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Article · January 2013

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Wind Characterization at the Alaiz-Las Balsas experimental wind farm using high-resolution simulations with mesoscale models. Development of a "low cost" methodology that address promoters needs.

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April 2013, Spain

Abstract

With the goal of performing high-resolution wind resource assessment in regions characterized by highly complex terrain, the CENER experimental wind farm, located at Alaiz-Las Balsas (EWF), is simulated using a methodology based on a modeling chain with state-of-the-art mesoscale models. This methodology is validated through observations obtained from the 120m tall met masts located at the EWF site. The evaluation focuses on the performance of the simulations to reproduce the vertical wind variability observed in the measurements from the meteorological towers. In order to optimally set-up the models, a sensitivity analysis of the seven Weather Research and Forecasting system (WRF) Planetary Boundary Layer (PBL) schemes, using the Advanced Research WRF (WRF-ARW) core and the Non-Hydrostatic WRF (WRF-NMM) core is performed. The outputs from the SKIRON model simulation are used as input to the best WRF model configuration and an entire year, at the site's location is simulated and the results thoroughly analyzed. The results indicate that even though the SKIRON model is able to capture the essential wind characteristics, the new methodology is able to further improve the performance by introducing better resolved local effects that occur at the EWF site. The dependency of model performance versus the orography and land cover databases is discussed, along with a study of model performance taking into account the stability measured at the site.

Keywords: High-resolution, complex terrain, mesoscale, model-chain, Alaiz-Las Balsas experimental wind farm.

1. Introduction

Mesoscale models are typically used to obtain a preliminary coarse wind map in order to identify suitable areas for wind energy deployment. Long term mesoscale model simulations provide very useful information to locate such regions and help planning measurement campaigns for wind energy deployment.

Although the accuracy of mesoscale models is usually enough to simulate and characterize the wind flow forced by large-scale phenomena (temporal and spatial), up to horizontal resolutions near the 3-5 kilometers, there's still a large uncertainty in the prediction of meteorological phenomena that occur at smaller scales. These phenomena are often driven by local sub-grid topography such as, local circulations, valley winds, breezes or inversions affecting near-surface atmospheric stability. Due to the inherent difficulty of performing wind resource assessment over highly complex terrain this paper explores the possibility of using a mesoscale model-chain methodology to extract the relevant meteorological information for wind resource characterization.

Within the wind energy community it is a common practice to use a wide variety of models, from the mesoscale to the microscale range in order to obtain the best possible wind characterization at any given region or site. In this paper, a methodology (mesoscale model chain) based on dynamical downscaling from the global scale (GFS) to the local scale (500m) by nesting WRF model into SKIRON is presented.

The goal of this study is to develop a methodology that can be applied in areas with highly complex terrain. For this purpose, the EWF site, provides an unique opportunity to validate state of the art models and methodologies. The site offers the possibility to conduct an exhaustive validation, taking into account wind shear, stability, vertical profiles of wind and temperatures, etc., since it has 6 IEC-calibrated positions to install prototypes of machines of up to 5 MW each, and 5 additional meteorological tall towers, 120 meters high.

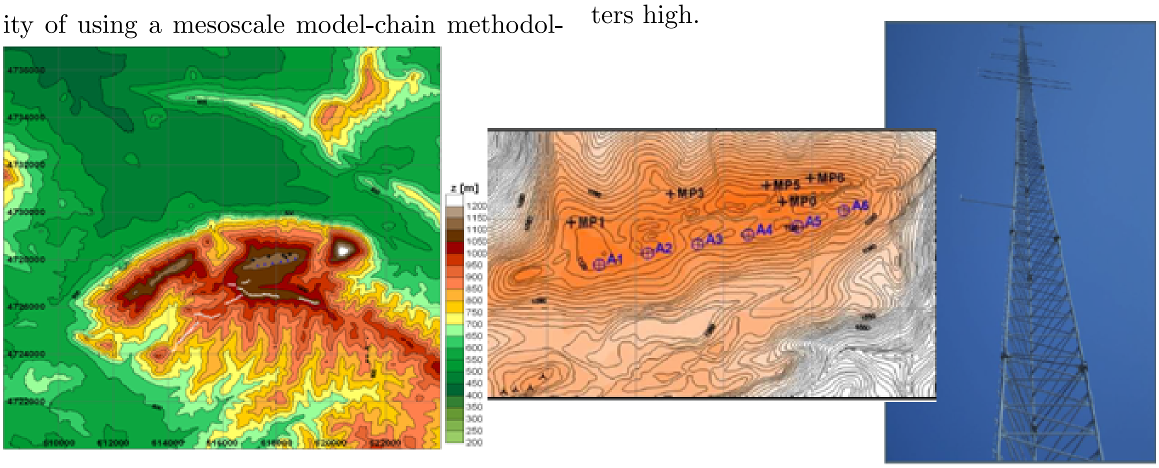

Figure 1: Alaiz Topography EWF (left), location of meteorological towers (center) and MC4 met mast (right).

