A comparison of MM5 and meteo mast wind profiles at Cabauw, The Netherlands and Wilhelmshaven, Germany

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ABSTRACT

The model MM5, developed at Pennsylvania State University / NCAR, was used to study wind regimes at Cabauw, The Netherlands and Wilhelmshaven, Germany. The main goal was to model wind profiles in the lower Boundary Layer, and to compare results with measured profiles. For Cabauw, The Netherlands, a study for the period of 2^{nd} - 22^{nd} April 1993 has been conducted with 4 two-way nests up to 1x1km horizontal resolution and 25 vertical levels, of which four below 200 meter. Initialisation was made with 2.5°×2.5° NCAR/NCEP - reanalysis data. The wind profiles were calculated using Blackadar, ETA and MRF PBL numerical schemes of MM5. Additionally for these PBL-schemes time series of wind speed have also been investigated. The time series of measured wind speed were very similar to the MM5 output. The 21 day-averaged vertical wind profiles at the three different PBL-schemes were also similar to the wind profiles calculated from measurements. A second set of simulations of wind regime have been conducted over Wilhelmshaven, Germany for the period 22^{nd}-28^{th} December 2003. Simulated profiles have been compared to wind measurements recorded by a 130 m meteorological mast. The MM5 two way nesting capabilities have been used in order to get a horizontal resolution of 1 km at the final domain, 31 sigma levels are used in the vertical direction. NCEP-FNL analysis provide the simulation with the necessary initial and boundary conditions. The PBL schemes under study have been MRF, Blackader, ETA Mellor-Yamada-Janjic, Burk-Thompson, and Gayno-Seaman PBL schemes. Results show noticeable influence of PBL parameterization on simulated wind profile. The run conducted according to ETA PBL scheme seems to produce a mean wind profile with the best agreement with measured data. A simple sensitivity study reveals that horizontal resolution plays, on these terrain conditions, a minor role with respect to parameterization for the simulation of wind on the lower PBL.

1. Introduction

Wind energy applications traditionally require long term series of wind observations to properly plan and forecast position, features and energy yield associated to a given turbine. For wind energy projects planned on flat terrain, short term (1-2 years) wind measurement are normally used to describe wind speed and direction on the site of interest. If long term observations (10 years or more) are available for a location not so

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distant from the prediction site, short term observations can be correlated with long term data to reduce the influence of inter-annual variations. The implicit assumption underlying the use of correlation methods is that the prediction site and reference site belong to the same micro-climatic area. This condition easily occurs for flat coastal areas where, indeed, nearly the totality of wind installations are based on direct measurement and correlation methods (Gerdes and Strack 1999). The more the features of terrain gain in complexity, the less the information provided by methods based on correlation are reliable. There are many techniques used for wind resource assessment (Landberg et al. 2003). One of those, relevant to obtain information on wind flowing over a complex orography (or where the availability of observations is poor, such as over offshore regions) is represented by the use of numerical models. Presently, different typologies of numerical models have being adopted for wind energy assessment. Most of them have been initially developed for purposes marginally related to wind energy applications. With computational resources presently available, the use of numerical weather prediction (NWP) models is also possible for long term wind simulations. These models, can be applied on a resolution (1-3 km) relevant for wind resource assessment. MM5 is a numerical weather prediction model developed by the Pennsylvania State University and National Center for Atmospheric Research with the ability to simulate the atmospheric conditions with resolution ranging from 100 km to 1 km. Version 3 of MM5 is a non-hydrostatic prognostic model with explicit description of pressure, momentum and temperature. A more complete description of the MM5 model can be found in (Grell et al. 1994). Several studies, e.g (Zhang and Zheng 2004) and (Braun and Tao 2000) investigated the influence of the MM5 PBL parameterization on the simulated wind conditions in the PBL. These studies focuses on the performance of the model with respect either to surface wind speed (through verification against standard 10 m observations) or to deep soundings of the whole PBL. Attention to the output of the model in the lower PBL (which is of main interest in wind energy applications) has been scarce up to now. An attempt to review the formulation of the existing PBL schemes presently implemented in MM5 is given by (ATMET 2003). Their study mainly focus on the capability of each scheme to reproduce the diurnal wind speed cycle using surface observations as reference. No information about the ability of the model to simulate wind in the lower surface layer is provided in this work. The aforementioned considerations motivated us to further investigate the influence of the PBL parameterization on simulated wind profiles with the use of high-accuracy wind observations recorded by two different meteorological masts. Since the relative little knowledge presently available on this topic, it seemed reasonable to perform the verification under simple conditions. For these reasons, simulations are verified against observations taken at sites with flat and relatively homogeneous terrain. Two set of simulations have been carried out. One set of runs is conducted over Cabauw, The Netherlands. The second set of simulation has been performed over Wilhelmshaven in the north-west Germany. Results, in this case, are compared with a 130 m meteorological mast. Next section provides a description of the model configuration used for simulations at Cabauw and outlines the observational dataset used for the verification, Section 3 describes the outcomes from the simulations at Cabauw and presents results of the comparison with observational data. Section 4 and 5 have the same function of Section 2 and 3: in the case model configuration, observational dataset and model results refer to the simulation conducted over Wilhelmshaven. Conclusions and discussion of results are given in the final section.

