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Sensitivity of simulated wind speed to spatial resolution over complex terrain

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Abstract

Preliminary results from simulations performed with the Weather Research and Forecasting (WRF) model for the development of a wind atlas of the Trentino region in the Alps are presented. One-year-long model simulations are validated against a dataset composed of quality-controlled data from surface weather stations. In particular, the paper investigates how the accuracy of the simulated wind speed is affected by the model spatial resolution in a region characterized by very complex terrain.

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Keywords: Wind atlas; WRF model; complex terrain; spatial resolution; wind surface observations.

1. Introduction

Wind speed over complex terrain is strongly influenced by mechanical and thermal local effects induced by the topography, which make the wind field strongly variable both in space and time. In particular thermally-driven local circulations, which develop on clear-sky days during the warm season, are distinguishing features of complex-orography regions, and significantly affect the local wind climatology. To this regard, mountain valleys are often characterized by the presence of slope winds, which blow along sidewall slopes (i.e. perpendicular to the valley axis), and valley winds, flowing along the valley longitudinal direction. Slope winds are generated by the buoyancy

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forces which arise from the heating/cooling of the air close to the valley slopes; they generally blow up-slope (anabatic winds) during daytime and down-slope (katabatic winds) during nighttime [1,2]. Valley winds, which typically blow up-valley during the day and down-valley at night, are generated by the horizontal pressure gradients induced by the temperature differences between different cross-sections of the valley, or between the valley and the adjacent plain [3,4]. Due to the above-mentioned processes, the simulation of the wind field over complex terrain with numerical meteorological models is still not an easy task, which requires adequately fine spatial resolutions to be reached in order to properly capture the spatial variability of the wind field.

In the present paper results from one-year-long (year 2009) numerical simulations with the Weather Research and Forecasting (WRF) model [5] over the Trentino region, in the Italian Alps (Fig. 1), are validated against a dataset from ground-based weather stations, to investigate the influence of the spatial resolution of the simulations on the accuracy of the simulated wind velocity. In particular, results from simulations with a resolution of 6, 2 and 1.2 km are evaluated. This study represents the initial stage of a broader project aiming at developing a wind atlas for Trentino, which will be based on the results of ten-year-long WRF simulations. This project is challenging, due to the complex orography of the region, where thermally-driven circulations develop in the warm season, also in connection with the presence of many lakes, and in particular Lake Garda [6,7].

The paper is organized as follows: the dataset from the surface weather stations used for the model validation is presented in Section 2, along with some brief notes on data-quality assurance and on the model set-up, while Section 3 is devoted to the comparison between model results and observations. Finally, some conclusions are drawn in Section 4, together with an outlook on future work.

2. Experimental dataset and model set-up

2.1. Experimental dataset

A dataset composed of wind speed (WS) observations from surface weather stations was used to validate model results. The weather stations belong to two networks permanently operated by public local bodies: the local weather office (Meteotrentino) and the Edmund Mach Foundation. As can be seen in Fig. 1, the weather stations are quite homogeneously distributed over Trentino and cover different altitudes, ranging from 80 m a.s.l. to 1000 m a.s.l. All measurements are hourly averages taken at 10 m above ground level. Data were quality-controlled following the procedures reported in Jiménez et al. (2010) [8] and Chávez-Arroyo and Probst (2013) [9]. In particular, the following tests were applied:

- plausible value check: $0 \leq WS \leq 30$ m s^{-1};
- repetition of consecutive equal records of WS: in calm conditions ($WS \leq 0.5$ m s^{-1}) data were manually checked when more than 12 consecutive equal records occurred, while data were automatically discarded when more than 24 consecutive equal records occurred; in non-calm conditions ($WS > 0.5$ m s^{-1}) data were discarded when more than 5 equal records occurred. The division between calm and non-calm conditions is necessary because in calm situations periods with constant WS are much more frequent;
- step test: data were discarded when WS difference between two consecutive records was greater than 10 m s^{-1};
- control of the frequency of calms, to identify suspicious periods with long calm conditions;
- control of the moving average and variance of WS, to identify systematic errors.

The thresholds used in the tests aiming at detecting questionable consecutive equal records were identified by analyzing the frequency of occurrence for different numbers of consecutive repetitions. Similarly, the threshold for the step test was inferred from the frequency distribution of the absolute difference between consecutive records.