2. Methodolgy

State-of-the-art operational mesoscale models have limitations when trying to simulate regions with very steep mountains and localized weather patterns since they can only resolve the atmosphere physics up to scales in the order of a few kilometers. In the case of SKIRON, an horizontal resolution of 0.05° (5km) provides the overall best performance [3]. Increasing the resolution beyond this value results in incompatibilities with the physical parameterizations of the model. In order to meet the needs of wind energy developers in complex terrain it is necessary

to further downscale the simulations to sub-km range.
To this end, a study of all the WRF-ARW (version 3.3) PBL parameterizations [1], and the WRF-NMM version [2] is conducted at the EWF. The model configuration that produced the best results is compared with the wind mapping methodology based on SKIRON at 5km[3]. Due to computational limitations it is impossible to generate a long-term simulation for each possible configuration, so a smaller period is chosen. Based on the measured wind rose, it is possible to see that the two predominant wind sectors at the EWF are North and South (Figure 7). Two weeks are simulated, the first one had persistent Northerly winds (15 March 2010 to 23 March 2010) while the second one had persistent Southerly winds (13 of May 2010 to 21 May 2010). The preliminary results show that neither of the model configurations are able to improve the results obtained with the SKIRON model, so, an alternative methodology is developed, by trying to take advantage of SKIRON capacity to produce very good results in wind forecast/assessment and the capacity of the WRF model to process a wide range of extra information that can be added by the user. An entire year is simulated in order to reflect the yearly climatology, using SKIRON's outputs as initial conditions to the WRF-NMM model and the results validated at several heights.

2.1. Observational data

It is very difficult to find suitable measurements that can be applied to the validation of wind resource assessment in complex terrain. Usually validation is limited to surface meteorological stations that can only provide 10m height wind. CENER's experimental wind farm offers an unique opportunity to validate wind resource assessment methodologies in highly complex terrain, due to its high quality measurements at several heights.
The EWF site is located at the North-East of Spain, in the region of Navarre. The terrain in this area is characterized by its high complexity, where the presence of mountains with very steep slopes is very common (Figure 1).The experimental wind farm consists of one hill of two kilometers long arranged WNW-ESE, with an average elevation of 1100m above sea level (a.s.l.). The "Alaiz" wind farm, operated by ACCIONA and composed of 50 wind turbines is located 1.5 kilometers southwards. The site is surrounded by a forest area, merged with areas of scrub and woodland. The area of the site at the top of the hills is considered as clear, with a roughness length of 0.03m. At the EWF site there are 5 met masts. The reference mast in this study, MP5, has a height of 118 meters and includes cup anemometers at (40, 78, 90, 102 and 118) m, wind vanes at (78, 90, 102 and 118) m temperature measurements at (81, 97 and 113) m and vertical propellers at (78 and 118) m (Figure 1). The mast also has a pressure sensor and one rain sensor. All the anemometers are calibrated following MEASNET (Measuring Network of Wind Energy Institutes) procedures and have ENAC accreditation according to the UNE-EN ISO/IEC 17025. The met mast database is synchronized using 10 minutes averages.
The MP5 reference mast has an annual data availability of 83% with most of the data loss during the winter season. The 40 m height wind won't be used due to the low percentage of available data.

2.2. Input Data

The same input data is used to initialize every simulation in order to obtain the same initial conditions in all possible configurations. All mesoscale models use the GFS 12UTC data, with a horizontal resolution of 1°x1° degrees and 3 hours frequency, as forcing conditions. The topography and land cover used in all the domains, except in the innermost domain of the model chain approach, are obtained from the GTOPO30 database of the U.S. Geological Survey (USGS). The resolutions of the databases used in each domain are described in the Table 1. For the innermost domain, in the model chain approach, a higher resolution topographic dataset is used, the SRTM 90m [4], generated by NASA and the Corine Land Use, 2006 [5]. The improved topographic and land cover database that are used in the smaller domain are useful to better represent the real conditions of the site [6].

Model	Domain			
	1	2	3	4
ARW	10min	5min	2min	30s
NMM	10min	5min	2min	30s
Mod.Chain	30sec	30sec	SRTM90m	
	30sec	30sec	Corine	

Table 1: Topographic and Land Cover resolution used in the several domains.

Figure 2 and Figure 3 show significant differences between the two topographies and land uses, which can contribute to substantial differences in the final results.

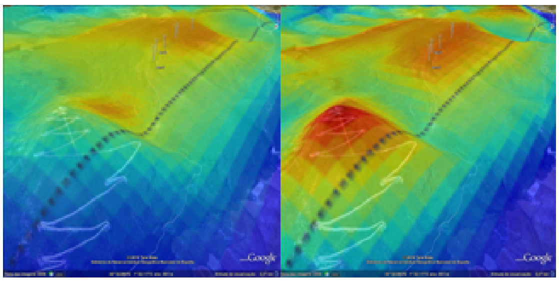

Figure 2: Differences between the GTOPO30s (left) and SRTM90m (right)

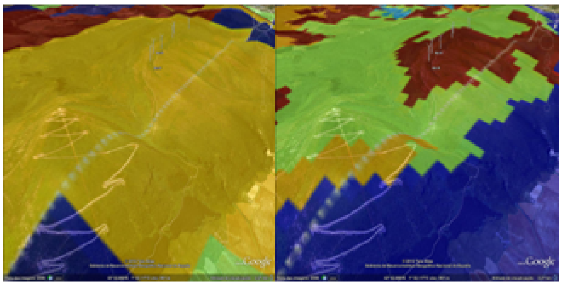

Figure 3: Differences between the USGS 30sec (left) land cover and the Corine Land Cover (2006) at 30 sec (right).

