

Sensitivity of high-resolution operational weather forecasts to the choice of the planetary boundary layer scheme

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Abstract

In the frame of this paper three widely used planetary boundary layer parameterisations are evaluated for their ability to forecast near-surface temperature and wind speed. The analysis is based on the operational forecasts produced by the Pennsylvania State University — National Center for Atmospheric Research MM5 model over the Athens Area (Greece) during the warm period of 2002. The near-surface temperature and wind forecasts at a grid increment of 8 and 2 km over the highly complex terrain of the Athens Area are statistically verified against the available surface station observations. The results of the analysis showed that the increase in horizontal resolution (from 8 to 2 km) increases the forecast accuracy especially for temperature. As it concerns the forecast skill of each scheme it seems that the MRF scheme produces the best forecasts as it concerns the near-surface temperature while for the near-surface wind the ETA scheme gives the best results. Blackadar schemes present a consistently good behaviour for both temperature and wind forecasts.

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1. Introduction

Since June 2001 the National Observatory of Athens (NOA), produces high-resolution weather forecasts over Greece (8-km grid increment) and very high-resolution forecasts (2-km grid increment) over Athens area, using the Pennsylvania State University — National Center for Atmospheric Research Mesoscale Model, (MM5). The need for high-resolution accurate weather forecasts over the area has been stressed in Kotroni and Lagouvardos (2004). These authors have evaluated one-year weather forecasts

over the area of Athens with the aim, among others, to contribute to the pending question if increasing horizontal resolution produces better forecasts (Mass et al., 2002).

The planetary boundary layer (PBL) scheme implemented in a model plays a decisive role on the accuracy of forecasted state and flow within the PBL. Considerable progress has been made during the last decades with the aim either to develop new or to improve existing PBL schemes (Mellor and Jamada, 1974; Blackadar, 1979; Zhang and Anthes, 1982; Janjic, 1994; Hong and Pan, 1996; Shafan et al., 2000, among others). Furthermore, a number of studies have been dedicated to the evaluation of the ability of various PBL schemes to realistically reproduce PBL parameters, based on the comparative analysis of multiple schemes performance for selected case studies. In most of these studies the PBL schemes as

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implemented in MM5 model have been evaluated. Indeed, [Bright and Mullen \(2002\)](#) investigated the sensitivity of the simulation of the southwest monsoon on the choice of the PBL scheme and found that nonlocal schemes such as Blackadar and MRF schemes were more efficient for the simulation of the deep monsoon PBL, than the local schemes (ETA and Burk-Thompson). More recently, [Zhang and Zheng \(2004\)](#) studied the ability of various PBL schemes to realistically reproduce the diurnal cycles of surface winds and temperatures using a 3-day simulation of summertime weak-gradient flows over the Central United States. Furthermore, [Berg and Zhong \(2005\)](#) have evaluated Blackadar, MRF and Gayno-Seaman schemes over two areas characterized by simple and complex terrain variations and concluded that there is a little gain in the overall accuracy of the forecasts of PBL characteristics with increasing complexity of PBL scheme and thus the use of the relatively quick MRF scheme may be desirable. All the above-mentioned studies were based on the analysis of case studies and thus there was no statistical characterization of the behaviour of the selected PBL schemes.

In the frame of this study three widely used PBL schemes (Blackadar, MRF and ETA) are evaluated for their skill to predict near-surface temperature and wind for a relatively long period in order to obtain some characterization on the statistical behaviour of each one of them. The verification is based on the operational forecasts produced with MM5 model over the highly complex terrain of the area of Athens (Greece) for the period June to October 2002.

The paper is structured as follows: Section 2 is devoted to a brief description of MM5 model, the model set-up and the data sets. Section 3 presents the results of the comparison, while the last section is devoted to some final remarks and prospects of this work. A brief description of the evaluated PBL schemes is given in Appendix A.

2. Model set-up and data sets

2.1. Description of the operational chain

MM5 model (version 3) is a widely used non-hydrostatic, primitive equation model using terrain-following coordinates ([Dudhia, 1993](#)). Several physical parameterisation schemes are available in the model for the boundary layer, the radiative transfer, the microphysics and the cumulus convection. The operational weather forecasting chain at NOA uses the combination of Kain–Fritsch ([Kain and Fritsch, 1993](#)) convective scheme, with the highly efficient and simplified microphysical scheme

proposed by [Schultz \(1995\)](#). This choice has been proven to provide the most skilful precipitation forecasts over Greece ([Kotroni and Lagouvardos, 2001](#)). Concerning the choice of the boundary layer scheme, the current operational chain at NOA uses the MRF scheme proposed by [Hong and Pan \(1996\)](#).