2. Planetary boundary Layer parameterization in MM5

Several approaches can be used to parameterized boundary layer and subgrid scale (SGS) processes. Schemes used for the parameterization of PBL can be classified, in general, according to the order closure, the local/non local description of the eddy diffusivity, the similarity theory used to derive variables over the surface layer (i.e. the lowest model layer). A good description of the principles underlying PBL parametrization, together with an overview of the most common techniques used to parameterize PBL phenomena in mesoscale models can be found in (Stull 1988) and (Garratt 1992). In MM5, six different parameterization schemes are selectable, plus one “Bulk scheme” in which PBL is treated as a single slab (only suitable for very large resolution simulations and therefore not considered in this analysis). Tab. 1 summarizes the principal properties of PBL schemes implemented in the model.

3. Model configuration and observational data at Cabauw

a. Model configuration

A first set of simulations were performed over the area of Cabauw - The Netherlands, using 5 domains with 4 two-way nests with an horizontal resolution for the last 4^{th} nested domain equal to 1.1 km (see Fig.1). The model was run at 25 levels in the vertical direction with four levels below 200 m (namely at 40, 80, 140 and 200 m). The model top was fixed at 100 hPa. The runs

were made for the period 2 to 22-4-1993 and conducted according the physics reported in Tab. 2.
Simulations have been initialized only once, using 3D analyis fields of temperature, wind speed, pressure, geopotential height, zonal and meridian wind component as initial conditions. The integration was performed for a period of 21 days provided boundary conditions for the outer domain. Both initial and boundary conditions are derived from interpolation of the six-hourly NCEP/NCAR reanalysis (Kalnay et al. 1996) on the model's grid. In order to prevent the solution to drift far away from the analysis, grid nudging is also performed. At each time step the solution for temperature, wind components and mixing ratio are nudged towards the respective values in the analyis. In other words, if S is a scalar variable resolved by the model and $\mathcal{F}(\mathcal{S})$ represents the *physical* forcing terms acting on S, the tendency of S can be written as:

$$\frac{\partial S}{\partial t} = \mathcal{F}(S) + G_S(\hat{S}_0 - S) \qquad (1)$$

where G_S is the *nudging coefficient* for the variable S and $\hat{S}_0$ is the value of S in the analyis.

b. *Observational database*

The Cabauw meteorological mast is located in the middle of The Netherlands near Utrecht and is operated by the Royal Netherlands Meteorological Institute (KNMI). The surroundings are flat and dominated by grassland with some small rivers. The met mast is 200 m high. For each wind speed measurement at 10, 20, 40, 80, 140 and 200 m three booms are installed to minimize the shadow effects by the mast. A closer description of the mast and the surroundings can be found in (Beljaars and Bosfeld 1997). Only wind speed data at 40, 80, 140 and 200 m were used to verify the MM5 run, not considering the lower levels since MM5 was expected to be very inaccurate in this region. The data of the Cabauw mast were plotted in comparison to the model results (3 hourly).

Name	Abrr.	Theory	Diffusivity
Blackader	BLK	K-theory	non-local
Hong-Pan	MRF	K-theory	non-local
Pleim-Chang	P-X	K-theory	non-local
Gayno-Seaman	G-S	TKE	Local
Burk-Thomphson	B-T	TKE	Local
Mellor-Jamada	ETA	TKE	Local
Name	**Similarity**	**PBL height**	**stability**
Blackader	MO	H from T	4 regimes
Hong-Pan	MO	H from Ri_b	4 regimes
Pleim-Chang	MO	H from T	4 regimes
Gayno-Seaman	MO	H from TKE	4 regimes
Burk-Thomphson	Louis	H from TKE	2 regimes
Mellor-Jamada	MO	H from TKE	2 regimes

TABLE 1. PBL schems properties.