In order for the WRF preprocess correctly interpret the Corine Land Cover, it is necessary to convert the 44 original soil classifications to the standard 24 USGS equivalent [7].

2.3. WRF Model Configuration

Both WRF-ARW and NMM model versions are tested using the same domain configurations. The following physical parameterizations are used in the ARW version: Kain-Fritsch cumulus parameterization, WRF Single-Moment 3-class scheme, Unified Noah LSM land surface scheme, Rapid Radiative Transfer Model and Dudhia shortwave radiation parameterization. All the PBL parameterizations available in the WRF-ARW 3.3 version are tested: ACM2 (Asymmetric convective model [8]), MRF (Medium Range Forecast Model[9]), MYJ (Mellor-Yamada-Janjic[10]), MYNN2 (Mellor-Yamada Nakanishi and Niino level 2.5[11]), MYNN3 (Mellor-Yamada Nakanishi and Niino level 3 [12]), YSU (Yonsei University Scheme [13]) and QNSE (Quasi-Normal Scale Elimination [14]).

PBL Scheme	Surface Layer
ACM2	Monin-Obukhov
MRF	Monin-Obukhov
MYJ	Eta Similarity
MYNN2	Monin-Obukhov
MYNN3	MYNN
QNSE	Monin-Obukhov
YSU	Monin-Obukhov

Table 2: PBL parameterizations tested at the EWF

The WRF-NMM version is executed using the recommended physical parameterizations [15]. The domains are centered at the experimental wind farm and the resolutions go from 20km x 20km in the outermost domain to 740m x 740m in the innermost domain. All domains have 50 vertical levels from the surface until the top of the atmosphere (50 hPa).

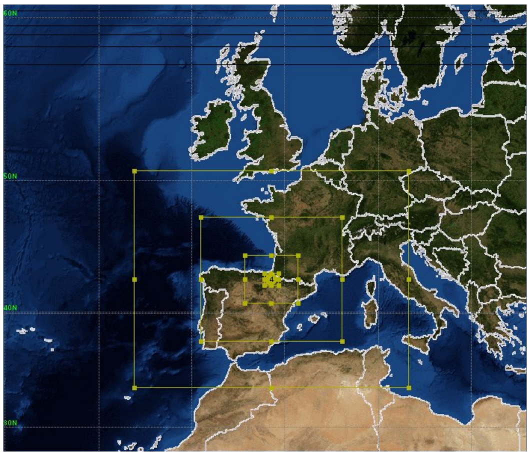

Figure 4: Domain Configuration at the EWF to both WRF model versions

2.4. SKIRON Model Configuration

CENER uses the SKIRON model to perform long term simulations. The regional weather forecasting system SKIRON was developed for operational use at the Hellenic National Meteorological Service.

Figure 5: SKIRON domain (0.05°x0.05° horizontal resolution)

The physics options used are the Betts-Miller-Janjic convection scheme, Ferrier microphysics scheme, Lacis and Hansen shortwave radiation scheme, Fels and Schwarzkopf long wave radiation scheme, Noah land surface scheme with 12 types of vegetation, 7 types of soil texture and 4 soil layers, Mellor-Yamada 2.5 turbulence scheme and PBL, with Monin-Obukhov similarity theory in the surface layer and Paulson stability functions [16].

The SKIRON model domain (Figure 5) is configured with a horizontal resolution of 0.05°x0.05° degrees and 50 vertical levels generating outputs every hour [17].

2.5. Mesoscale model chain

Two, two-way nested domains with 1.67kmx1.67km in the outermost domain and 550mx550m in the innermost domain and 50 vertical levels are configured in WRF-NMM by using simultaneously the high resolution topography (SRTM90m) and a recent land cover database (CorineLandUse90m) in the higher resolution domain. A coarse domain (0.05°x0.05° and 50 vertical levels) is simulated with SKIRON and the outputs from that simulation are used as initial conditions, with an hourly frequency, to the WRF domains in a one-way nesting approach, replacing the GFS data used before.