2.2. Model set-up

The horizontal domain used for the simulations is composed of four one-way nested domains (Fig. 1). The three outer domains have a grid spacing of 54, 18, and 6 km, while simulations in the inner domain are performed with two different resolutions: 2 and 1.2 km. However, the spatial extension of the inner domain is identical for both the resolutions tested. As to the vertical resolution, 28 levels are used. Initial and boundary conditions are supplied by the 6-hourly National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis data on 1-degree grids. The simulations are initialized at 0000 UTC of the last day of each month and finish at the end of the following month; the first day, spuriously affected by the initialization, is not considered for the analysis. More frequent initializations were also tested, but results did not differ significantly. The model output is written every 15 minutes. As to the physical settings of the model runs, the Noah [10], and the Yonsei State University [11] schemes are used for land surface and planetary boundary layer parameterizations respectively. The microphysics scheme adopted is the WRF single-moment 3-class simple ice scheme [12]; the Kain-Fritsch cumulus scheme [13] is used in the three outer domains, while no cumulus parameterization is adopted in the inner domains, in order to avoid artifacts and unrealistic patterns in the reconstruction of precipitation. The Rapid Radiative Transfer Model [14] is used for the long-wave radiation, and the Dudhia scheme [15] for the short-wave radiation, including the effects associated with slope inclination and topographic shading. Moreover, the correction for wind speed over complex terrain proposed by Jiménez and Dudhia (2012) [16], which parameterizes the effects of unresolved topographic features, is adopted. For the topography, a dataset with an original spatial resolution of 1" (~ 30 m), obtained from the Viewfinder Panoramas website (http://www.viewfinderpanoramas.org), is used, while the land use is provided by the Corine Land Cover 2006 dataset (http://www.eea.europa.eu), characterized by a 100-m spatial resolution. Corine originally contains 44 classes of different land use categories, that were reclassified into the 20 Modis classes (+3 special classes for urban land use), in order to fit the WRF look-up tables [17,18].

3. Results

As introduced above, model results from the domains of 6, 2 and 1.2 km of resolution were validated against WS observations from different surface weather stations. In particular, in the following analyses the hourly averaged observations are compared to the corresponding values simulated by the model, obtained as the average of the four outputs written every 15 minutes for each hour.

Table 1 shows the Mean Errors (MEs) and the Mean Absolute Errors (MAEs) between model results and observations. MAEs are generally rather small for all the simulations, of the order of 1 m s^{-1}, and MEs are lower than 1 m s^{-1}. In most cases there is a slight improvement of the model performance as resolution becomes finer, but this behavior is not systematic. In fact, it can be noted that at some weather stations the lowest MAEs are found for the 6-km simulation.

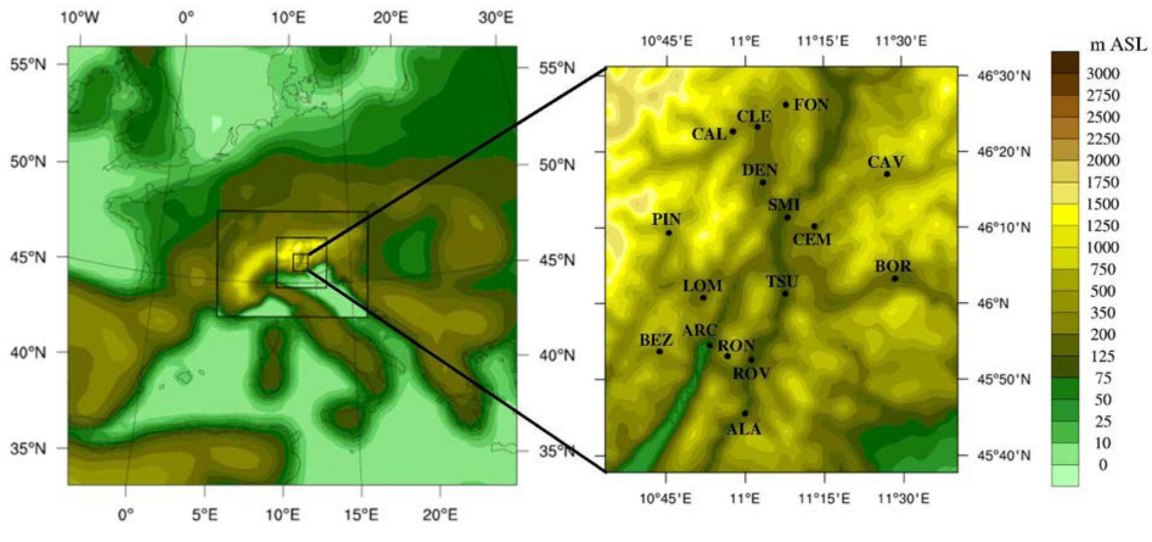

Fig. 1. The four domains used for the simulations. The right panel shows the inner domain (in the simulation with a resolution of 1.2 km), along with the locations of the stations used for the validation of model results.

