Short-term Forecasting Using Advanced Physical Modelling – The Results of the Anemos Project

Results from mesoscale, microscale and CFD modelling

G. Giebel[1], J. Badger[1], I. Martí Perez[2], P. Louka[3], G. Kallos[3], A. M. Palomares[4], C. Lac[5], G. Descombes[6]

[1] Risø National Laboratory, DK-4000 Roskilde, Gregor.Giebel@risoe.dk

[2]CENER, [3]IASA, [4]CIEMAT, [5]MeteoFrance, [6]ARIA

Abstract

A possible solution to the problem of forecasting wind farms output in complex terrain sites comes in the form of high-resolution, advanced numerical flow models trying to improve on the NWP models shortcomings. These models can be linear flow models like Risø's WAsP, or AriaWind, meso-scale models like the well-known MM5 community model, MeteoFrance's MesoNH or IASA's RAMS model, or full-blown CFD models (Computational Fluid Dynamics) like Fluent or Mercure. The idea of all models is the same: use higher resolution calculation and input data bases plus a more complete physics descriptions than the NWP model to try to capture the local air flows, be it in the mountains or at a land-sea border. While NWP models typically have a horizontal resolution of 5-10km, the meso-scale models employed here can go down to 500m.

The new approaches were tested at three sites: Alaiz, a complex terrain site in northern Spain, Ersa-Rogliano, a two-cluster wind farm on the narrow tip of Corsica, and four wind farms in the eastern end of Crete.

For MM5, several Planetary Boundary Layer parameterisations were tried out, and it was found that the Blackadar scheme performed not as good as the MRF or ETA PBL schemes. The last bit in horizontal resolution might not be necessary, the same accuracy can be gained with a larger finest nested area. A higher number of vertical levels in the lowest 100m above the surface helps. MM5 could improve on the simple HIRLAM forecasts in Alaiz. The accuracy of the MM5 forecasts seems to depend a lot on the accuracy of the driving model (NCEP 6-hourly or GFS hourly).
KAMM could explain the turning effects of the wind for the Spanish test case. A domain size of 400x400 km^2 was needed. However, a MOS system (where data is available) might do as good.
For RAMS in Corsica and Crete, the second model level (46m a.g.l.) performed usually better than the 10 m wind. Using 500 m horizontal resolution helped here (probably due to the much better orography description used in comparison to MM5).

In general, the models revealed the problem of representativity of a single measurement for a whole region. We are comparing model output valid for an area with a measurement in one particular point. Another issue which has to be solved from case to case is whether it is worth to use the calculation power needed.

1 Introduction

While NWP models are good enough for many cases (relatively flat and uniform terrain, gentle hills), they have problems in complex terrain and in coastal areas. Some of these problems can be attributed to the relatively coarse horizontal resolution, often in the tens of kilometres, employed by the meteorological institutes. This limitation typically comes from limitations in computing power. Another change that leads to coarse resolution is the change in the modelled physics: for a resolution of tens of kilometres, the hydrostatic assumption can be made, rendering the atmosphere incompressible. For higher resolutions, the numerically more expensive, but also more accurate hydrostatic equilibrium has to be modelled explicitly. This category of models is called meso-scale models, and some meteorological institutes already use them as their standard model.

In order to increase the accuracy of the forecasts, the NWP can be processed statistically to generate power prediction forecasts directly or can be adapted to the area of interest through mesoscale/microscale models before doing the statistical corrections. How far the use of dedicated mesoscale or microscale models increases the accuracy of the results, is the topic of this report.

This paper is a short summary of the report describing in detail the results that have come out of the modelling exercises [1]. In the Deliverable 4.1a Model Description [2], we already described the models used for this exercise. There, we have shown an impressive array of different calculation tools for atmospheric flow. From NWP to CFD, the scale of area covered, the requirements in computing hardware and the resolution of the calculation meshes is wide ranging. Horizontal scales between few metres and many kilometres are employed, and calculation times range from seconds on simple PCs to many hours on dedicated supercomputers.
Here in this report, we try to analyse the effect of resolution and model physics on the accuracy within the different approaches.

There are two different modelling approaches employed here. On the one hand, we have nested models, which run every time the driving NWP model is run. MM5 is the prime example of this class, but also MesoNH or RAMS are used like this. They use the NWP model as boundary and initial condition, and run nested “inside” the NWP model. On the other hand, we have models that start from one given scenario for the atmospheric flow over the given terrain, and then calculate as long as it takes to reach a steady state for the model. KAMM and Aria Wind, but also the different CFD models are part of this group. While the results of the nested models are functionally very much alike the NWP input, the results of the steady-state models yield a look-up table of “translations” from the overall NWP wind to a site-specific wind.

There are a number of dedicated NWP models being used in the Anemos project. However, some of them are not from a project partner. Therefore, while they were described in the Model Description report, the results are reported elsewhere, especially in Task 2.4 [3]. In WP4, we concentrate on the results from the longer term NWP models of IASA, which is reported elsewhere [4].

In the project, we settled on a number of exercises, being in complex terrain and/or near-shore. Since for some models it was numerically too expensive to simulate for a long time, some specific times were found, where either the weather changed a lot in the course of a few days, or where some other factors made the short period interesting. The three main exercises were run for the highly complex terrain site at Alaiz, near Pamplona, Spain, at one wind farm consisting of two clusters on a narrow but high tongue of land in the Mediterranean (Ersa-Rogliano on the French island of Corsica), and Rokas and three other wind farms on Crete. The results are reported for each case separately. But first, let us shortly recapitulate the different approaches employed.

1.1 MM5

The Fifth-Generation NCAR / Penn State Mesoscale Model is the latest in a series that developed from a mesoscale model used by Anthes at Penn State University in the early 1970’s. Since that time it has undergone many changes designed to broaden its usage. These

include (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, and (iii) a four-dimensional data assimilation capability as well as more physics options, and portability to a wider range of computing platforms.
The MM5 model is best described as a non-hydrostatic, sigma-coordinate model designed to simulate and predict mesoscale and regional-scale atmospheric circulations. Sigma surfaces near the ground follow the terrain, and the higher-level sigma surfaces tend to approximate isobaric surfaces.

Four different schemes for the Planetary Boundary Layer (PBL) parameterisation have been used: Blackadar, MRF, ETA and Gayno.

Both Spanish institutes CENER and Ciemat have used MM5 for their modelling. One important difference is that CENER has chosen to nest MM5 in the operational GFS forecasts (Global Forecasting System, made at NCEP in the US), while Ciemat has used the NCEP Reanalysis dataset as their driver. Reanalysis has a much lower horizontal and temporal resolution than GFS. Also, while the CENER results also used LocalPred as a MOS system, Ciemat reported the straight MM5 results without even a bias removal step. The application of MM5 by ARIA Technologies used input data for terrain and land use are provided by the USGS (United States Geological Survey) database. The meteorological input data has been taken from the AVN model (NWP model, analysis data made at NCEP in US).

1.2 The KAMM/WAsP approach

The mesoscale model KAMM is used to identify flow features in the region of a wind farm. By checking the observed wind characteristics it is possible to see if the KAMM modelled wind features are important in practice. The next step is to see if the KAMM model results can be applied to wind speed and power prediction.

The steps in this approach are i. to examine the wind characteristics for the site of interest given by an operational meteorological forecast model, ii. to examine the observed wind characteristics for the site of interest, iii. to employ the KAMM model to determine mesoscale flow characteristics in the region of the wind farm, iv. to incorporate the KAMM results into a wind speed and farm power prediction system. For this case the prediction system is based on Risø's Prediktor system.

The above steps have been carried out for two locations: Alaiz in northern Spain and Ersa in northern Corsica.

The Karlsruhe Atmospheric Mesoscale Model, known as KAMM, is a 3-dimensional, non-hydrostatic atmospheric mesoscale model [5]. It has its origins in applications in regional flow and dispersion research. It uses a terrain following coordinate system. Typically 20, 40, 100 and 160 metres are the approximate heights of the lowest four levels.