Three one-way nested grids are used: Grid 1 (with a 24-km horizontal grid increment) covering the major part of Europe, the Mediterranean and the northern African coast, Grid 2 (8-km grid increment) covering the Greek territory and all the Greek islands, and Grid 3 (2-km grid increment) covering the entire Athens area and the adjacent water bodies ([Fig. 1](#)). In the vertical twenty-three unevenly spaced full sigma levels are defined.

The 0000 UTC Global Forecast System (GFS, provided by the National Centers for Environmental Predictions—NCEP, USA) gridded analysis fields and 6-hour interval forecasts, at 1.25° lat/lon horizontal grid increment, are used to initialise the model and to nudge the boundaries of Grid 1. As a one-way strategy has been selected for the operational chain, Grid 2 uses Grid 1 forecasts (at 2-h interval) and Grid 3 uses Grid 2 forecasts (at 1-h interval) as boundary conditions. No preforecast spin up period or assimilation of additional observations is used in the operational MM5 model chain.

For the period June–October 2002, two additional experiments were conducted at operational basis, keeping all other model features and set-up the same except the choice of the PBL. Indeed, the operational chain was repeated: (a) using ETA PBL for all three Grids and (b) using the Blackadar PBL for Grids 1 and 2 (Grid 3 was not run due to limitations of computer resources). [Table 1](#) summarizes the details of each experiment. Some details on the PBL schemes are given in Appendix A.

2.2. Data sets

For the verification, 2-m temperature and 10-m wind speed and direction measured at 4 surface stations (Penteli, Thission, Zografou, and Hellinikon) deployed within Athens area were used. The locations of the stations are given in [Fig. 1](#). Penteli station is located at ~500 m on a mountainous area northwest of the main Athens urban centre, Thission is on a hill in the Athens urban centre, Zografou is near the centre in the University campus and Hellinikon is a coastal station. The mean (ME) and the mean absolute (MAE) errors have been calculated for the period June to October 2002 and for the valid hours 00, 06, 12 and 18 UTC and for forecast hours from $t+24$ up to $t+48$ at 6-hour intervals. To avoid introducing additional uncertainty

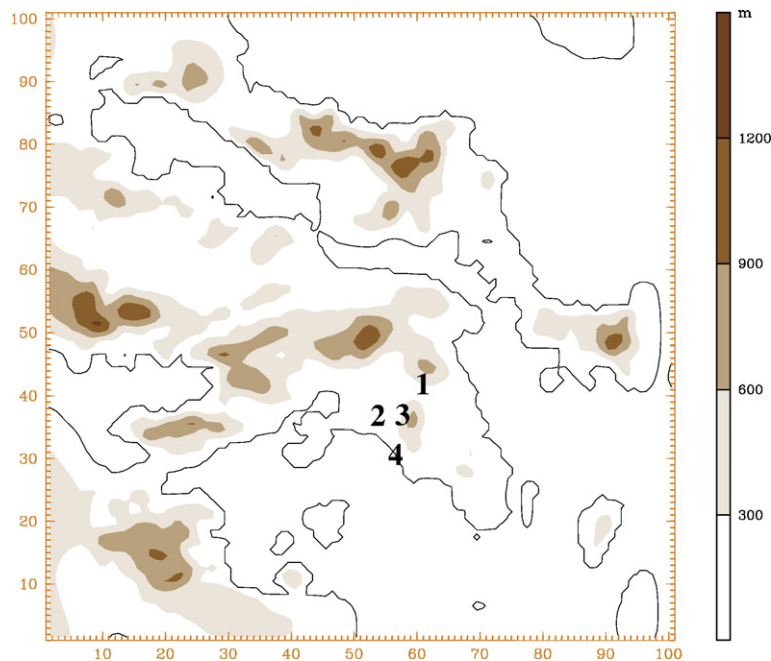


Fig. 1. Extent of Grid 3 domain, with the model topography contoured at 300 m interval. The numbers indicate the location of the surface stations used in the verification (1: Penteli, 2: Thission, 3: Zografou and 4: Hellinikon).

due to interpolation and because of the complex terrain and land water distribution of the Athens area, the model forecasts were extracted from the grid point nearest to each station site. The land use of each model point remains the same from Grid 2 to Grid 3 (urban in Thission, rural in Penteli and Hellinikon) except for Zografou where the land use changes from rural in Grid 2 to urban in Grid 3. The statistical measures have been calculated for Grid 2 (8 km) for all three PBL schemes while for Grid 3 (2 km) the verification was made for ETA and MRF scheme.