Table 1. ME ($m\ s^{-1}$) and MAE ($m\ s^{-1}$) of hourly WS between model results and observations for the different spatial resolutions of the simulation domains. See Fig. 1 for station names.

Station	6 km		2 km		1.2 km	
	ME	MAE	ME	MAE	ME	MAE
ALA	0.42	1.46	-0.31	1.40	-0.56	1.36
ARC	-0.59	1.08	0.03	1.13	-0.13	1.12
BEZ	0.64	1.15	0.11	0.81	-0.04	0.82
BOR	1.80	2.15	0.78	1.14	0.69	1.13
CAL	0.54	1.39	-0.35	0.92	0.20	1.18
CAV	2.06	2.35	0.34	1.06	0.15	1.01
CEM	0.32	1.10	0.52	1.17	1.08	1.56
CLE	0.68	1.12	0.60	1.02	0.37	0.92
DEN	0.87	1.19	0.47	0.95	0.20	0.78
FON	-0.09	1.52	-0.51	1.38	-0.05	1.31
LOM	0.43	1.25	0.74	1.34	0.69	1.23
PIN	2.08	2.30	0.15	0.84	-0.27	0.80
RON	-0.56	0.93	0.28	1.13	0.34	1.10
ROV	-0.05	1.07	-0.21	1.07	-0.10	1.11
SMI	-0.62	1.28	-0.14	1.31	0.27	1.38
TSU	-0.40	1.10	0.15	1.26	0.56	1.43

An important information which will be provided with the wind atlas is the modelled WS probability density function (PDF). For this reason it is useful to evaluate how the model reproduces the observed PDFs. Here the results from some selected weather stations are reported (Figs. 2–5), which are representative of the different behaviors found. Results are shown for the whole year, the summer season (June, July and August) and the winter season (December, January and February), in order to evaluate the model performance in different situations. In fact, during wintertime WS variability is mostly connected to synoptic events, while during summertime thermally-driven circulations significantly mark the local wind climatology. From Figs. 2–5 it can be seen than in wintertime PDFs are characterized by a very high occurrence of low wind velocities, while in summertime stronger winds are more likely to occur. In particular, at SMI, a station located on the floor of the wide Adige Valley (Fig. 1), the observed PDF displays a secondary peak around 4-5 ms^{-1} (Fig. 5), which corresponds to the typical velocity of the up-valley wind developing in the afternoon of summer sunny days in most of the major valleys of Trentino.

The performance of the model associated with the three resolutions tested varies at the different weather stations. However some common features can be distinguished. First, a significant improvement of the model performance is found at almost all the weather stations going from the 6-km to the 2-km simulation. In fact, in most cases the 6-km simulation does not capture correctly the observed PDFs, while a better agreement is found for the 2-km simulation. On the other hand, a similar improvement occurs only for 10 out of the 16 weather stations analyzed when going from the 2-km to the 1.2-km simulations. To this regard, 4 different behaviors can be recognized. At some weather stations there is a continuous improvement in the model performance as the resolution becomes finer, and the PDF from the 1.2-km simulation is in good agreement with the observed PDF. This is the case, for example, of ROV weather station, whose modelled and observed PDFs are reported in Fig. 2. At other stations there is continuous improvement in the model performance with finer resolutions, but the PDF from the 1.2-km simulation is still not in complete agreement with the observations (e.g. BOR weather station; see Fig. 3). This is the case of the weather stations with very high occurrence of low WSs, especially in the winter period. For these stations the model progressively gets closer to observations, but still at 1.2 km fails to capture the PDF peak at low wind velocities.