Figure 6: SKIRON/WRF-NMM model configuration

	Var.	ACM2	MYJ	YSU	MYNN2	QNSE	MRF	NMM	SKIRON
BIAS	Vel78	45,52	43,88	42,42	49,57	51,08	49,00	40,49	6,37
	Vel118	42,02	38,75	40,71	45,54	44,74	44,75	32,39	7,67
	T81	-27,53	-26,60	-29,93	-28,98	-24,32	-30,09	-21,19	
MAE	Vel78	49,44	47,59	44,97	51,86	54,09	51,57	45,42	17,25
	Vel118	45,29	42,95	43,00	47,27	48,03	47,01	37,33	15,94
	T81	29,24	28,59	31,51	30,61	26,32	31,44	25,90	
RMSE	Vel78	59,94	58,18	53,29	62,14	65,85	62,14	52,94	20,74
	Vel118	55,24	52,86	51,02	56,99	58,82	56,71	44,87	19,12
	T81	32,98	32,23	34,56	33,99	30,11	34,54	30,61	
$\mathbf{R^2}$	Vel78	0,35	0,33	0,44	0,37	0,29	0,33	0,42	0,53
	Vel118	0,41	0,36	0,46	0,42	0,34	0,39	0,47	0,64
	T81	0,8	0,8	0,82	0,82	0,8	0,82	0,74	

Table 3: PBL parameterizations and SKIRON's standard methodology errors(%)

In order for the WRF-NMM model properly read the information provided by the SKIRON model, a new set of reference tables and changes to the pre-process code are developed. Four new reference tables are created; the first is used to decode the SKIRON outputs, and has the information regarding all the variables generated by the SKIRON simulation; the second is used to generate the domain topography and contains the definitions of the new SRTM90m topography; the third contains the definitions of the new CorineLandUse90m and finally, the last one indicates the interpolation methods which will be used to process each new variable. Every new variable is then defined in the WRF-NMM model and the new definitions are added to the Registry file. The physics options are the same as the ones used in the two weeks simulations, both to SKIRON and to the WRF-NMM.

3. Results

Based on the site's measured wind rose(Figure 7), two predominant wind sectors were identified (North [337.5° to 22.5°] and South [157.5° to 202.5°]).

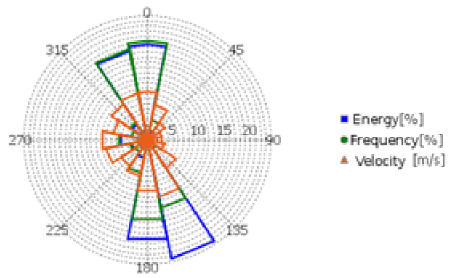

Figure 7: Wind Rose (78m) at the EWF

Due to computational constraints, in a first phase, two weeks are chosen (one week with predominantly Northerly Winds, and another with Southerly Winds) and 8 WRF configurations are tested.

3.1. PBL Parameterizations, WRF-NMM and SKIRON validation

Since the errors behavior is similar in all the different heights validated, only two wind levels, and one temperature is shown in the Table 3.

None of the WRF configurations is able to improve the results obtained with the mesoscale model SKIRON, but the WRF-NMM simulation produced the lowest errors. Another aspect to take into account is the difficulty of successfully run WRF-ARW in areas with very steep mountains and high-resolution (lower than 1km) that doesn't seem to affect the NMM version.

	Var.	DOM1	DOM2	SKIRON
	Vel78	9,48	6,53	17,33
	Vel90	9,18	6,63	18,32
	Vel102	8,04	5,79	17,63
BIAS	Vel118	6,71	4,74	16,90
	T81	-11,38	1,21	
	T97	-10,93	1,76	
	T113	-6,86	6,32	
	Vel78	22,04	20,49	28,24
	Vel90	22,00	20,65	28,50
	Vel102	21,41	20,26	27,81
MAE	Vel118	21,17	20,23	27,27
	T81	16,67	11,53	
	T97	16,39	11,53	
	T113	14,32	12,50	
	Vel78	28,24	26,58	34,91
	Vel90	28,28	26,74	35,09
	Vel102	27,59	26,37	34,44
RMSE	Vel118	27,43	26,45	33,92
	T81	20,77	15,28	
	T97	20,55	15,33	
	T113	18,41	16,48	
	Vel78	0,63	0,65	0,56
	Vel90	0,63	0,65	0,57
	Vel102	0,63	0,65	0,57
R^2	Vel118	0,62	0,64	0,57
	T81	0,94	0,97	
	T97	0,95	0,97	
	T113	0,95	0,97	

Table 4: Global Errors(%) and correlation coefficient in the model-chain methodology

Another advantage of the NMM version version is its lower computational requirements, which can be an important factor when comparing to other high-resolution simulation models. Due to the results and simplicity, at this point WRF-NMM and SKIRON are chosen for the model chain configuration.

3.2. Model Chain - SKIRON and WRF-NMM

A new approach is developed by combining both mesoscale models.
One coarse domain is simulated using SKIRON with a 0.05°x0.05° horizontal resolution and the hourly outputs are used as initial conditions to the WRF-NMM model. One entire year is simulated using this methodology in order to validate the yearly climatology of the study region.