3. Verification results

3.1. Temperature

Table 2 presents the verification results for 2-m temperature. Comparison of the statistical results for all schemes for the forecast hours $t+24$ and $t+48$ [both representing forecasts valid at 0000 UTC (+3 h for LT)] show that there is no noticeable increase of the forecast error. This remark probably implies that for the selected warm season, the diurnal errors in the schemes dominate any error growth in the model with forecast time.

Inspection of the MAE of Grid 2 for all forecast times revealed that the MRF scheme produces the best scores with an average MAE that ranges from 1.8 (Penteli) to 3.1 °C (Thission). The BLA produced the second best

scores (that were quite close to those of MRF) while the ETA PBL resulted in the largest errors with an average MAE ranging from 2.3 (Penteli) to 3.6 °C (Hellinikon).

In order to test the statistical significance of the differences between the respective forecasts from the above schemes, a Wilcoxon signed rank test has been applied (Wilks, 2006). The test results (Table 3) indicate that in most of the cases the various forecasts differ between each other significantly in a 95% level of confidence. This remark holds also for the comparisons between the forecasts provided by the same PBL scheme but with a different grid increment, except for Penteli station. Since this station area is characterized by highly complex topography and a high altitude (507 m) it seems that an even higher grid increment is needed in order to obtain a more representative grid point. For the rest of the locations, the increase of the horizontal grid increment from 8 (Grid 2) to 2 km (Grid 3) improves the forecasts

Table 1
Details of each operational chain used in this study

Experiment name	No. of nests	Grid spacing (km)	Grid size (grid points)
MRF	3	24, 8, 2	220 × 140, 151 × 130, 101 × 101
ETA	3	24, 8, 2	220 × 140, 151 × 130, 101 × 101
BLA	2	24, 8	220 × 140, 151 × 130

Table 2

Mean and mean absolute error of the 2-m temperature forecasts (in °C) from $t+24$ to $t+48$, at Penteli, Thission, Zografou and Hellinikon stations

Time	Mean error (°C)					Mean absolute error (°C)					Mean error (°C)					Mean absolute error (°C)				
	bla2	mrf2	mrf3	eta2	eta3	bla2	mrf2	mrf3	eta2	eta3	bla2	mrf2	mrf3	eta2	eta3	bla2	mrf2	mrf3	eta2	eta3
Penteli											Thission									
24	-0.9	-0.8	-0.8	-1.8	-1.5	1.4	1.4	1.4	2.0	1.9	-3.2	-3.0	-1.8	-4.0	-2.9	3.2	3.0	2.1	4.0	2.9
30	-1.1	-0.8	-0.8	-1.9	-1.8	1.7	1.6	1.5	2.1	2.1	-2.3	-1.8	-0.1	-2.2	-1.1	2.6	2.2	1.4	2.4	1.7
36	-0.5	0.0	0.1	-0.8	-0.6	2.6	2.5	2.4	2.8	2.8	-2.8	-2.3	0.2	-0.5	0.0	3.6	3.1	2.1	2.3	2.2
42	-1.0	-0.8	-0.8	-1.8	-1.7	1.9	2.0	1.8	2.4	2.3	-3.9	-3.6	-2.3	-4.4	-3.1	4.0	3.8	2.9	4.5	3.5
48	-1.0	-1.0	-0.9	-1.9	-1.5	1.6	1.6	1.7	2.2	2.0	-3.2	-3.1	-1.7	-4.0	-2.9	3.2	3.1	2.3	4.0	3.1
All	-0.9	-0.7	-0.6	-1.6	-1.4	1.8	1.8	1.8	2.3	2.2	-3.1	-2.8	-1.2	-3.0	-2.0	3.3	3.1	2.1	3.4	2.7
Zografou											Hellinikon									
24	-2.3	-2.1	-0.9	-3.0	-1.7	2.4	2.3	1.7	3.1	2.2	-2.6	-2.3	-1.3	-3.3	-2.4	2.8	2.5	2.0	3.4	2.7
30	-2.9	-2.5	-0.6	-3.6	-1.0	2.9	2.6	1.1	3.6	1.4	-2.3	-1.9	0.0	-3.0	-1.0	2.4	2.1	1.3	3.0	1.5
36	-2.1	-1.6	0.4	-2.4	2.0	3.2	2.8	2.0	3.5	2.5	-3.4	-3.0	-0.4	-3.4	0.0	3.9	3.4	1.9	3.9	1.9
42	-3.3	-3.1	-1.6	-4.1	-2.2	3.5	3.4	2.5	4.2	2.9	-3.9	-3.8	-2.1	-4.5	-3.1	4.0	3.9	2.7	4.6	3.4
48	-2.4	-2.3	-1.0	-3.1	-1.7	2.6	2.5	1.8	3.2	2.2	-2.6	-2.2	-0.9	-3.2	-2.1	2.7	2.4	1.9	3.3	2.5
All	-2.6	-2.3	-0.8	-3.2	-0.9	2.9	2.7	1.8	3.5	2.2	-3.0	-2.6	-1.0	-3.5	-1.7	3.2	2.9	1.9	3.6	2.4