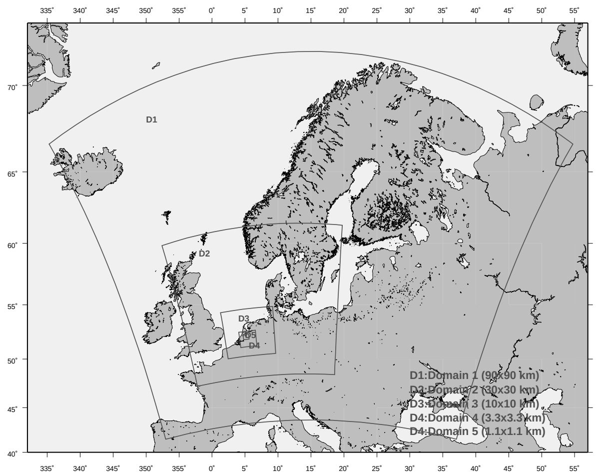

FIG. 1. Representation of areas covered by each simulation domain in Cabauw. The coarse Domain (D1 in the figure) has grid distance equal to 90 km. Domain 2 (D2), Domain 3 (D3), Domain 4 (D4) have grid distance equal to 30 km, 10 km, 3.3 km, 1.1 km respectively.

4. Results at Cabauw

Results of the Cabauw simulation show that wind speed is reasonably described by the MM5 model. The visual investigation of the time series of the simulation in Fig.2 shows a good agreement with the measurements. However, during the simulation time speed ups with an extension lower then 12 hours occurs (2.4., 9.4, 11.4., 21.4.) which are not captured by the simulation. That leads to the explanation that these high wind speed episodes are caused by synoptic weather instead of the local surface boundary conditions. The comparison of the simulations based on different PBL-schemes shows no crucial visual difference if we compare only one height. Observing vertical mean profiles for the whole time period we can investigate a different shape. The simulations based on the MRF and ETA scheme repre-

PHYSICS	SCHEME
Radiation	*Cloud Radiation*
Cumulus	*Grell*
Explicit cumulus	*Dudhia*
Surface scheme	*Five-Layer Soil Model*

TABLE 2. List of the physics option used for the simulations over Cabauw.

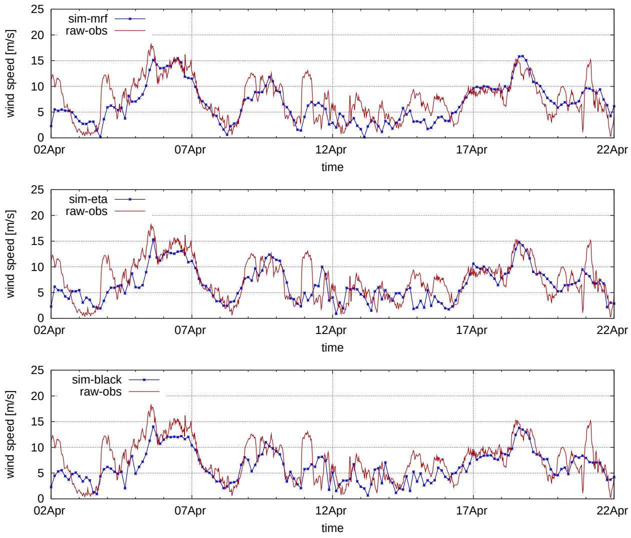

FIG. 2. Time series of the observed and simulated wind speed at 140 m for Cabauw. Figures refer to simulations using MRF (top), ETA (middle) and Blackadar (bottom) PBL schemes.

sents the wind shear quite well, where the BLK scheme underestimates the wind shear up to 80 m significantly.