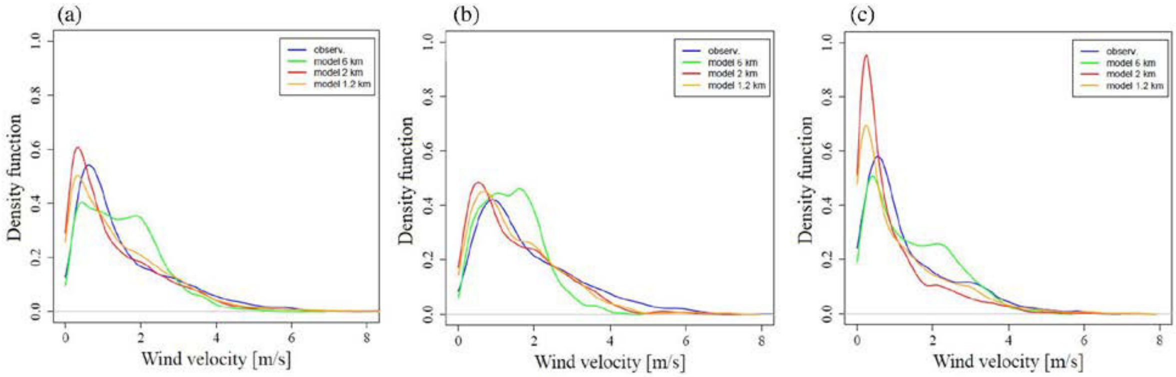

Fig. 2. PDFs of observed and simulated wind speed at different spatial resolutions (see the legend), for ROV weather station for (a) the whole year (b) summer and (c) winter.

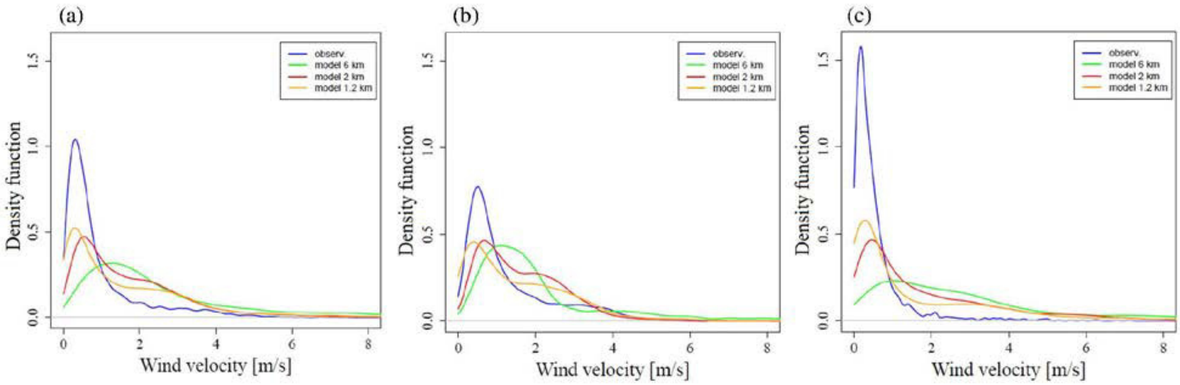

Fig. 3. As in Fig. 2, but for BOR weather station.

The third group of weather stations represents situations in which the model performance remains rather similar for the 2-km and the 1.2-km simulations. This is the case, for example, of ARC weather station, whose observed and simulated PDFs are reported in Fig. 4. At this station the agreement between model results and observations is rather good for both the 2-km and the 1.2-km simulations. Finally, at two weather stations (SMI and TSU), both located in the northern part of the Adige Valley, the model performance worsens significantly for the 1.2-km simulation compared with the 2-km simulation, where the agreement between modelled and observed PDFs was good (Fig. 5 refers to SMI). A closer comparison between model results and observations highlighted that this is due, especially in the warm season, to the fact that in the 1.2-km simulation the model sees a too long persistence of a rather stronger up-valley wind in the late evening and a later development of the weaker down-valley wind [16]. As a consequence, the PDF peak at low wind speeds is not well captured.

4. Conclusions and outlook on future work

Preliminary results from simulations with the WRF model performed for the development of a wind atlas for the Trentino region, in the Italian Alps, were validated against a dataset from local surface weather stations. In particular, different model resolutions were tested, to evaluate how the model performance depends on the grid size in a region characterized by a very complex orography, where the correct simulation of WS is still a challenging task.