The lower boundary is also prescribed an elevation and aerodynamic roughness, z_0, so that roughness effects due to difference surface types (land and sea) or land usage (urban, crops, forest, etc) can be modelled.

The atmospheric flow is initialized using a forcing wind in geostrophic and hydrostatic balance. The forcing flow is prescribed by giving a vertical profile, using 4 different heights above sea level, of wind speed, direction and temperature. The forcing does not change in the horizontal direction. For more details about the model can be found in [2].

The profiles used for the KAMM modelling here are uniform wind speeds of 5, 10, 15 and 20 m/s at all heights. Three temperature stratifications have been used: standard, neutral, and stable. An alternative velocity profile, which featured an increasing wind speed with height, was also tested for the Alaiz case.

In order to incorporate the knowledge obtained from the KAMM simulations into wind speed predictions, the Prediktor framework is extended upon. In addition to the WAsP derived flow adjustments to wind speed and turning, the KAMM derived flow adjustments are also used.

In summary, WAsP is made up of a set of models and tools used to calculate a generalized wind climate for an area using wind measurements made at a particular location within that area [6]. The generalized wind climate can then be used to predict the wind characteristics at a new location. These steps require the modelling of local effects due to orography, roughness and in some cases obstacles.

The ordering of the application of the adjustments/corrections is:

i. WAsP corrections (sectorwise)
ii. KAMM corrections (sectorwise, speed dependent, [stability dependent])
iii. MOS corrections (sectorwise linear OR isotropic linear)
iv. Output wind speed prediction

The MOS sectorwise corrections are based on NWP direction.

It has can be seen from the results of the mesoscale modelling that atmospheric stability plays a important role in determining how the local wind is influenced by topography. Ideally the stability would be a dimension of the correction matrix. There has not been sufficient stability information within the NWP model data available so far in this project. However, data from another NWP model will be used to see if a stability dimension can be built into the correction matrix.

Stability information from the NCEP/NCAR reanalysis data (near surface and 850hPa pressure level temperature) has been used to determine if there is any relationship between the large-scale stability and the error in the wind speed prediction. Such a relationship would indicate that large-scale stability from NCEP/NCAR could improve the forecast as part of a correction matrix dimension. Results showed that there was no clear relationship, suggesting that the NCEP/NCAR data cannot be readily be used for this purpose.

1.3 Other models

The Regional Atmospheric Modelling System (RAMS v4.3.0) is a highly versatile numerical code, developed by scientists at Colorado State University and Mission Research Inc/ASTeR Division. It is a merger of a non-hydrostatic cloud model and a hydrostatic mesoscale model. It has been developed in order to simulate atmospheric phenomena with resolution ranging from tens of kilometres to a few meters. It has several capabilities but the most important are the two-way interactive nesting of any number of grids, the incorporation of one of the most advanced cloud microphysical process algorithms, a surface parameterization scheme able to utilize information on land-use and soil texture at subgrid scale, an advanced radiative transfer scheme able to describe radiative processes at cloudy environment, a full soil temperature and moisture model and a hydrological model providing partitioning of rain water. It uses various level of complexity turbulence scheme.

CFD codes are yet another class of models, not requiring too much parameterisation, as here the complete equations of motions are solved for very small air parcels, down to a horizontal resolution of a few metres. In this project, Fluent and AriaLocal based on the MERCURE code have been used.

1.4 Modelling of flow using MINERVE and MERCURE

ARIA started a parameterization study to combine a CFD code (ARIA Local, based on the MERCURE code) and a simple mass-consistent code (ARIA WIND/MINERVE code). The methodology developed by ARIA consist of:

- Evaluation of output from first model run based on a simple model (ARIA WIND).
- Initialization of the CFD code by using the meteorological field from the first model.

ARIA applies ARIA WIND and ARIA LOCAL nesting on the Alaiz and Corsica cases. The aim is improve the first solution of a simple model (ARIA WIND) with a CFD code (ARIA LOCAL). The chosen method permits to reduce the time of calculation.

The method employed (combination of mass consistent model with CFD codes) allows to reduce the CFD CPU time and the quality of the results. It is possible with this method to evaluate the approximations made by a simple model. Topography effects as wake effect zone are calculated with higher precision.

The meteorological nesting is implemented using the MINERVE calculation results to impose the boundary and initial conditions for MERCURE. An identical 3D MERCURE mesh is therefore needed, as the data interpolation is not possible between MINERVE and MERCURE meshes.

2 Results for Alaiz

Alaiz is in the north of Spain, in the province of Navarra near the town of Pamplona. The wind farm consists of 49 Gamesa G47 660-kW turbines and a single LW50 750-kW Lagerwey one. The wind farm is located on a ridge, roughly 1000 m above sea level. The site is quite complex. The data period agreed upon was all of December 2003, but some partners used a longer period (one year) for their trials. This data period also coincides with the test case for the purely meteorological forecasts, reported in [3]. The standard NWP model is Hirlam 0.2°, with a horizontal resolution of 17 km.

NWP and Observed Wind Characteristics

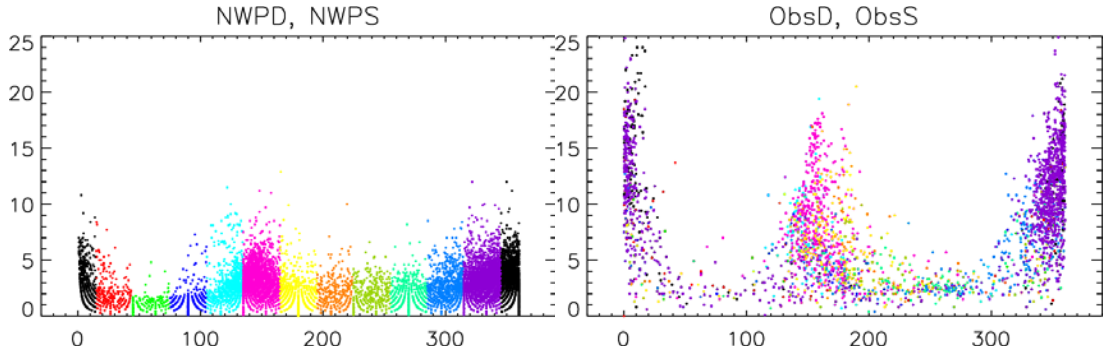


Figure 1: Left, the numerical weather prediction model wind speed (NWPS, on y-axis) plotted against NWP direction (NWPD, on x-axis) for a complete year of data. The colour of the data points indicates the NWP direction sector. Right, the observed wind speed (ObsS, y-axis) plotted against observed wind direction (ObsD, x-axis) for the same period as the NWP model data. The colour of the data points indicates the NWP direction sector.

The NWP and observed wind speed vs wind direction distributions are shown in Figure 1. In both the NWP and observed wind the northern and southern wind directions are the most frequent and exhibit fastest wind speeds. However the observed wind speeds tend show a much enhanced wind speed for the northern and southern sectors. The colouring of the points gives an indication of how well the forecast wind direction agrees with the observed wind direction.

2.1 KAMM (Risø)

The results from the KAMM mesoscale modelling is that the topography of the region dramatically increases the wind speeds from the north and south directions and to turn the wind so that it comes from either a northerly or southerly direction.

This wind speed enhancement and turning effect of the topography is somewhat dependent on the wind speed, profile and stability configurations. These effects are displayed in Figure 2 and Figure 3.

The concentrating or focusing and the wind speed enhancement effect of the wind due to topography are felt most strongly when the wind speed is low or when the stability is high. This can be seen by comparing the plots for the 5 m/s and 20 m/s respectively. It can also be seen in Figure 3, that the 10 m/s high stability plot resembles the 5 m/s and the low stability plot resembles the 20 m/s plot.