The three different schemes are represented with their initials (bla, mrf, eta) while the number indicates the respective grid (2 or 3). The best result in each category is marked with bold characters.

markedly, in terms of MAE. For example, the total MAE at Thission reduces from 3.1 °C to 2.1 °C when using MRF. The decrease of the forecast errors at 2 km is also observed for ETA, although the errors remain larger than those of the MRF. The decrease of forecast errors with

increased resolution is more important for the three out of the four stations (Thission, Zografou, Hellinikon). This feature can be partly attributed to the fact that for those three stations the model points at 2 km are located at heights that are closer to the real ones than the model

Table 3

Significance of the differences between the various temperature forecasts

Temperature		mrf2					eta2					bla2					mrf3					eta3				
		24	30	36	42	48	24	30	36	42	48	24	30	36	42	48	24	30	36	42	48	24	30	36	42	48
mrf2	Hellinikon						○	○	○	○	○	○	○	○	+	○	○	○	○	○	○	+	○	○	○	+
	Thission						○	○	○	○	○	○	○	○	○	+	○	○	○	○	○	+	○	○	○	○
	Zografou						○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Penteli						○	○	○	○	○	○	○	○	○	+	+	+	+	+	+	○	○	○	○	○
eta2	Hellinikon	○	○	○	○	○						○	○	+	○	○	○	○	○	○	○	○	○	○	○	○
	Thission	○	○	○	○	○						○	+	○	○	○	○	○	○	○	○	○	○	○	○	○
	Zografou	○	○	○	○	○						○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Penteli	○	○	○	○	○						○	○	○	○	○	○	○	○	○	○	○	+	+	+	○
bla2	Hellinikon	○	○	○	+	○	○	○	+	○	○						○	○	○	○	○	○	○	○	○	○
	Thission	○	○	○	○	+	○	+	○	○	○						○	○	○	○	○	○	○	○	○	○
	Zografou	○	○	○	○	○	○	○	○	○	○						○	○	○	○	○	○	○	○	○	○
	Penteli	○	○	○	○	+	○	○	○	○	○						+	○	○	+	+	○	○	+	○	○
mrf3	Hellinikon	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○						○	○	○	○	○
	Thission	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○						○	○	+	○	○
	Zografou	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○						○	○	○	○	○
	Penteli	+	+	+	+	+	○	○	○	○	○	+	○	○	+	+						○	○	○	○	○
eta3	Hellinikon	+	○	○	○	+	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○					
	Thission	+	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	+	○	○					
	Zografou	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○					
	Penteli	○	○	○	○	○	○	+	+	+	○	○	○	+	○	○	○	○	○	○	○					

Symbols (○) indicate a statistically significant and (+) a statistically insignificant difference, in the 95% level of confidence.

Table 4

The actual heights of the stations and the heights of the different grid points of the model

Location	Height (m)			Grid 3– Grid 2 height (m)	Temperature difference (°C)
	Actual	Grid 2	Grid 3		
Penteli	505	256	289	33	−0.3
Thission	107	203	53	−150	1.5
Zografou	219	315	239	−76	0.8
Hellinikon	15	274	138	−136	1.4

The temperature increase due to the modification of the height has been calculated by assuming a dry adiabatic lapse rate.