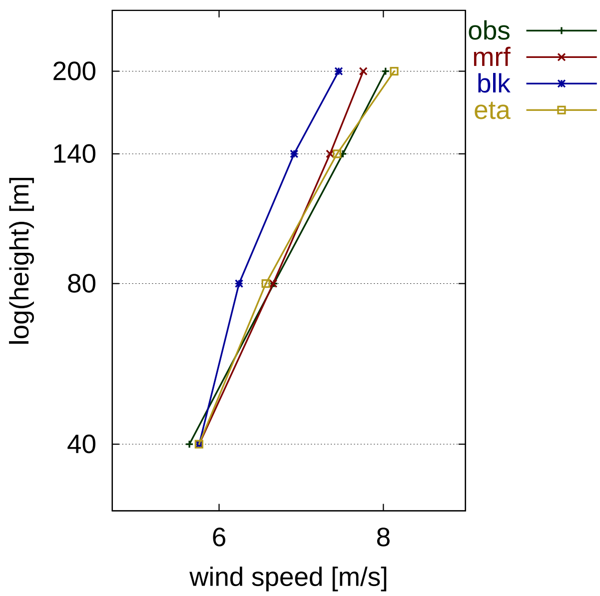

FIG. 3. Mean observed and simulated vertical wind profile at Cabauw.

5. Model configuration and observational data at Wilhelmshaven

a. *Meteorological situation*

The second set of simulations have been performed for the period 22nd-28th December 2003. This period was characterized by a low pressure slowly moving from the Scandinavian Peninsula towards Central Europe. Wind at 850 mb is steadily south-westerly for the whole period, with maximum speeds of 40 m/s. NCEP FNL analysis (NCEP 2006) showed high cloud cover over the region of interest (northern Germany) during the period under concern. This meteorological situation has been favourable to the presence of near-neutral atmospheric stability conditions. A time series of the Bulk Richardson number (Ri_b, not shown) has been calculated on the base temperature, wind speed and pressure measured at the meteorological mast in Wilhlemshaven. Ri_b was greater than 0 and below 0.25 (neutral conditions) for most of the simulated period.

b. *Model configuration*

In order to investigate the influence of parameterization on the simulation of the near-neutral wind profile, five different simulations have been performed using the following PBL schemes: Hong-Pan (MRF), Blackader (BLK), Mellor-Yamada-Janjic (ETA), Burk-Thomphson (B-T), Gayno-Seaman (G-S). The other physics options, which have been kept as fixed as possible for all the simulations, are reported in Tab.3. NCEP FNL (NCEP 2006) analysis with 1° resolution provide the simulation with the initial and boundary conditions. 31 sigma levels are used in the vertical direction with nine layers in the lowest 130 m. The model top is fixed at 10 hPa. The simulation has been performed on four nested domains (as shown in Fig.4) using a two-way interaction between the parent domain and the nested domain. The grid distance over the final domain is 1 km. When possible 4DDA is used to nudge the coarse domain towards the analysis and the NOAH land surface model (Mitchell 2001) is used to provide lower boundary conditions.

	Index	40m	80m	140m	200m
BLK	RMSE (m/s)	1.95	2.31	2.72	2.94
	BIAS (m/s)	0.07	0.47	-0.62	-0.59
ETA	RMSE (m/s)	1.97	2.44	2.97	3.18
	BIAS (m/s)	0.07	-0.14	-0.10	0.09
MRF	RMSE (m/s)	1.94	2.47	2.96	3.10
	BIAS (m/s)	0.07	-0.06	-0.19	-0.29

TABLE 3. Root Mean Squared Error and Bias for the considered PBL schemes for simulation in Cabauw.

c. Observational dataset

The observational data used for the assessment of stability and for the verification of the model are taken at a 130 m meteorological mast equipped with five cup-anemometers (at 32 m, 62 m, 92 m, 126 m, 130 m) and two thermometers (at 2.5 and 90 m). Wind speed measurements are post-processed in order to correct the effect caused by the structure of the tower. Another earlier study (Strack 1999) stressed the influence of the surrounding wind turbines and of the non-homogeneous roughness length on the wind profile and turbulence intensity registered at the anemometers. Furthermore the study identified the south and south-west sectors as relatively undisturbed. These issues should not affect the comparison since the wind was mostly southerly, south-westerly for the almost the complete period of the simulation.

6. Results at Wilhelmshaven

A visual investigation of the time series of the simulated and observed wind speed reveal significant differences between the five simulations according to the used PBL parameterization. Fig.5 shows results for the period from 22^{nd} December to 28^{th} December. From these figures it is possible to detect a phase error that affect three PBL schemes (BLK, G-S, B-T) in predicting the low wind speed episodes that occurred on the 22nd December at 21 UTC. All the mentioned schemes seem to predict the episode about two hours in advance. This error was not present for ETA and only slightly visible for MRF. Observing the complete time series and referring to the statistical indexes reported in Tab.5 , it is possible to state that ETA and BLK better fit the measurements, with MRF presenting the largest (fast) error. The average simulated wind profiles, presented in Fig.6, show a general overestimation with respect to the observed profile. The wind profile simulated by BLK has a good agreement with observation at 62 m but it presents a low wind shear compared with the observed profile. The wind shear seems to be better reproduced by ETA and B-T schemes (that have a very similar formulation) but they are affected by a "fast" bias. In order to get an impression on how resolution affects the accuracy of the simulations, two further runs have been performed with the ETA PBL parameterization at 2 and 3.3km resolution. An analysis of the time series (see Fig. 5.d) and of the relative statistical indices (not shown) revels that, under these conditions, a decrease in resolution from 1 to 3 km do not degrade significantly the score of the verification.