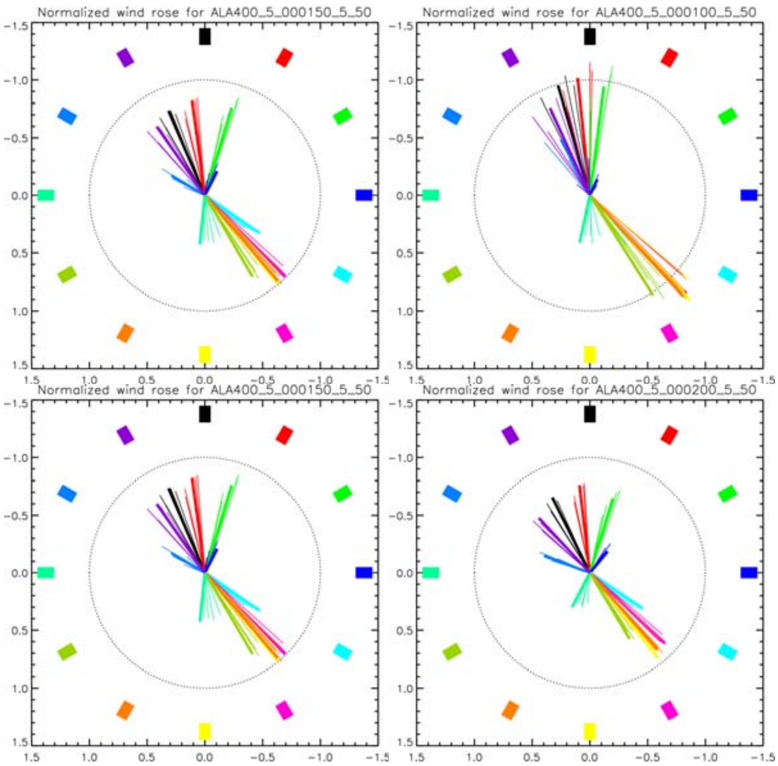


Figure 2: Diagrams showing the mesoscale effect on the geostrophic wind forcings. Each wind forcing direction is indicated with rectangle of a particular colour, e.g. the sector centred on 30 degrees is red, the simulated winds at 50m at the wind mast site for a given forcing are show by lines of the same colour. The direction on the diagram indicates the direction where the wind comes from and the length indicates the wind speed "speed-up". The dotted-line circle represents a "speed up" of 1, meaning that wind speed at 50m is the same as the forcing. "Speed-up" above 1 indicates a wind at the mast faster than the forcing wind speed and below 1 indicates a wind at the mast slower than the wind forcing. The thinner lines indicate simulated wind directions at the neighbouring grid points to the mast. The geostrophic wind forcing for the 4 graphs above is, top-left: 5 m/s, top-right: 10 m/s bottom-left: 15 m/s, bottom-right: 20 m/s.

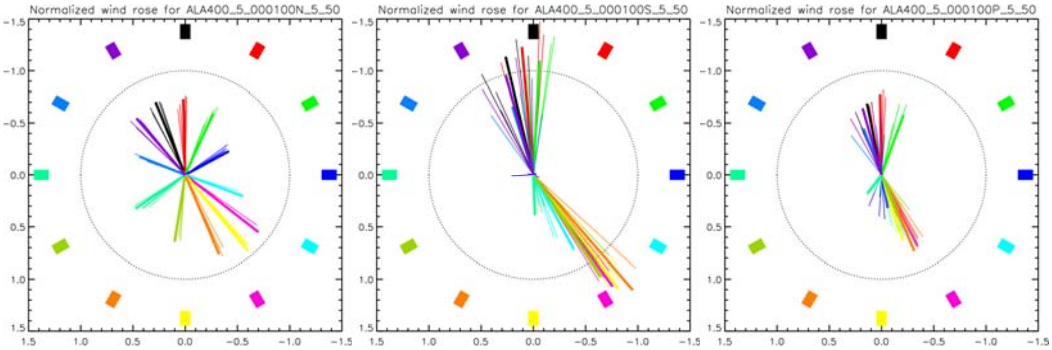


Figure 3: As in Figure 2, but using a more thermally neutral stratification (left), a more thermally stable stratification (middle), or different velocity profile (right).

Prediction skill

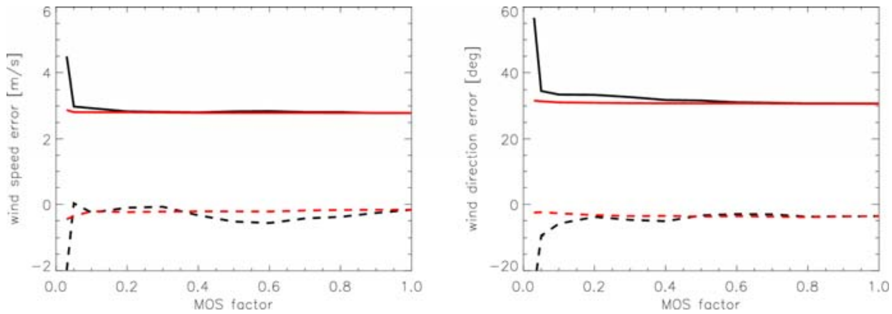


Figure 4: The mean error (dotted) and mean absolute error (solid) on wind speed (left) and wind direction (right) using the direction dependent model output statistics [MOS(sectorwise)] method, plotted against the MOS factor, the ratio of the data used to make the MOS corrections. The black lines show the errors when data is used congruently from the start of the dataset for MOS fitting. The red lines show the errors when data is selected randomly from the dataset. Forecast horizons from 9 to 24 hours are used to calculate the error statistics.

Forecast horizons from 9 to 24 hours were used to calculate the error statistics using the most straight forward linear isotropic model output statistics (MOS) to correct the NWP output of wind speed and direction to the observed wind speed. The MOS factor indicates how much of the data is used to do the MOS fitting. The absolute mean error on speed and direction vary slightly as MOSFactor increases. The variation of the errors is more pronounced when the data is used congruently (black lines), rather than randomly sampled (red lines). The performance is improved when the MOS is made sectorwise. However this method makes the error more sensitive to low MOS factors, where less data is available for the per sector data fitting.

Incorporating the WAsP corrections into the method one finds first when coupled with the isotropic MOS method slight improvement compared with isotropic MOS alone. However there is no difference in performance with the WAsP corrections coupled with sectorwise MOS compared with sectorwise MOS alone.

Coupling the KAMM corrections with the isotropic MOS method produces an only very slightly better forecast than the coupling of WAsP corrections and isotropic MOS for wind speeds and produces a much worse wind direction prediction. Using KAMM corrections and sectorwise MOS produces predictions no better than using sectorwise MOS alone.

Combining all 3 correction methods with sectorwise MOS gives errors as shown in Figure 4. There is no overall improvement with the addition of the extra complexity in the correction method. Table 1 gives a summary of the results for MOS factor equal to 1. Without MOS the error values are high due to the large bias in the NWP wind speed values.

Configuration	Isotropic MOS		Sectorwise MOS	
	ME	MAE	ME	MAE
MOS	-0.245	3.214	-0.193	2.800
WAsP MOS	-0.239	3.175	-0.193	2.800
KAMM MOS	-0.177	3.349	-0.192	2.819
KAMM WAsP MOS	-0.170	3.333	-0.192	2.819

Table 1: Predicted wind speed mean error and mean absolute error for different correction configurations for the Alaiz case. Note: MOS factor is 1.

Conclusions for KAMM in Alaiz:

Mesoscale modelling has been used to determine the regional flow characteristics for Alaiz. Features present in the observed wind have been captured by the modelling, such as the dominance of the northerly and southerly winds.