points at 8 km, as shown in Table 4. In the same table, a rough estimation of the temperature increase due to the modification of the height (by simply using the dry adiabatic lapse rate) showed that an increase of the mean values by 1.0–1.5 °C may be easily obtained. As a result, although the inspection of the ME scores in Table 2 but also of the mean temperature graphs in Fig. 2 reveals that all schemes systematically underestimate the temperature, increase in horizontal resolution results in a clear decrease of the ME. The largest cold bias is evident for the forecast hour $t+42$ (corresponding to 18:00 UTC valid time) showing a model trend for a faster cooling

compared to the observations during the evening and night hours for all PBL schemes. The temperature underestimation is more important at Thission, a typical urbanized area. In this station ETA gives the larger deviation between mean forecasted and observed temperatures during the night and afternoon hours, enhancing significantly the diurnal temperature range, especially for Grid 2 (Fig. 2b). The same behaviour of the ETA scheme is also evident at Zografou and Hellinikon stations (Fig. 2c, d). At this point one should mention that the model points that correspond to Zografou station at Grids 2 and 3 are characterized by a different land use, Grid 3 being urban. Comparison of the behaviour of MRF and ETA schemes reveals that MRF forecasts from Grid 2 to Grid 3 present a homogeneous shift towards warmer temperatures decreasing the ME compared to observations, while the ETA scheme gives a peak during noon hours overestimating the observed temperatures. This feature could be attributed to the way the ETA scheme treats the urban characteristics of the grid point. This behaviour raises the question of investigating alternative parameterisations of the role of the urbanization in the heat balance, as a key factor for an improved temperature representation (Dandou et al., 2005).

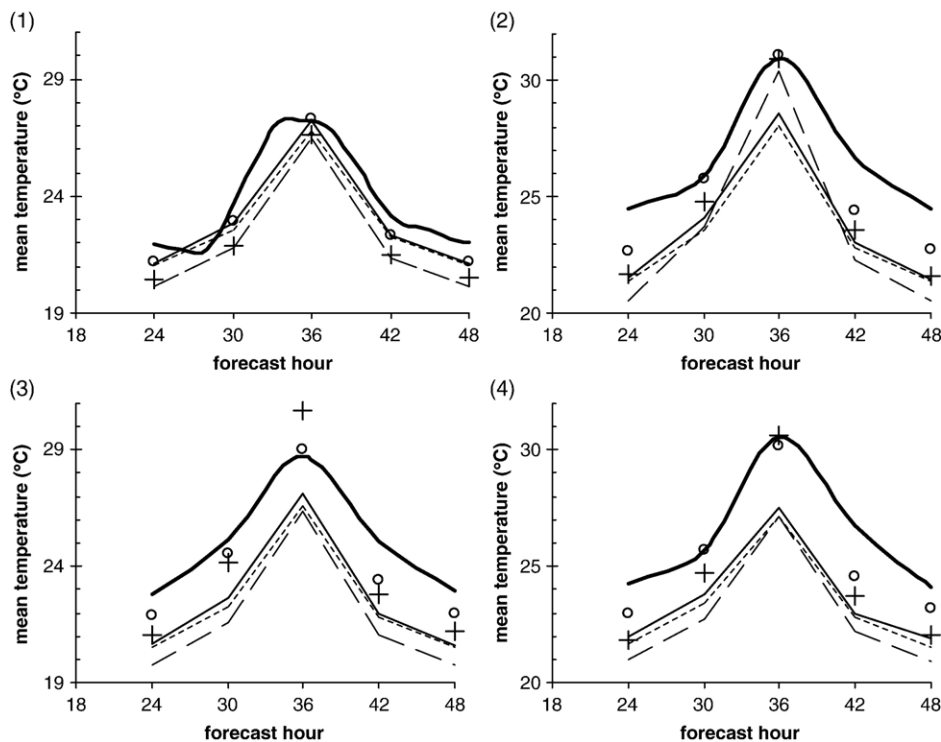


Fig. 2. Comparison of the mean forecast temperatures by MRF2 (—), BLA2 (.....), ETA2 (— · —), MRF3 (○), ETA3 (+), with the respective observed values (——) at the stations of Penteli (1), Thission (2), Zografou (3) and Hellinikon (4). The numbers next to the PBL initials indicate the grid used (Grid 2 at 8 km and Grid 3 at 2 km).