3.2.1. Global Results

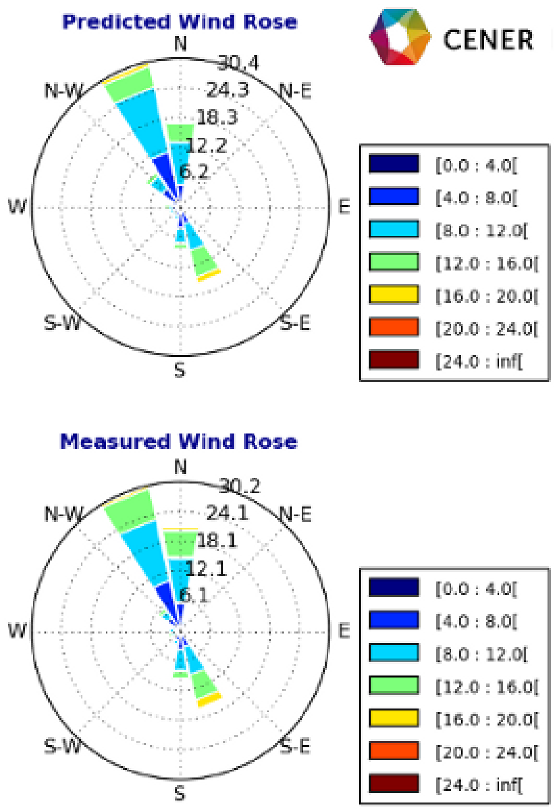

Figure 8: Predicted/Measured wind roses (78m) at the EWF for the one-year period

In the Table 4, standard statistical performance indicators [24] (Bias, MAE, RMSE and R^2) are calculated in all the different heights and validated in both SKIRON and WRF-NMM domains.

It is noticed that the model-chain improves the results obtained with SKIRON and highly improves the results from the WRF-NMM configuration presented before (See Section 3.1). In the innermost domain the wind Bias is around 4 to 6% in the entire year, while both MAE and RMSE decrease around 8% when comparing with the standard SKIRON simulation. The correlation coefficient also increases in all the validated heights.
Regarding the temperature validation, it's possible to see that the Bias is very low, while the MAE is always smaller than 15% in the entire period. The 0.97 correlation obtained in all the validated heights reflect the excellent results provided by this approach.
The predicted wind rose (78 m) also reflects accurately the behavior of the wind in the interest region, when the simulated and measured wind rose are compared.
The wind daily pattern doesn't seem to be well predicted during the nighttime, as can be seen in the Figure 9. During daytime the predicted and measured wind speeds are well adjusted, but during the night, the model underestimates the wind in all the validated heights.

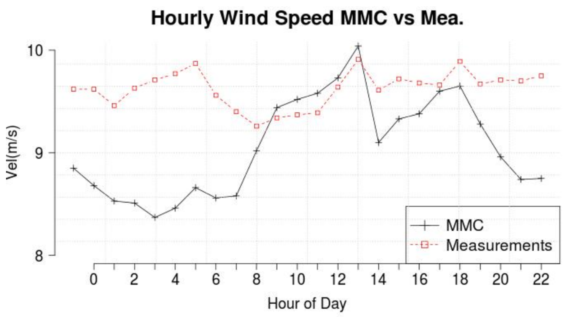

Figure 9: Predicted/Measured wind speed (78m) in the one-year period

The vertical wind profile, represented in the Figure 10 clearly shows a different behavior in the wind during daytime (12:00 UTC) and nighttime (00:00 UTC).
A more detailed study is needed to try to understand that discrepancy in the results during the nighttime (See Section 3.2.2).

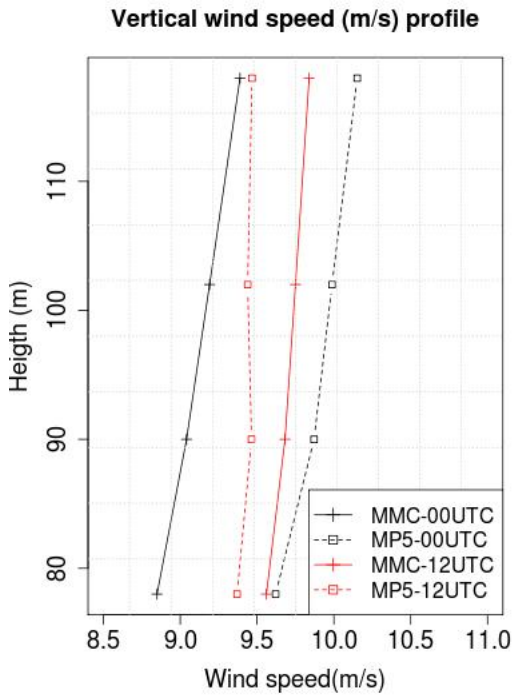

Figure 10: Predicted/Measured vertical wind profile, at 00 and 12 UTC, in the one-year period

Taking advantage of all the instrumentation at the EWF, the wind shear is calculated in all the different levels. The behavior is similar in all the heights, so in order to simplify the results, only the mean hourly wind shear between the levels 102-78m and 118-90m are presented.

