	0.85	0.52	0.51
	3	9.9	0.73	1.19	0.44	0.34	11.9	0.59	0.87	0.59	0.50
4. Anargyroi	1	7.3	0.36	0.49	0.77	0.43	7.5	0.17	0.66	0.78	0.51
	2	8.1	0.40	0.49	0.76	0.51	8.0	0.18	0.60	0.78	0.61
	3	7.9	0.39	0.50	0.76	0.50	9.2	0.20	0.59	0.79	0.63
5. Pentavrysos	1	5.4	0.35	0.61	0.64	0.42	2.4	0.09	0.46	0.75	0.50
	2	6.1	0.40	0.63	0.67	0.40	4.0	0.16	0.50	0.77	0.47
	3	6.6	0.44	0.66	0.70	0.44	4.9	0.19	0.48	0.74	0.53
6. PPC village	1	6.5	0.36	0.51	0.71	0.44	7.2	0.19	0.44	0.79	0.58
	2	6.9	0.39	0.50	0.68	0.42	8.1	0.21	0.44	0.77	0.59
	3	7.6	0.40	0.54	0.69	0.40	9.3	0.24	0.45	0.72	0.60
7. Mavropigi	1	-4.3	-0.24	0.35	0.74	0.39	-31.4	-0.77	0.94	0.34	0.53
	2	-3.7	-0.22	0.30	0.76	0.41	-29.8	-0.75	0.88	0.33	0.53
	3	-3.8	-0.22	0.30	0.71	0.44	-30.2	-0.74	0.89	0.35	0.57
8. Pontokomi	1	6.1	0.47	0.79	0.56	0.32	6.7	0.29	0.76	0.58	0.35
	2	6.6	0.51	0.87	0.57	0.27	7.2	0.31	0.88	0.61	0.25
	3	6.3	0.47	0.84	0.62	0.30	7.1	0.30	0.83	0.61	0.29
9. Petrana	1	9.9	0.74	1.04	0.45	0.45	14.0	0.64	0.88	0.53	0.56
	2	9.8	0.73	1.07	0.45	0.39	14.3	0.66	0.95	0.51	0.50
	3	9.9	0.74	1.11	0.37	0.40	14.5	0.66	0.94	0.49	0.53
10. Koilada	1	1.3	0.09	0.45	0.62	0.49	-4.1	-0.16	0.47	0.59	0.51
	2	2.2	0.16	0.40	0.63	0.44	-3.1	-0.13	0.46	0.60	0.43
	3	2.0	0.14	0.50	0.58	0.38	-3.0	-0.12	0.51	0.52	0.43
11. Kato Komi	1	8.4	0.75	1.22	0.38	0.44	11.5	0.73	1.12	0.49	0.59
	2	8.6	0.77	1.29	0.47	0.37	12.0	0.75	1.26	0.49	0.47
	3	8.7	0.80	1.33	0.38	0.47	12.1	0.77	1.24	0.40	0.59

Table 1 presents the results of the evaluation. The following statistical metrics are used (Chang and Hanna, 2004, 2005):

$$\text{Mean Bias: } \mathrm{MB} = \overline{C_O} - \overline{C_P}$$

$$\text{Fractional Bias: } \mathrm{FB} = \frac{\left(\overline{C_O} - \overline{C_P}\right)}{0.5\left(\overline{C_O} + \overline{C_P}\right)}$$

$$\text{Normalized Mean Square Error: } \mathrm{NMSE} = \frac{\overline{(C_O - C_P)^2}}{\overline{C_O} \cdot \overline{C_P}}$$

$$\text{FAC2= Fraction of data that satisfy } 0.5 \le \frac{C_P}{C_O} \le 2.0$$

$$\text{Correlation coefficient: } R = \frac{\overline{\left(C_O - \overline{C_O}\right)\left(C_P - \overline{C_P}\right)}}{\sigma_{C_O}\sigma_{C_P}}$$

where C_O are the observations, C_P are the predictions, an overbar denotes an average over the dataset, and σ_C is the standard deviation over the dataset.

According to the literature, models are in general less capable of accurately predicting aerosol concentrations than predicting concentrations of other pollutants (e.g. Yu *et al*, 2008, Zhang *et al*, 2006, Vautard *et al*, 2007). This may be the reason that there are relatively few studies in the literature which contain detailed evaluations with statistical metrics for particulate matter (e.g. Bessagnet *et al*, 2004, Zhang *et al*, 2006, Hogrefe *et al*, 2007, Yu *et al*, 2008). Furthermore, most of these studies refer to simulations at large spatial scales, with grid resolutions of at least 8 x 8 or 12 x 12 km, or more. An exception is Yu *et al*, 2008, where the finest nest has a resolution of 3 km, very close to the 2 km resolution used in the present study. However a difference between Yu *et al*, 2008 and the present study is that in the former the topography is quite flat, while in the latter the topography is quite complex. Also, in any case in the aforementioned studies the domain of interest is surrounded by larger domains for which emissions inventories are available, while in the present study the finest domain is used alone in CMAQ because of lack of detailed emissions inventories for the surrounding regions. Thus the effect of distant sources is not taken into account.

In Table 1 the stations are ordered approximately from north to south. The first station is that of Florina, for which the results are the worst over all stations with very strong underestimation of both $PM_{2.5}$ and PM_{10} concentrations and bad correlation coefficients. However the Florina station is inappropriately located next to a localized source of PM (a dirt road with truck traffic), and thus its measurements are not representative for the town of Florina. The PPC is planning to move the station to a more appropriate location soon.