Modelling trials with different domain sizes have shown that a 400x400km domain was required for Alaiz in order to capture these features. Smaller domains do not include enough of the important topographic features, which play a role in the wind flow for Alaiz. It is important that the elevated regions to the east and west of the farm are included.

The results have also shown that stability plays an important rule in the Alaiz wind flow. For cases of high stability the mesoscale speed-up and turning effects are enhanced compared to the neutral stability cases. Enhancement of the mesoscale speed-up and turning effects is also seen for low wind speeds, compared to high wind speeds, for a given stability.

While the qualitative characteristics of the Alaiz farm are seen in the modelling work, it has been found that there are several issues that need to be solved in order to fully exploit advantages that the offline mesoscale modelling may be able to offer for short term predictions. These difficulties and the ongoing work on their solutions are given in the conclusions to this document.

2.2 MM5 (CIEMAT)

CIEMAT ran MM5 for December 2003 in Alaiz (Spain), nested in reanalysis data. The results of applying the two chosen parameterizations (Blackadar and MRF) have been compared with the actual measurements in Alaiz.

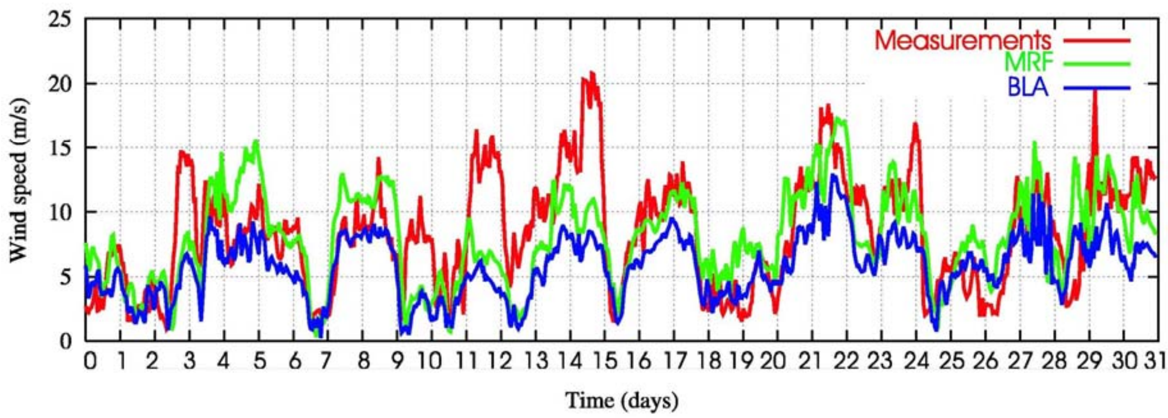


Figure 5: Comparison of measurement data with the MRF and BLACKADAR PBL parameterisations of MM5 during December 2003. In red the measured data, in green the MRF output of the MM5 analysis and in blue BLACKADAR output.

The Error Analysis:

The corresponding error parameters, according to the common evaluation protocol, are shown at the following table. The normalization was done using the mean forecasted wind speed.

This table shows higher errors in the Blackadar than in the MRF parameterisation of PBL in this case. However, the R2 for MRF is lower, and as there is no bias removal step (MOS), the high bias of the Blackadar parameterisation might make it look worse than it actually is. This topic is under further investigation.

	ALAIZ	BLACKADAR	MRF
$\hat{\mu}(m/s)$	8.40	5.80	8.07
$\hat{\sigma}^2(m/s)^2$	18.40	5.86	12.67
$\hat{\sigma}(m/s)$	4.29	2.42	3.56
$\bar{e}(m/s)$		2.59	0.33
$\hat{\sigma}_e^2(m/s)^2$		10.24	8.41
$\hat{\sigma}_e(m/s)$		3.31	3.64
RMSE (m/s)		3.30	3.60
NRMSE		0.57	0.45
MAE (m/s)		3.20	2.90
NMAE		0.55	0.36
R(k)		0.68	0.31
Covariance		6.66	8.89
R^2		0.64	0.58

Table 2: Error analysis for CIEMATS MM5 runs for all of December 2003. Alaiz are the measurements.

There is one particular period (dec. 14-16th) in which both the predictions of the two parameterizations are quite different from the measurements. The main reason is that in these days, a cold front is crossing the Iberian Peninsula. It seems that neither of these parameterizations can take this feature and the corresponding increase of wind speed into account. Further investigations on this matter will be continued.

2.3 MM5 (CENER)

CENER has used the MM5 model to calculate wind forecasts for the Alaiz area in Spain. The objective of the work carried out with MM5 was to determine the optimum configuration of MM5 to forecast the wind, studying the sensitivity of the model to some critical parameters.

There is one important restriction to the optimisation of the model; it is the limitation on the time to calculate the forecasts. From the point of view of the end user, and taking into account the operation of the markets and the system operation, the forecasts have to be delivered before a limit hour. This means that the calculations have to be finished within a given time (in Spain the daily market closes at 10 a.m.). If one configuration of the model (i.e. size of domains or grid resolution) has a computational time that is not viable for an operational forecast it is discarded, independently of the quality of the results.

With the objective of improving the wind forecasts and having in mind the above mentioned limitation, the following model parameters have been studied:

- Terrain resolution:
    - Size of the last nested domain.
    - Nesting options.
    - Grid resolution.

- Planetary boundary layer parameterisations:
  - MRF.
  - Blackadar.
  - Gayno Seamann.
  - Blackadar-MRF.

After MM5 optimisation a comparison between MM5 and HIRLAM was made. The comparison allowed determining the errors in power production forecasts that can be obtained with each model.

MM5 terrain configuration

The first parameter to be analysed was the size of the last domain that is centred at the wind farm. In principle, the domain has to be big enough to have all the relevant topographic and dynamic information of the area; but the size of the domain is connected to the computational time. Therefore, the optimum configuration is the one that minimises the wind prediction forecasts without increasing the computational time above the limit.

The results of this study show that the calculation time is related to the size of the nested domains, the spatial resolution and also to the number of sigma levels. Although the relation of the calculation time is not exactly linear with the number of calculation points (different grid resolutions imply the activation of different parameterisation), the tendency is to increase the calculation time with the grid points.

To extend this study, an analysis of the relation between wind prediction errors and size of the last domain was carried out. The following results were obtained with the following configuration:

- MM5 + LocalPred.
- Alaiz test case.
- June – October 2003.

The number of vertical levels included in the first 100 m above ground level plays a significant role in wind power forecasts. For most horizons, the error is significantly better using the higher number of sigma levels. The reason is a better description of the vertical profile in the area of operation of the wind turbines.

In order to determine the relation between grid resolution and prediction errors, two cases were analysed: 9 km and 3 km grid resolution. The results correspond to the period September – December 2003 at the Alaiz test case. Forecasts calculated using MM5+LocalPred.

	MONTH	Wind speed forecasts			Power production forecasts			
		R2	RMS	MAE	R2	NRMSE (%)	NMAE (%)	Error Index (%)
4 domains (3 km grid resolution)	September	0.51	2.68	2.11	0.46	25.60	15.34	0.72
	October	0.53	3.47	2.60	0.45	27.28	19.24	0.53
	November	0.45	2.84	2.14	0.56	19.41	12.16	0.77
	December	0.25	4.42	3.24	0.34	31.11	21.19	0.63
3 domains (9 km grid resolution)	September	0.48	2.74	2.14	0.45	25.19	15.13	0.71
	October	0.52	3.47	2.69	0.46	27.23	19.26	0.53
	November	0.46	2.87	2.15	0.57	19.45	12.23	0.78
	December	0.20	4.73	3.42	0.27	33.59	23.16	0.69

Table 3: Monthly variation of wind predictions and power productions forecasts for 9 km and 3 km grid resolution. Average values for 00-72 hours forecast horizons.