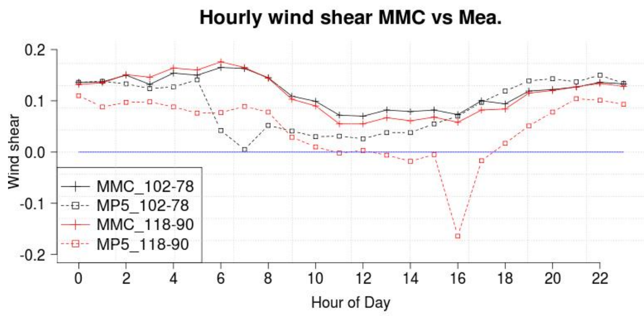

Figure 11: Predicted/Measured hourly wind shear between the levels 102-78m, and 118-90m, in the one-year period

The model follows the pattern of the wind shear, but fails to detect when an inverted wind profile occurs. The differences between the two levels in the predicted wind shear are relatively low when compared with the differences recorded in the measurements.

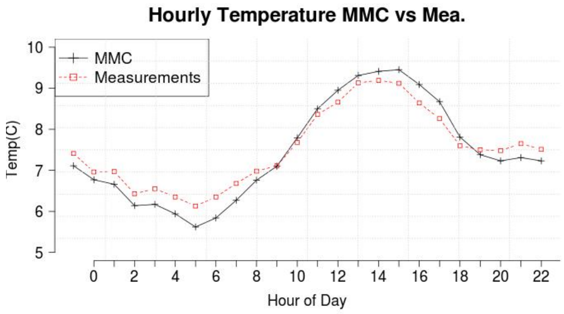

Figure 12: Predicted/Measured Temperature at 81m in the one-year period

Looking at the temperature validations it's possible to ascertain the excellent results obtained both in the daily pattern and the vertical profile, which is obtained by averaging the temperatures at every available height.

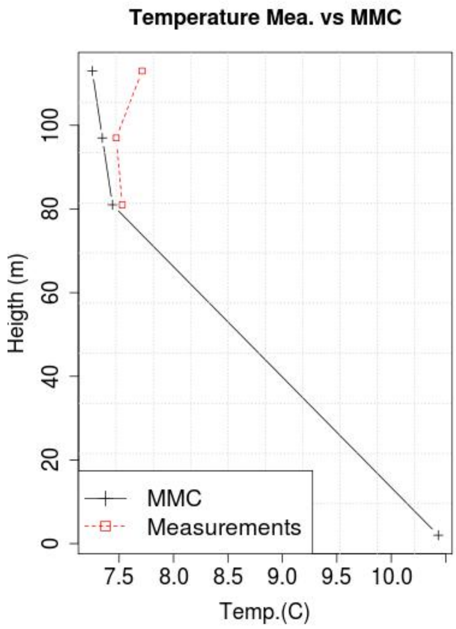

Figure 13: Predicted/Measured vertical temperature profile in the one-year period

The lowest Bias near the surface could be explained by the updated land cover database in the WRF-NMM inner domain simulation which is closer to the real conditions.

3.2.2. Results in the predominant sectors

Due to the differences in the wind behavior referred in the previous section, a more detailed validation is conducted with the main goal to determine the main reason behind those differences. The two predominant wind sectors are studied, and the table 5 shows the results obtained in the North and South sectors. It's possible to see that the discrepancy in the daily wind pattern appears to be mostly influenced by the Southern wind.

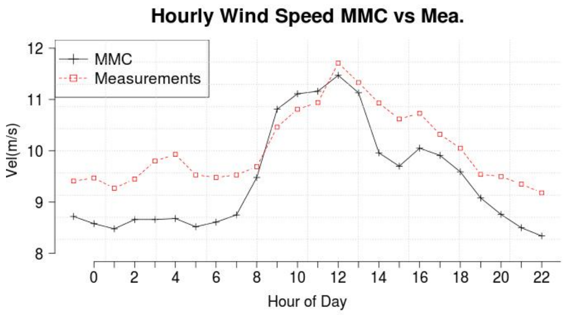

Figure 14: Predicted/Measured Wind Speeds (78m) to the North Sector, in the one-year period

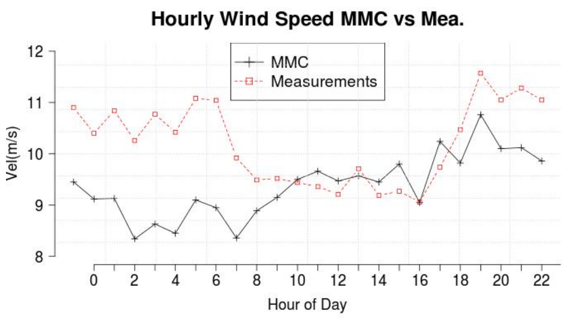

Figure 15: Predicted/Measured Wind Speeds at 78m, to the South Sector, in the one-year period

The Figure 14 and Figure 15 also show that the differences during nighttime are more pronounced in the South sector wind. In the Northern sector, the model follows the daily measured pattern, even though the errors are also larger during nighttime.

In the vertical wind profile it is easily noticeable that the largest differences are detected in the Southern sector during the night.