7. Summary

Results presented in the previous sections can be summarized as follows:

1. the PBL parameterization affects significantly simulated wind condition;
2. the influence of parameterization was visible both on the wind speed time series evolution and (even more clearly) on the mean wind gradient;
3. the observed wind evolution presents time variability that seem not be correctly reproduced by the simulation. These errors are probably associated to large synoptic situations which are described with insufficient resolution in the boundary conditions: the fact that those errors occur in larger extent for the simulations performed with $2.5^{\circ}\times2.5^{\circ}$ resolution suggests us that the problem do not relies on MM5 (and its parameterization) but on too temporally and spatially coarse BCs;
4. the analysis of wind profile indicates a general overestimation of wind speed for all PBL schemes with respect to the observation for Wilhelmshaven. For Cabauw an overall underestimation of measured wind profile is visible;
5. the analysis of wind profile indicate that wind shear is properly described by the ETA (B-T presents similar results). BLK scheme show in all the experiments a too low wind shear;
6. changing the resolution from 1 to 3 km produce no significant differences regarding the accuracy of the simulation.

8. Aknowledgemnts

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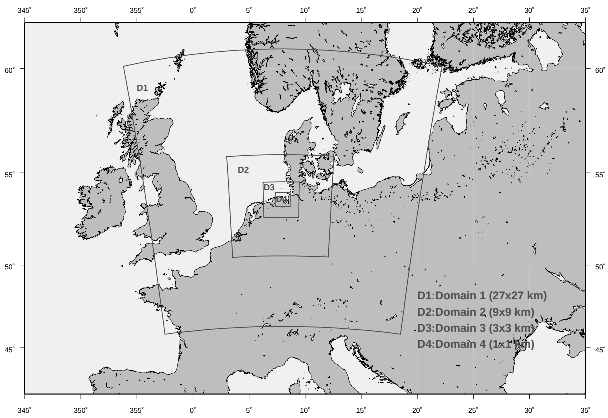

FIG. 4. Representation of areas covered by each simulation domain for the simulation over Wilhelmshaven. The coarse Domain (D1 in the figure) has grid distance equal to 27 km. Domain 2 (D2), Domain 3 (D3), Domain 4 (D4) have grid distance equal to 9 km, 3 km, 1 km respectively.

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PHYSICS	SCHEME
Radiation	*Cloud Radiation*
Cumulus	*Grell*
Explicit cumulus	*Dudhia*
Surface scheme	*Depending on PBL scheme*

TABLE 4. List of the physics option used in for the simulations. The surface model interects directly with the PBL scheme and in some cases the choice of the surface model is forced by the used PBL scheme. When possible the NOAH land surface model is used (e.g. in simulations conducted according the Mellor-Yamada-Janjic (ETA) and Hong-Pan (MRF) PBL scheme).