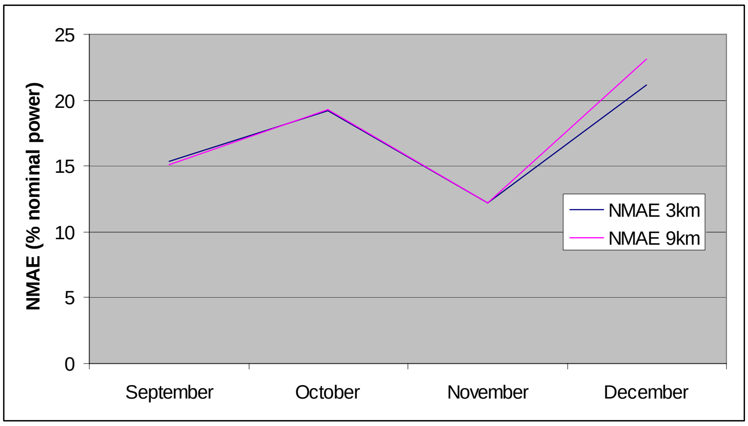


Figure 6: NMAE of power production predictions. Alaiz test case. 3 km vs 9 km grid resolution.

Figure 6 shows that there is no significant improvement of the wind speed forecasts when increasing MM5 grid resolution from 9 km to 3 km. The biggest difference of the error index was obtained in December being 6% lower for the 3 km grid resolution.

MM5 planetary boundary layer parameterisations

In this part of the work 4 different PBL parameterisations were analysed. Wind speed forecast errors and power production forecast errors are presented for the simulated cases. Simulated period May – October 2004. Alaiz wind farm. Forecasts calculated using MM5+LocalPred.

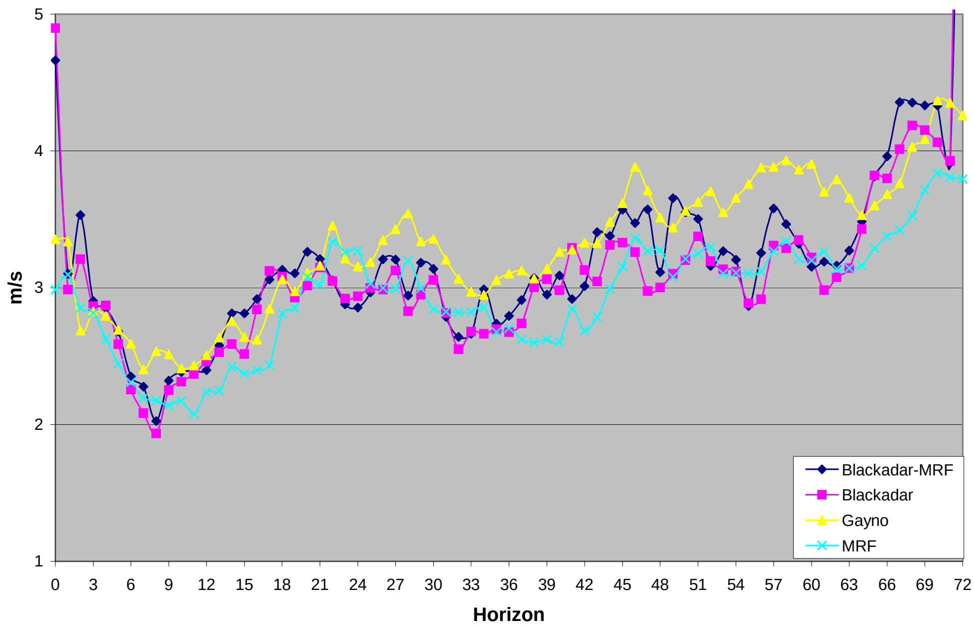


Figure 7: RMSE of wind speed predictions. MRF, Gayno, Blackadar and Blackadar-MRF PBL parameterisations. Alaiz test case.

According to Figure 7, MRF PBL parameterisation gave the best results for the majority of the forecasts horizons, it also can be seen that Gayno parameterisation performed worse that the other ones for the majority of the forecast horizons.

Value of MM5 for wind power predictions

The objective being to get the best wind power forecast, we have carried out a comparison between the relatively coarse GFS NWP versus the MM5 high-resolution modelling results. For this comparison, the MOS corrections were used to simulate the real operation of the CENER complete forecasting system but using the two different NWP.

	GFS 1º+MOS	MM5 3km+MOS
NMAE	31,09	20,07
NRMSE	38,67	28,06
R2	0,25	0,36

Table 4. Wind power prediction errors using GFS 1º and MM5 3km NWP.

The previous table shows that there is a significant improvement of wind power forecasts by the use of MM5 in comparison to GFS. Mesoscale modelling is useful to improve the accuracy of the forecasts even using a statistical correction like the MOS.

Conclusions of MM5 optimisation for power production forecast

The calculation time is related to the size of the nested domains, the spatial resolution and also to the number of sigma levels. A configuration with 25 x 25 grid points, 3km grid resolution with two-way nesting gives reasonable calculation times for on line operation.

The following conclusions are valid for MM5 + LocalPred forecasts:
There is no significant improvement in the wind speed and power production forecast errors for Alaiz when increasing the grid resolution from 9 km to 3 km. This means that similar accuracy can be obtained with less computational effort. Part of this result can be explained due to the effect of the MOS included in LocalPred model, the MOS removes part of the NWP errors reducing the differences between the 9 km and 3 km grid resolution configurations.

MRF PBL parameterisation was the best one in terms of wind speed and power production prediction errors for the studied periods.

2.4 MM5 (ARIA)

First, ARIA applied MM5 to the December 2003 period for two different configurations: one-way and two-way interactions. MM5 has the capability of multiple nesting running at the same time and completely interacting. In the case of two-way interaction the nesting ratio is always 3:1, whereas for the one-way interaction the ratio can be larger.
The resolution of the smallest domain is the same in the two calculations corresponding to a 2 km mesh grid. The resolution of the largest domain is 10 km for the one-way case and 18 km for the two-way case. The MRF scheme for the evolution of the planetary boundary layer is used for this site.

The measurements carried out at the mast at a level of 55 m a.g.l. (X=617.451 km; Y=4726.519 km; Z=1095 m, UTM coordinates) have been compared to the results from the neighbouring grid point of the MM5 model (height of level 2 of MM5 model: 44 meters).

The one-way and two-way configurations give accurate results for Alaiz during the December 2003 period. However, for the small domains containing less grid points, the two-way nesting does not improve the results significantly compared to the one-way nesting. The one-way run could be therefore be an acceptable solution if it is desired to reduce the calculation time for this type of calculation.

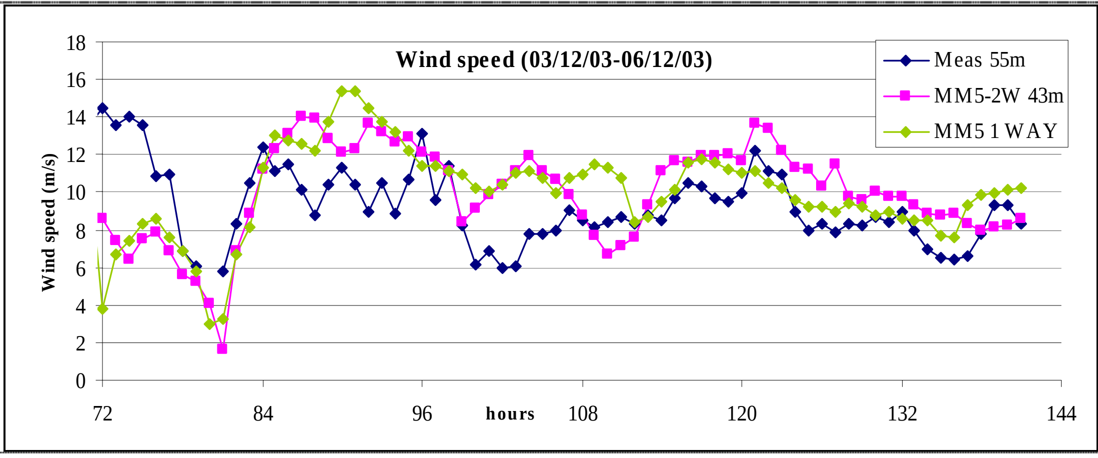


Figure 8: MM5 modeling output from the 03/12/2003-06/12/2003 period at the Alaiz site

The precision of the meteorological fields increases by carrying out nesting calculations with the MM5 model: the extractions of the nearest grid point of MM5 approaches measurements as the resolution of calculation increases. A 2-way MM5 simulation for the month of December 2003 was carried out and the results of wind speed, wind direction and temperature for the 3 resolutions (18km-6km-2km) can be found in Table 5 as well as in the figures above.