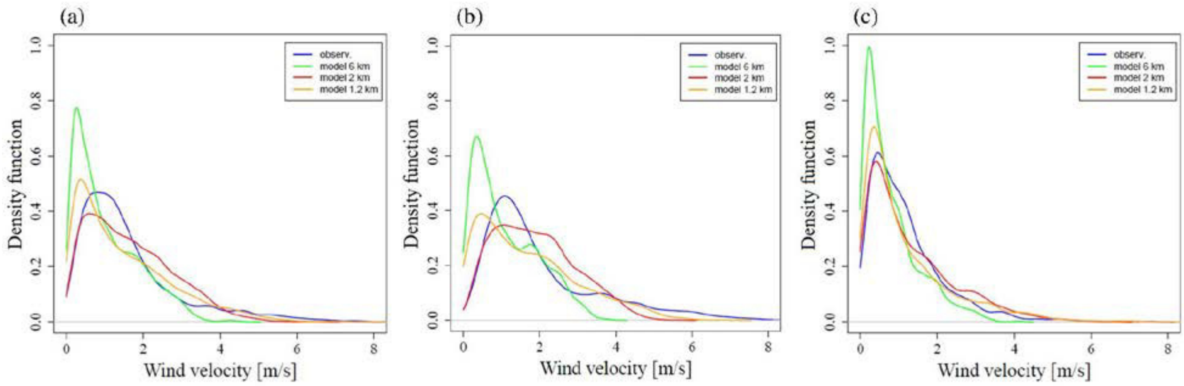

Fig. 4. As in Fig. 2, but for ARC weather station.

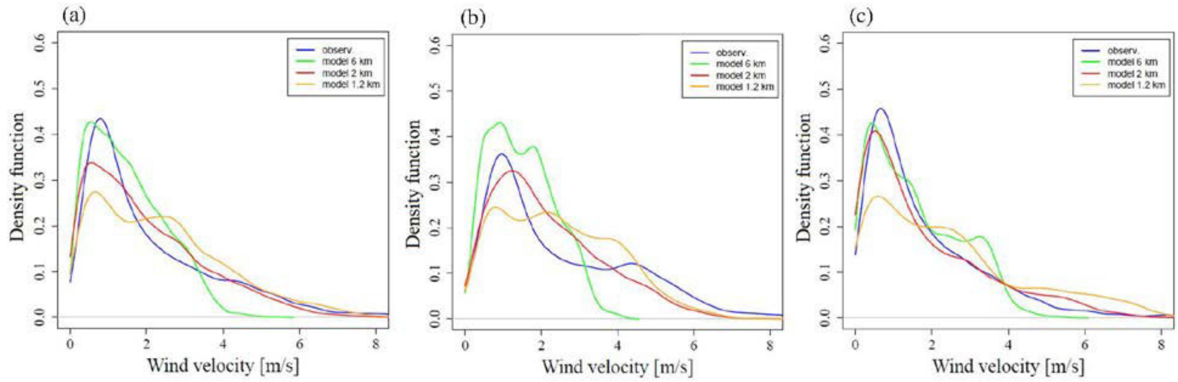

Fig. 5. As in Fig. 2, but for SMI weather station.

It was found that MAEs between model results and observations are generally rather small, of the order of 1 m s^{-1} for all the resolutions tested, but, differently from what expected, a clear improvement in the model performance as the resolutions become finer was not found. A useful insight was gained from the comparison between the observed and the modelled PDFs. A significant improvement in the agreement between model results and observations was observed for almost all the weather stations moving from the 6-km to the 2-km simulations. In particular, it was highlighted that the 6-km simulations are not adequate for the development of the wind atlas, as PDFs are badly reproduced for most of the weather stations analyzed. On the other hand, different behaviors were found comparing the 2-km and the 1.2-km simulations, as a model performance improvement was observed only for slightly more than half of the weather stations analyzed. In particular, for two weather stations, located in a similar geographic context, on the floor of the major valley of Trentino, the model performance gets significantly worse in the 1.2-km simulation, especially due to an overestimation of the duration of the up-valley wind in the evening. However, in most cases the results from the 1.2-km resolution simulation displays a reasonably good agreement with observations, and outperforms the 2-km simulation. Accordingly, the 1.2-km resolution set-up will be used for the development of the Trentino wind atlas. It is likely that results would be in better agreement with observations at increasingly finer resolutions: in a previous work [17] it was shown that the WRF model, with a resolution of 500 m, was able to capture with good accuracy the wind reversal from up-valley to down-valley in the Adige Valley, including SMI and TSU weather stations. However, it appears not feasible to perform 10-year-long simulations with such a fine resolution, due to the high computational cost of the runs. Therefore, to overcome the observed weaknesses of the model, especially in capturing the high occurrence of low wind speeds at some weather stations (cf. Fig. 4), the simulations will take advantage of four dimensional data assimilation (FDDA) of both quality-checked surface observations and radiosoundings, to better capture both local processes and synoptic events. Radiosoundings data will be assimilated in the three outer domains, while wind observations from surface weather stations will be assimilated in the inner domain.

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