Table 5

As in Table 2, but for the wind speed (in m/s)

Time	Mean error (m/s)					Mean absolute error (m/s)					Mean error (m/s)					Mean absolute error (m/s)				
	bla2	mrf2	mrf3	eta2	eta3	bla2	mrf2	mrf3	eta2	eta3	bla2	mrf2	mrf3	eta2	eta3	bla2	mrf2	mrf3	eta2	eta3
Penteli											Thission									
24	−0.7	0.8	0.7	0.1	−0.2	1.4	1.5	1.7	1.3	1.3	− 0.3	1.3	0.4	0.6	− 0.3	1.1	1.5	1.3	1.0	1.0
30	0.4	0.8	0.7	0.6	0.3	1.6	1.7	1.9	1.6	1.7	0.9	1.3	0.4	1.0	− 0.2	1.4	1.6	1.4	1.5	1.1
36	0.5	0.4	0.4	0.4	0.1	1.9	1.7	1.6	1.7	1.7	−1.1	−1.2	− 0.5	−0.9	− 0.5	1.7	1.7	1.3	1.6	1.2
42	−0.4	0.9	0.9	0.2	0.1	1.5	2.0	2.1	1.7	1.9	−1.8	−0.5	− 0.1	−0.7	−0.7	2.1	1.6	1.4	1.5	1.7
48	−0.8	0.8	0.9	0.1	0.1	1.5	1.7	1.9	1.3	1.6	−0.4	1.3	0.3	0.6	−0.4	1.3	1.7	1.5	1.3	1.1
All	−0.2	0.8	0.7	0.3	0.1	1.6	1.7	1.8	1.5	1.6	−0.6	0.5	0.1	0.1	−0.4	1.5	1.6	1.4	1.4	1.2
Zografou											Hellinikon									
24	0.8	2.3	0.9	1.5	0.3	1.2	2.3	1.2	1.6	1.0	0.1	1.8	1.1	0.9	0.4	1.4	2.1	1.9	1.7	1.6
30	1.7	2.1	0.4	1.7	0.1	1.8	2.2	1.3	1.8	1.0	0.6	1.1	0.3	0.7	− 0.3	1.7	1.8	1.6	1.8	1.6
36	0.7	0.6	0.0	0.9	0.4	1.6	1.4	1.1	1.4	1.2	−0.4	−0.6	−0.3	−0.3	0.0	1.4	1.6	1.3	1.5	1.5
42	0.5	1.7	1.3	1.2	0.7	1.1	2.0	1.7	1.4	1.3	−1.4	0.1	0.0	−0.6	−0.7	2.1	1.9	1.9	1.9	2.0
48	0.5	2.2	0.9	1.4	0.3	1.2	2.2	1.3	1.6	1.1	0.0	2.0	1.2	0.9	0.3	1.6	2.5	2.2	1.9	1.7
All	0.8	1.8	0.7	1.3	0.4	1.4	2.0	1.3	1.6	1.1	−0.2	0.9	0.5	0.3	− 0.1	1.7	2.0	1.8	1.8	1.7

3.2. Wind speed

The statistical results of the analysis for the wind speed are summarized in Table 5. Furthermore the results of the application of the Wilcoxon signed rank test are given in Table 6, indicating that in most of the cases (although to a lesser degree than for temperature, see Table 4) the various forecasts differ between each

other in a 95% level of confidence. The same remark is drawn for the comparisons between the forecasts provided by the same PBL scheme but with a different grid increment, except for Penteli station.

More specifically, a general improvement of the statistical scores of Grid 3 compared to Grid 2 is evident, consistent with the increase of resolution. For example, the total MAE at the station of Zografou decreases from