The modelling of the December 2003 period permits to evaluate the error between the measurements and the nearest grid point of the MM5 model (2km-6km-18km resolution):

- Average Wind speed
- Mean Error (ME)
- Mean Absolute Error (MAE)
- Root Mean Square Error (RMSE)
- Normalized MAE
- Normalized RMS

	MM5 (18km) 44 magl	MM5 (6km) 44 magl	MM5 (2km) 44 magl
Average (m/s)	5.02	5.77	8.25
ME (m/s)	3.23	2.5	-0.02
MAE (m/s)	3.42	3.18	2.5
NMAE	0.68	0.43	0.29
RMSE (m/s)	4.38	4.29	3.3
NRMSE	0.87	0.74	0.4

Table 5: Wind speed error analysis for ARIA MM5 modelling.

Conclusions:

The mean wind speed measured at the site during the month of December 2003 is 8.3 m/s. From Table 5 it can be noted that the calculation errors decrease as the model resolution is refined. The nesting allows to improve the meteorological calculation; it should however be observed that MM5 is not recommended to apply for resolutions below 1km. Our simulation has shown that the results can be improved down to a 2 km resolution. Globally, the wind speed increases and temperature decrease according to the measurements when the resolution becomes higher for Alaiz case. Local effects as speed-up, atmospheric stability due to topographic data, land-use data and soil model was modeled with more accuracy. The most improvement for wind speed and temperature results occurs when going from 6 km down to 2 km nesting. In order to further improve the results when even higher resolution is required, nesting with other models (such as ARIA WIND) is described in chapter 2.6.

2.5 MM5 + CFD (CENER)

In this chapter the results corresponding to the nesting of MM5 (with 3 km horizontal resolution) and the CFD model Fluent are presented. The objective is to determine if there is a reduction in the wind speed prediction errors when MM5 NWP are refined with a high resolution CFD simulation of the wind flow in the wind farm. The description of the CFD model used is in the Model Description report [2].

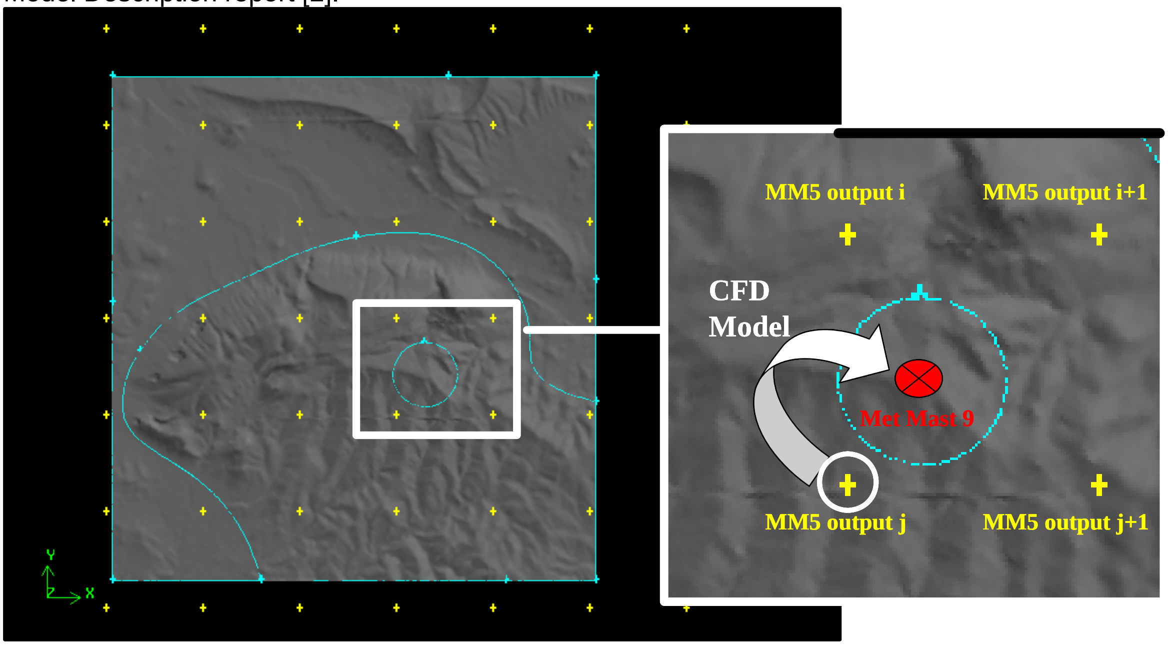


Figure 9: CFD downscaling of MM5 NWP. 3D view of the Alaiz area and MM5 grid.

The configuration of Fluent used to simulate the wind field in Alaiz had the following characteristics:

- Digital terrain model defined by a node every 50 metres (max. computational capability).
- Quad-Pave scheme (unstructured mesh) for ground-surface.
- The density mesh is about one node every 50m (works to study grid independence have been carried out).
- The volume is meshed using the Cooper algorithm and a ¨boundary layer¨ close to ground.
- Size of the domain: height=8x(z_{max}-z_{min}).
- Area: 14 km x 14 km.

Once the wind field is simulated for the area of the wind farm, the coupling between MM5 and Fluent is done taking the closest MM5 grid point to the reference mast, and by the use of the CFD relations the wind is transformed to the position of the reference mast (Alaiz 9):

$$U_{predicted\ point\ x}(\theta_i) = \left(\frac{U_{CFD\ point\ x}(\theta_i)}{U_{CFD\ point\ y}(\theta_i)} \right) U_{MM5output\ point\ y}(\theta_i)$$

The following figures show the results of the comparison between MM5, MM5+CFD, MM5+LocalPred and MM5+CFD+MOS (only CFD variables). The errors are given for December, for winds from the north sector only. The comparison gives the opportunity to see the effect of the MOS (LocalPred) when it is applied to MM5 NWP, also the CFD contribution can be determined with and without the effect of the MOS.

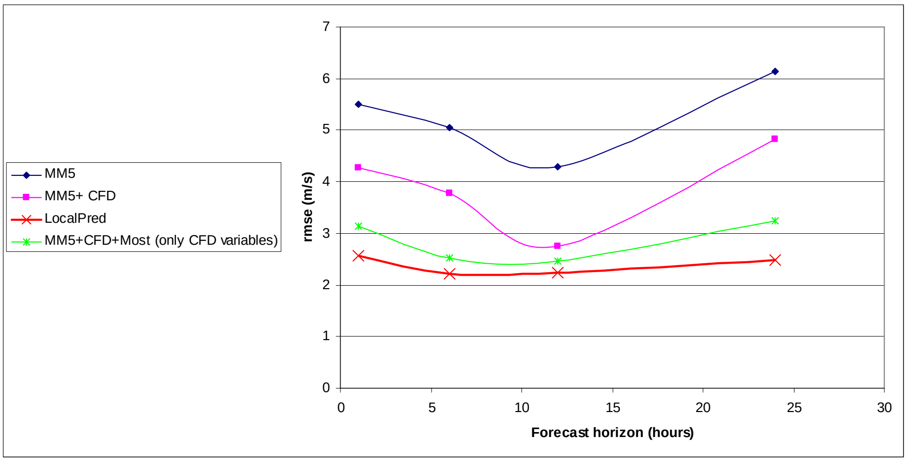


Figure 10: RMSE of wind speed forecasts. Alaiz wind farm. MM5, MM5+CFD, MM5+LocalPred, MM5+CFD+MOS (only CFD variables).