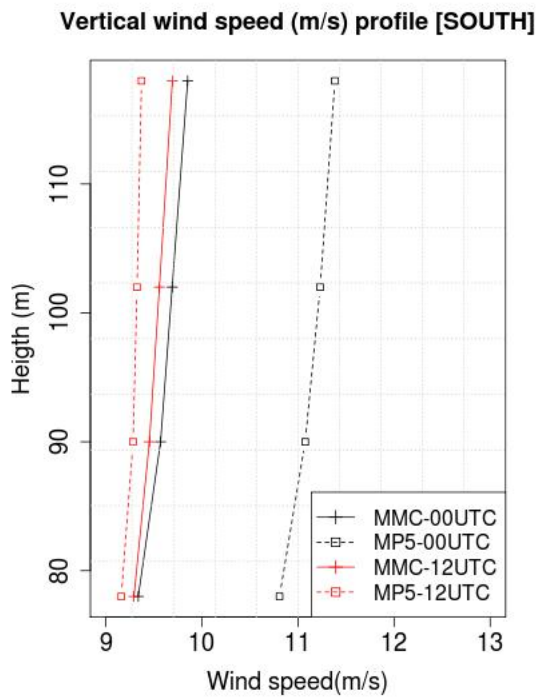

Figure 16: Predicted/Measured vertical wind profile, at 00 and 12 UTC, to the South sector, in the one-year period

The temperature doesn't reflect those differences, and both the analysis from the North and South sector have shown similar results to the ones obtained in the global validation presented in the previous section.

3.2.3. Results by measured stability

The atmospheric stability is classified based on the Froude number [18] that is calculated using the measurements from the MP5 meteorological tower. The Figure 17 allows to see that, when the wind speed is relatively high, the stability conditions assume almost exclusively conditions of "very stable" or "very unstable".

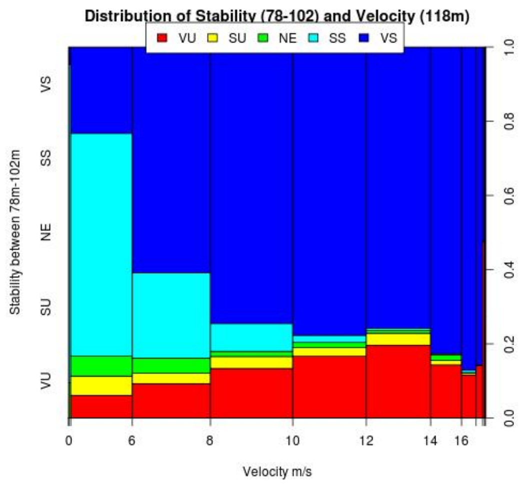

Figure 17: Atmosphere stability classification, obtained by the Froude number

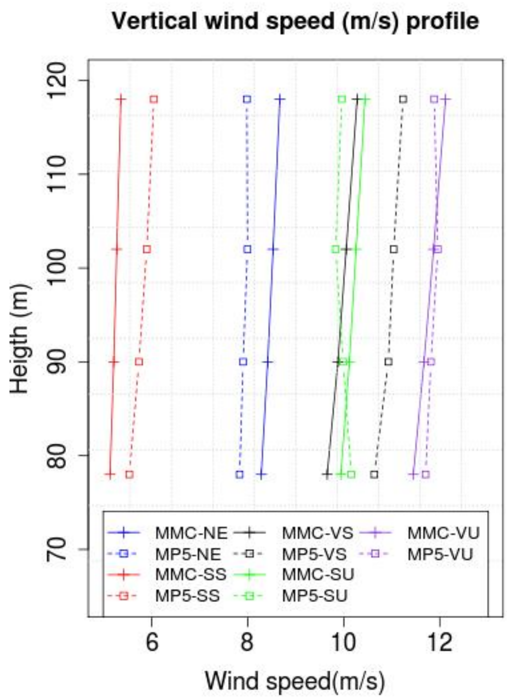

Figure 18: Wind vertical profile, at 00 UTC, discretized by the measured stability

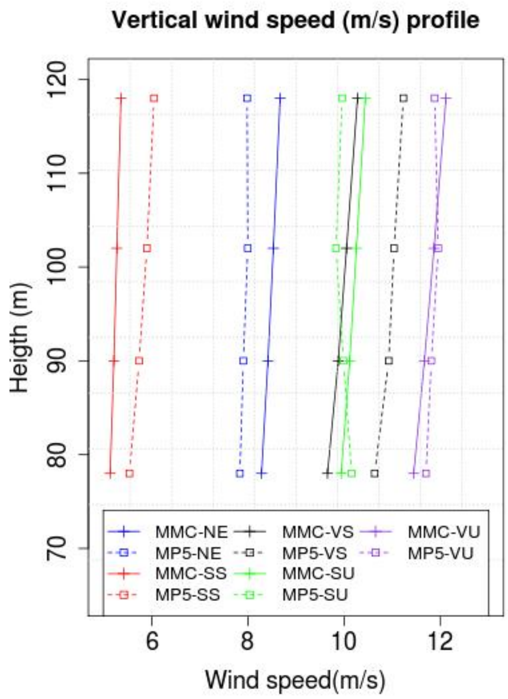

Figure 19: Wind vertical profile, at 12 UTC, discretized by the measured stability

When the vertical profiles, classified by atmospheric stability are plotted, it is possible to see a over prediction of wind speed in the neutral and very unstable profile during daytime, while the other profiles seem to adjust to the measurements. During nighttime, in very stable conditions the methodology under predicts the wind at the site's location. The model-chain is not able to predict inverted vertical wind speed profiles, neither during day nor during nighttime.