Table 6

As in Table 3, but for the wind speed forecasts

Wind speed		mrf2					eta2					bla2					mrf3					eta3													
		24	30	36	42	48	24	30	36	42	48	24	30	36	42	48	24	30	36	42	48	24	30	36	42	48									
mrf2	Hellinikon						○	○	+	○	○	○	○	+	○	○	○	○	+	+	○	○	○	○	+	○	○								
	Thission						○	○	+	○	○	○	○	+	○	○	○	○	○	○	○	○	○	○	○	○	○	○	+	○	○				
	Zografou						○	○	○	○	○	○	○	+	○	○	○	○	○	○	○	○	○	○	○	○	○	○	+	○	○				
	Penteli						○	○	+	○	○	○	○	+	○	○	+	+	+	+	+	○	○	○	○	○	○	○	○	○	○				
eta2	Hellinikon	○	○	+	○	○						○	+	+	○	○	+	+	+	○	+	○	○	+	+	○	○								
	Thission	○	○	+	○	○						○	+	+	○	○	+	+	○	○	+	○	○	○	+	○	○	○	+	○	○				
	Zografou	○	○	○	○	○						○	+	+	○	○	○	○	○	+	+	○	○	○	○	○	○	○	○	○	○				
	Penteli	○	○	+	○	○						○	○	+	○	○	○	+	+	○	○	○	+	○	○	○	○	○	+	+	○				
bla2	Hellinikon	○	○	+	○	○	○	+	+	○	○						○	+	+	○	○	○	○	+	○	+	○	+							
	Thission	○	○	+	○	○	○	+	+	○	○						○	+	○	○	○	+	○	○	○	○	+	○	○	○	+				
	Zografou	○	○	+	○	○	○	+	+	○	○						+	○	○	○	○	+	○	○	○	○	+	○	+	○	+				
	Penteli	○	○	+	○	○	○	○	+	○	○						○	+	○	○	○	○	+	○	○	○	○	○	○	○	○				
mrf3	Hellinikon	○	○	+	+	○	+	+	+	○	+	○	+	+	○	○						○	○	+	○	○									
	Thission	○	○	○	○	○	+	+	○	○	+	○	○	○	○	○						○	○	○	○	○				○	○	○	○	○	
	Zografou	○	○	○	○	○	○	○	○	○	+	+	○	○	○	○						○	○	○	○	○				○	○	○	○	○	○
	Penteli	+	+	+	+	+	○	+	+	○	○	○	+	+	○	○						○	○	○	○	○				○	○	○	○	○	○
eta3	Hellinikon	○	○	+	○	○	○	○	+	+	○	○	○	+	○	+	○	○	+	○	○														
	Thission	○	○	○	+	○	○	○	○	+	○	+	○	○	○	+	○	○	+	○	○														
	Zografou	○	○	+	○	○	○	○	○	○	○	+	○	○	○	+	○	○	○	○															
	Penteli	○	○	○	○	○	○	+	○	+	+	○	+	○	○	○	○	○	○	○															

2.0 and 1.6 to 1.3 and 1.1 ms^{-1} for MRF and ETA schemes, respectively. Only in Penteli, the complexity of the topography and the high altitude of the site maybe would necessitate an even higher resolution in order to better resolve the local flow.

In contrast to the temperature forecasts, for wind forecasts the local ETA scheme shows the best performance, with a total MAE ranging from 1.1 (Zografou) to 1.7 ms^{-1} (Hellinikon) for Grid 3. The largest errors for almost all schemes and grids are evident at $t+42$ forecast hour. For Grid 2, BLA produces almost equally accurate forecasts with ETA.

On the other hand, MRF results in the largest MAE and ME, overestimating systematically the wind speed especially during the evening and night hours (Fig. 3). This behaviour is mainly due to the existence of very low measured wind speeds during the examined period. When wind speeds $<1.5 \text{ ms}^{-1}$ are excluded from the comparison this underestimation is reduced significantly (not shown). This remark probably underlines an insufficient treatment of the surface fluxes at the stable nocturnal PBL, as MRF separates the PBL into less stability categories than the BLA scheme. As a result, this characteristic of MRF leads to systematic anomalies, especially during the transition hours of the day, when stable and unstable con-

ditions appear alternatively. Based on this result, it is in the authors future plans to investigate modifications in the stability categorization of MRF.

At this point, it should be mentioned that for the analysis of the wind direction, if the data corresponding to observed wind speed less than 2.5 ms^{-1} are excluded from the calculation (following the common practice) the sample reduces significantly. Nevertheless it should be noted that the resulting sample analysis does not show any improvement from Grid 2 to Grid 3 forecasts (not shown).

4. Final remarks and prospects

In the frame of this work three widely used PBL schemes, as implemented in MM5 model, have been statistically evaluated for their skill to forecast near-surface temperature and wind speed. The evaluated schemes are Blackadar and MRF (nonlocal schemes) and ETA (local scheme). The study area is Athens (Greece) that is characterized by highly complex terrain. The verification has been based on high-resolution forecasts at grid spacing of 8 km (for all three schemes) but also of 2 km (for MRF and ETA schemes) for a 5-month period (June 2002 to October 2002).