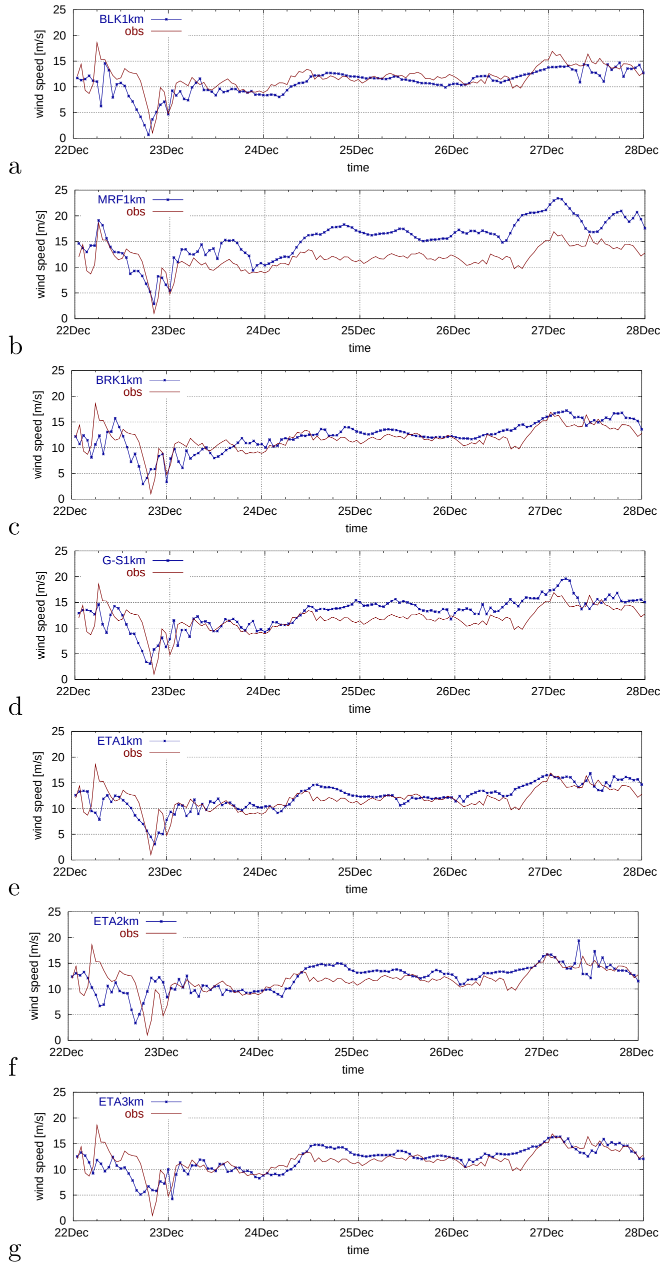

FIG. 5. Time series of the observed and simulated wind speed in Wilhelmshaven. values refer to wind speed at 130 m for the period 00 UTC 22nd December - 00 UTC 28th December. Fig 5.a, 5.b, 5.c, 5.d, present times series for Blackader, MRF, Burk-Thompson and Gayno-Seaman. Fig. 5.e, 5.f and 5.g present results obtained using ETA PBL scheme with gird space of 1km, 2km, 3.3km respectively

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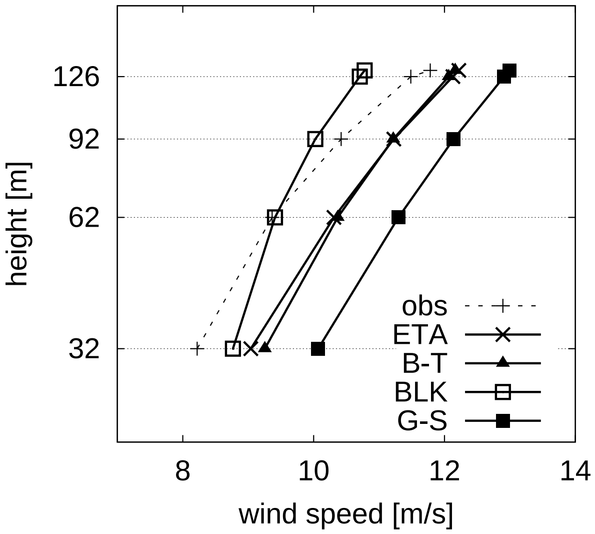

FIG. 6. Mean observed and simulated vertical wind profile at Wilhelmshaven.

	Index	32m	62m	92m	126m	130m
BLK	RMSE (m/s)	1.60	1.74	1.89	2.14	2.18
	BIAS (m/s)	0.55	0.04	-0.39	-0.78	-1.00
B-T	RMSE (m/s)	1.92	2.15	2.20	2.22	2.13
	BIAS (m/s)	1.04	1.00	0.80	-0.58	0.38
ETA	RMSE (m/s)	1.64	1.92	2.02	2.12	2.00
	BIAS (m/s)	0.82	0.94	0.81	0.64	0.44
G-S	RMSE (m/s)	2.46	2.71	2.70	2.71	2.55
	BIAS (m/s)	1.85	1.93	1.72	1.43	1.21
MRF	RMSE (m/s)	3.63	4.69	4.88	4.85	4.62
	BIAS (m/s)	3.22	4.16	4.23	4.01	3.77

TABLE 5. Root Mean Squared Error and Bias for the considered PBL schemes for simulation in Wilhelmshaven.