4. Conclusions

The paper allowed to ascertain the capacity of using state-of-the-art mesoscale models to simulate wind flow conditions at resolutions higher than one kilometer. In a first phase, three different models, and several PBL parameterizations were tested in order to obtain the model configuration which produced the lowest errors at the site's location. That analysis proved that neither WRF-ARW configuration, nor WRF-NMM were able to improve the results obtained with the mesoscale model SKIRON, used at CENER. Even though, it was possible to see that the WRF-NMM model simulation obtained the lowest errors among all the WRF configurations and had the advantage of using relatively less computational resources than all the others WRF configurations.
A different approach was developed by trying to combine the strongest assets of the two mesoscale models. A model chain methodology was developed, one entire year was simulated, at the heavily instrumented EWF, and the results validated at different heights. This new methodology consisted in going from a global meteorological scale to a resolution higher than one kilometer combining the SKIRON and WRF-NMM models, high-resolution topography and an updated soil type database. The high resolution topography and soil type databases used in the higher resolution domain proved to be very important, in order to generate surface and orographic properties closer to reality.
This approach provides another source of information that can be very important when trying to study regions with highly complex terrain that cannot be properly simulated with a conventional mesoscale methodology. Another advantage of this methodology is the possibility of simulate relatively large areas (250km x 250km, in this case), and relatively large periods (years), using low computational resources, which can be a key factor in operational use. This methodology can also be combined with a representative year methodology [23] and generate a final map that represents the long-term climatology at one given location.
The wind and temperature simulated with this

	Var	North			South		
		DOM1	DOM2	SKIRON	DOM1	DOM2	SKIRON
BIAS	Vel78	4,17	6,72	10,25	17,08	9,00	21,17
	Vel90	3,67	6,62	10,92	16,94	9,37	22,38
	Vel102	2,01	5,19	9,73	16,28	9,05	22,16
	Vel118	0,30	3,78	8,64	15,09	8,50	21,66
	T81	-14,74	-3,07		-10,39	-0,56	
	T97	-14,22	-2,76		-9,21	-1,80	
	T113	-8,96	-8,80		-5,47	-6,17	
MAE	Vel78	15,42	15,80	24,81	27,73	23,04	27,30
	Vel90	15,41	15,97	24,56	27,78	23,47	28,19
	Vel102	14,77	15,35	23,57	27,12	23,31	27,86
	Vel118	14,99	15,41	23,05	26,44	23,16	27,56
	T81	21,58	15,16		13,95	8,89	
	T97	21,33	15,07		13,21	9,21	
	T113	18,71	16,67		11,32	11,142	
RMSE	Vel78	19,79	20,17	30,43	34,43	29,26	33,69
	Vel90	19,69	20,38	30,24	34,67	29,68	34,62
	Vel102	18,89	19,61	29,08	33,90	29,45	34,34
	Vel118	19,63	20,41	28,60	33,08	29,20	33,94
	T81	26,90	20,04		17,21	11,89	
	T97	26,74	20,04		16,42	12,13	
	T113	24,06	21,91		14,47	14,04	
R^2	Vel78	0,72	0,75	0,46	0,64	0,65	0,73
	Vel90	0,71	0,74	0,47	0,64	0,65	0,73
	Vel102	0,71	0,74	0,48	0,65	0,65	0,74
	Vel118	0,68	0,71	0,48	0,66	0,66	0,74
	T81	0,94	0,97		0,94	0,97	
	T97	0,95	0,97		0,94	0,96	
	T113	0,95	0,97		0,94	0,97	

Table 5: Predominant Sectors errors(%) and correlation coefficient to the model-chain methodology

methodology show a decrease in the calculated errors in all studied levels. The wind had a very low Bias in the entire year, but a closer look had shown different behavior during day/nighttime and North/South sectors that seem to be correlated with each other. A more detailed analysis is needed in order to determine the origin of such discrepancies. Even with these differences, the model-chain improved the results obtained with the standard CENER methodology, which translates in lower Bias, MAE, RMSE and Error percentages; and higher correlation between predictions and measurements.

The temperature analysis indicated a very high correlation between predictions and measurements, especially at lower heights, that can be the result of using an updated land cover database that better represents the real conditions at the site's location.

Finally, it was possibly to see some differences in the wind speed errors when analyzing the vertical wind profiles, classified by the atmospheric stability given by the Froude number. The analysis shows that at high wind speeds, the atmosphere stability classification is almost entirely comprehended between very stable and very unstable conditions.

Regarding wind resource assessment, the model-chain accuracy proved to be quite good, but a more detailed analysis is still needed to better understand the overestimation in the wind speed under very stable conditions/daytime and the underestimation during nighttime/very unstable conditions. A future study should focus on the effect of certain atmospheric stability conditions in mesoscale model's accuracy.

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