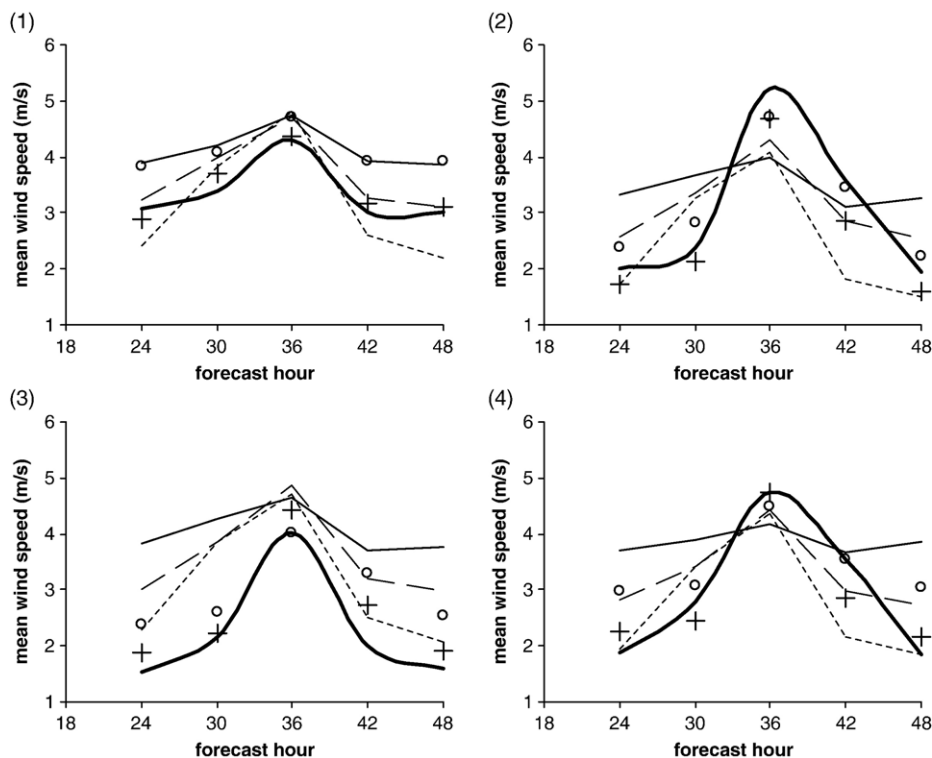


Fig. 3. As in Fig. 2, but for the wind speed.

The analysis showed that the forecasts are improved in general when increasing the horizontal resolution. The improvement is more significant for the temperature field, where increase in resolution results in a decrease of the model cold bias. For near-surface temperature MRF gives the best results with BLA the close second. ETA scheme produces much less accurate forecasts as evaluated in terms of the ME and MAE values.

Evaluation of the wind speed forecasts showed that the ETA scheme at 2-km resolution produced the most accurate results. At 8-km resolution the BLA scheme behaved equally well, while the MRF scheme over-estimated the lowest wind speeds, especially during the night hours producing thus increased errors compared to the other two schemes. The MAEs for the forecasted wind direction do not vary significantly with varying PBL scheme, while the increase in the resolution does not seem to improve the MAEs, although the MEs slightly decrease.

Based on these results, it is in the authors' plans to further investigate the role of the different PBL schemes in the model forecast accuracy. Namely, this study has only examined the behaviour during the warm period of the year. Extension of the analysis during the cold period of the year is necessary. Furthermore, the impact of modifications in the MRF scheme concerning at a first step the stability categorization will be investigated.

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Appendix A. Description of the planetary boundary layer schemes

In the Blackadar scheme (Blackadar, 1979; Zhang and Anthes, 1982), the stable and unstable regimes are treated differently. In the nocturnal regime, a first-order closure approach based on K-theory is used to determine

the turbulent fluxes. In that case, mixing is assumed to occur only between adjacent model layers. In contrast, the free-convective regime employs a nonlocal approach where buoyant plumes from the surface layer mix directly with all other layers within the PBL.

The MRF (Hong and Pan, 1996) is a first-order, nonlocal scheme based on the results of the large-eddy simulations. It is computationally the most economical (Bright and Mullen, 2002). It uses nonlocal K-theory during unstable conditions in which the counter gradient transports of temperature and moisture are added to the local gradient transports. The eddy diffusivities are obtained from a prescribed profile shape. During stable stratification the local K-approach is utilized for all prognostic variables, in a way similar to that used in Blackadar scheme but with a different stability categorization.

Finally, ETA scheme is based on the implementation of Mellor and Jamada (1974) level 2.5 model, in the NCEP ETA model (Janjic, 1994). It is a local, 1.5-order closure scheme with a prognostic equation for turbulent kinetic energy.

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