Figure 10 shows that MM5 wind speed forecasts can be improved by CFD calculations (a reduction of about 2 m/s in RMSE). Further error reduction is achieved when a MOS is used to correct MM5+CFD calculations. However, the standard configuration of MM5+LocalPred still gives the best results with a reduction of RMSE of about 0.5 m/s. The explanation for the better results corresponding to MM5+LocalPred is probably related to the fact that the MOS module included in LocalPred uses a number of MM5 grid points that are not used by the MOS in the case MM5+CFD+MOS.

As a summary, it can be said that CFD high resolution simulations can improve the accuracy of MM5 NWP, however the error reduction due to statistical MOS corrections is better than the error reduction obtained by the CFD.

2.6 CFD driven by mass-consistent model (ARIA)

In previous chapters, ARIA Technologies showed how to improve the meteorological results and wind energy production forecasts using MM5 and MM5 + ARIA WIND (MINERVE). Here, ARIA Technologies develops a method to improve the result with high resolution (<100 meters) using a CFD model driven by mass consistent model.

The aim is to compare the results of modeling with high resolution (100 meters) between CFD code (MERCURE: complex model) and a mass consistent model (MINERVE: simple model):

- Initialization and lateral conditions of CFD code driven by mass-consistent model
- Evaluation of output from a model run based on a simple model (MINERVE)

In order to estimate the approximate error made by a simple code (mass consistent model) in comparison to the CFD code, we define a stationary case for the most prevalent meteorological situation. In order to define which meteorological case study to choose, the wind distribution is analysed.

ALAIZ SITE: Wind Speed of 7,5 m/s at 55 magl / Wind Direction 160°
Neutral vertical atmospheric profile

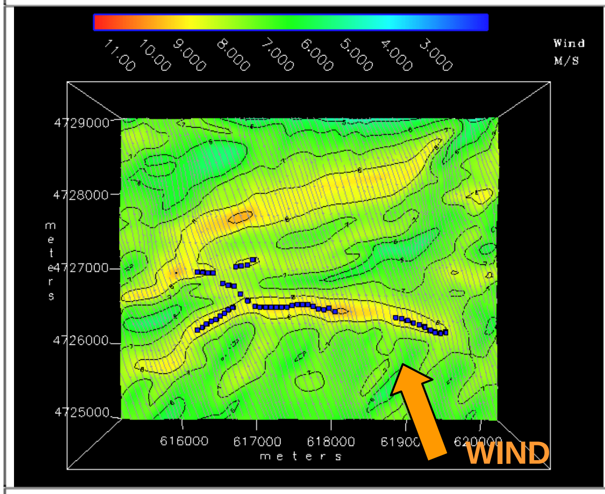
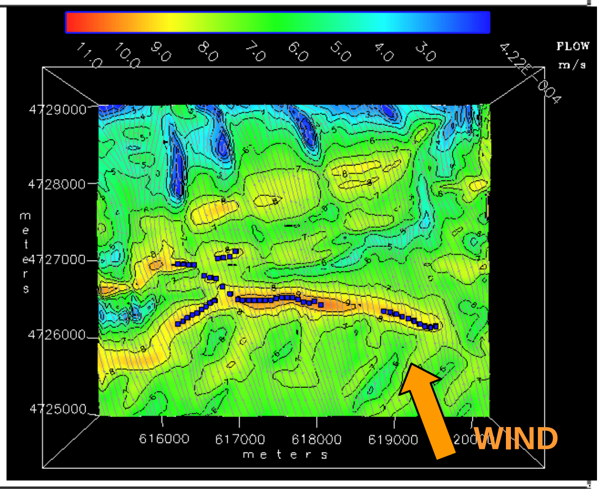
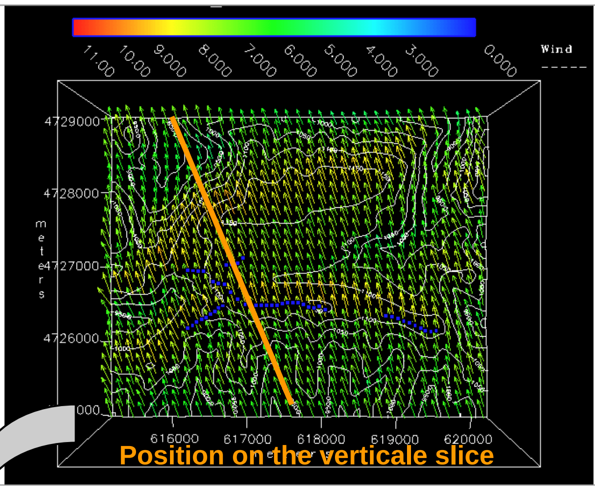
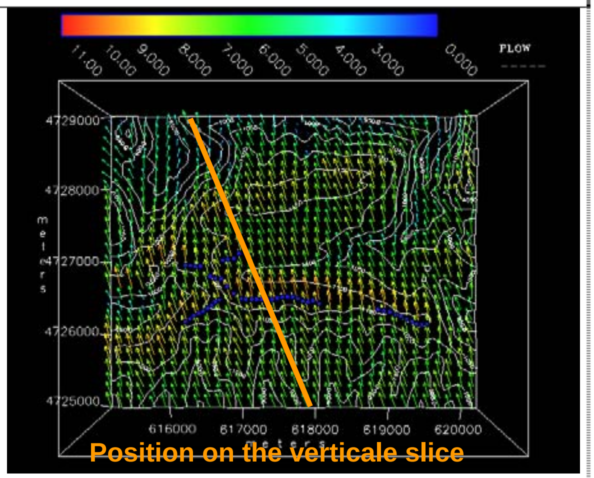
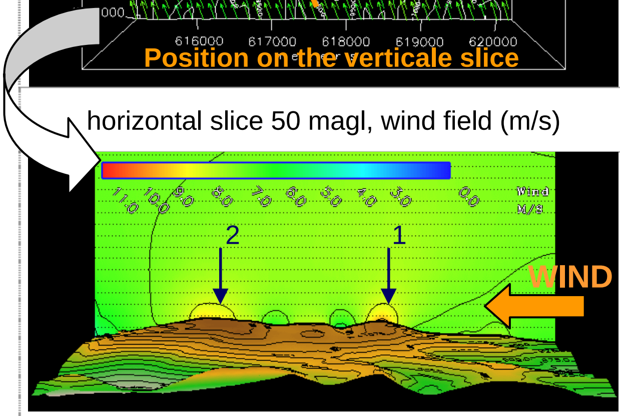
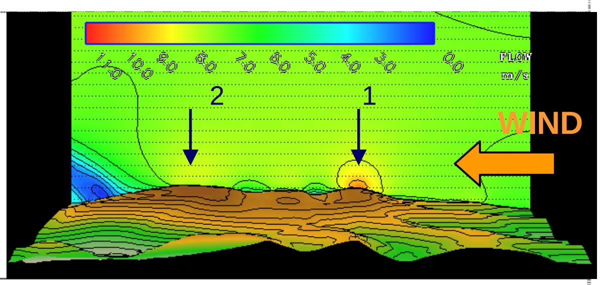
ARIA WIND (MINERVE: Mass consistent model)	ARIA LOCAL (MERCURE: CFD code)
	
horizontal slice 50 magl, wind field (m/s)	horizontal slice 50 magl, wind field (m/s)
	
horizontal slice 50 magl, wind field (m/s)	horizontal slice 50 magl, wind field (m/s)
	
Vertical slice in the wind axis, wind field (m/s)	Vertical slice in the wind axis, wind field (m/s)

Figure 11: A comparison of Aria Wind and Aria Local wind flow fields on Alaiz site

On the horizontal slice at 50 magl, the range of wind speed is different for the 2 models: the MINERVE values are found within the range of [3.5–10] m/s whereas the MERCURE values have a wider range [10e-4 – 11] m/s. The wind field of MERCURE model contain more contrast due to physical effects. On the top of the mountain where the wind farm is installed, MERCURE calculates higher wind speeds than MINERVE.