The next station is that of Vevi, close to the Meliti power plant. Here the situation improves as far as the statistical metrics are concerned, although it is still below what can be expected according to the literature. Again there is significant underestimation possibly due to deficiencies in the emissions inventory or to the omission of transboundary pollution from the F.Y.R.O.M.

Next we have the stations of Amyntaio and Anargyroi, to the north and west of the Amyntaio power plant and mine respectively. The results here improve further, but for Amyntaio they are not yet of acceptable quality. They can be seen to be quite acceptable for Anargyroi though, with the metrics having values similar to those reported elsewhere in the literature (see the aforementioned studies). It is notable that the model underpredicts the $PM_{2.5}$ concentrations with FB of 0.70 and 0.40 respectively for the two stations, and the PM_{10} concentrations with FB of 0.55 and 0.20 respectively. It is also notable that the model is more successful in predicting PM_{10} than $PM_{2.5}$ concentrations in terms of all the statistical metrics.

Next we consider the group of stations 5-8 (Pentavrysos, PPC village, Mavropigi, Pontokomi) which lie at the heart of the area of PPC industrial activity, close to the largest mines and power stations. The results are similar to those reported in the literature in most cases. Mavropigi is the only station where the model overpredicts the PM concentrations. In the other stations there is some underprediction with FB of around 0.40 for $PM_{2.5}$ and 0.20 for PM_{10}. The results for Pontokomi are slightly worse than for the other stations, except Mavropigi, whose PM_{10} results are not good at all (but the $PM_{2.5}$ results are better).

Finally, there is the group of stations 9-11 (Petrana, Koilada, Kato Komi) which lie south of the industrialized area. Actually, Koilada lies mostly to the east, and has good results, with a very slight overestimation of PM_{10}. The results for the other two stations are not as good, with strong underestimation of PM concentrations (FB of 0.65-0.80), although the values of the correlation coefficient appear to be acceptable.

DISCUSSION AND CONCLUSIONS

An important observation is that the model results are systematically better for PM_{10} than $PM_{2.5}$. It has been observed that (results not shown here), with the given emissions inventory, the CMAQ model predicts that in the vicinity of the lignite mines most of the PM_{10} come from the mines themselves. This is due to the high PM_{10} emissions from the mines (as assumed by the emissions inventory), and also due to the fact that the plant stacks emit at a distance from the ground (100-200 m) and so their emissions disperse before reaching the ground. Since many of the stations are located near mines, this may partially explain why the results for PM_{10} are better. However, this does not fully explain the results because the PM_{10} results are better in almost all cases, even for stations which are far from the mines. A likely explanation is that SMOKE/CMAQ cannot accurately simulate the mechanisms associated with $PM_{2.5}$. This is supported by studies like Bessagnet *et al*, 2004 and Zhang *et al*, 2006 where evaluation is performed also for individual $PM_{2.5}$ components, and appears to be true also for other models besides CMAQ.

Another general observation is the underestimation of particulate matter at almost all stations. This is a general trend noted in the literature, see e.g. the aforementioned studies or San Jose *et al*, 2008 for another example. The underprediction is very strong at stations which are away from the core area of industrial activity, like stations 1, 2, 9 and 11. This is due to the fact that the simulations take place only on a limited domain without proper account of sources outside the domain. However, the results for the rest of the stations are acceptable, which shows that MM5/CMAQ can be a valuable tool even in limited domains, if they contain strong sources. It must be noted that, like in most similar studies, resuspended particles and wind blown dusts are not included in the model, except for the lignite mines.

Finally, we must comment on the variation of model results with time elapsed since the start of each forecast. Table 1 shows that unlike what would be expected, the statistical metrics do not show a systematic degradation of the quality of the forecasts as time elapses. Sometimes the metrics of latter days are better than those of former days, and in general the differences are relatively small. This is shown also in Figure 3, where the three model time series are plotted against observations for PM_{10} at station 6, for which the metrics are amongst the best. Therefore it appears that the GFS initial / boundary conditions are not a crucial factor in determining the quality of the forecast, and other factors such as the emissions inventory are far more important.

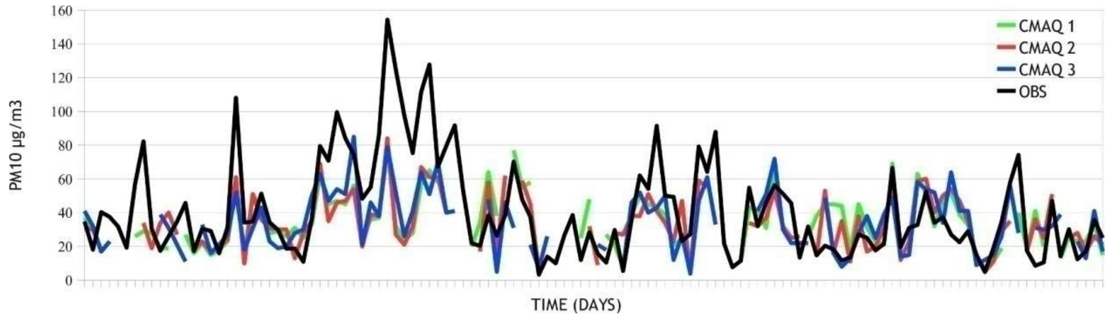

Figure 3. Time series of daily average PM_{10} concentrations at PPC village (station 6) for the whole four-month period – observations (black line) and predictions (coloured lines).

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