As the wind prevails from the south, wake effects appear on the mountain north of the mountain where the wind farm is situated. The two mountains (arrows 1 & 2 on the vertical slice) have similar altitudes, the wake effects can be seen on the vertical and horizontal slices in the figures above. The MERCURE code yields higher wind speeds than MINERVE on the top of the first (southern) mountain (a difference of 1 m/s). On the top of the second (northern) mountain, the situation is inversed. The MERCURE model on this mountain (arrow 2) accounts for the wake effect downstream the first mountain (arrow 1).

This case shows the approximation made with a mass consistent model (MINERVE) rather than a CFD code (MERCURE).

3 Results for Corsica (Ersa Rogliano)

The wind farm in Corsica consists of two clusters: Ersa and Rogliano. The site is quite hilly, and the complexity is even increased by the fact that it is a small tongue surrounded by water on three sides. The land here is narrower than the distance between NWP points, so it would not necessarily be seen as a land point by the NWP. The cluster at Ersa consists of 13 Nordex N43 600kW turbines, the cluster at Rogliano of 7 machines of the same type.
The dates for the exercise were chosen from 6 dates given by EdF, in our own perceived order of importance. The two mandatory ones were 2003/01/16 12:00 – 2003/01/18 11:50 and 2002/12/26 12:00 – 2002/12/30 23:50, denoted below as test periods 2 and 1. One reason to choose these two for our modeling was that they were sufficiently short.

NWP and Observed Wind Characteristics

For the case of Corsica, the standard NWP was Aladin, the operational model of MeteoFrance with a horizontal resolution of 0.1°, or about 9 km. Please see the NWP model report [3] for a description.

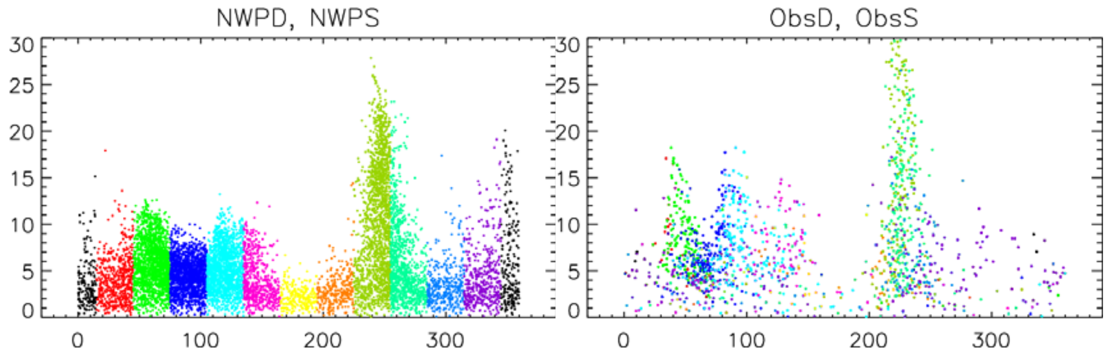


Figure 12: Left, the numerical weather prediction model wind speed (NWPS, y-axis) plotted against NWP direction (NWPD, x-axis) for 6 months of data. The colour of the data points indicates the NWP direction sector. Right, the observed wind speed (ObsS, y-axis) plotted against observed wind direction (ObsD, x-axis) for the same period as the NWP model data. The colour of the data points indicates the NWP direction sector.

The NWP and observed wind speed against wind direction distributions are shown in Figure 12. In both the NWP and observed wind the south-westerly exhibit fastest wind speeds. The data is shown for the where both measurement and forecast data concurrently available over the period from November 2002 to May 2003. Broadly, easterly winds are frequent in both NWP and observed winds. NWP northerly winds are not often seen in the observed winds. The observed wind speeds tend to be slower than the observed winds. The colouring of the points gives an indication of how well the forecast wind direction agrees with the observed wind direction.

For this conference paper, the results of KAMM modelling in Corsica have been omitted, as they are qualitatively similar to the results in Alaiz. Nevertheless, these results figure in the general conclusions on the KAMM modelling. The same is valid for the initialisation of the CFD model with a mass-consistent model done by Aria. IASA has run RAMS for the case of Corsica, but the conclusions are not sufficiently different from the conclusions for Crete to be shown here.

3.1 MM5 (CIEMAT)

CIEMAT has applied MM5 to the 6 chosen Corsica cases. The NWP data used in this case come from the NCEP analysis data base, with a 2.5°x2.5° resolution and a time step of 6 hours. It has been chosen two-way nesting, with 5 domains.

The results of applying two PBL parameterizations (ETA and MRF) have been compared with the measurements and the initial conditions coming from the NCEP data, for each case, calculating the corresponding error statistics.

As the two stations (SCITE and TDF masts) are very near one another, both the measurements and the MM5 outputs are very similar.

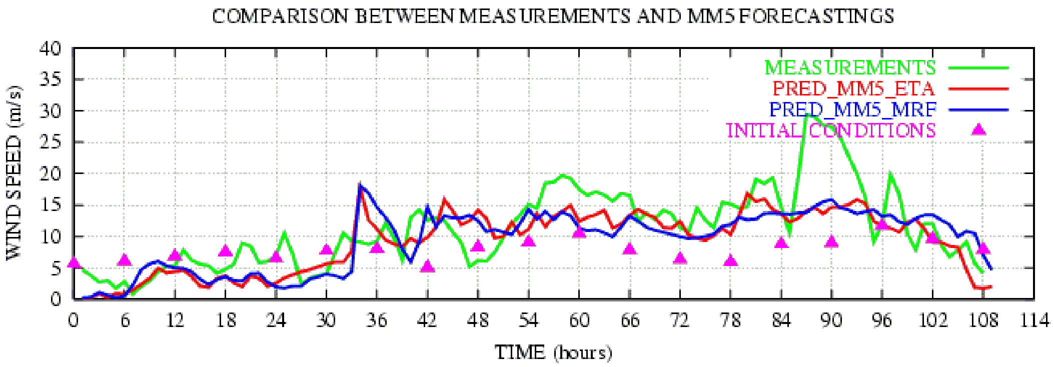


Figure 13: Comparison between SCITE measurements (in green), first interpolations of the NCEP data (in pink) and results of the two MM5 parameterisations (MRF and ETA in blue and red) for the period 26/12/2002 12:00 to 30/12/2002 23:50

No general conclusions are evident for all the Corsica cases for the MM5 downscaling. In some of the periods MRF is better than the ETA parameterization but in the other periods it is the contrary. The MM5 curves are softer than the actual curves, mainly because the NCEP analysis data are recorded every 6 hours, instead of the 1 hour step of the measurements.

The coefficient of determination of the linear regression (R^2) is, in general, high, but also the NRMSE is high. The coefficient of multiple determination S(k) is usually relatively low, and sometimes very low, what means that the model cannot explain the variance of the measurements.

Nevertheless, in all the cases the model (MM5) improves the initial conditions used by this model, interpolated to 135km from the 2.5° NCEP analysis data, which always underestimates the actual values.

3.2 MM5 (ARIA)

Corsica is an island situated in the Mediterranean characterized by complex topography. The climatological conditions are as a consequence also complex and the local effects are important, altogether making the meteorological modelling interesting as well as challenging. Comparisons of the model output have been made with measurement data taken from the TDF mast situated at Ersa-Rogliano (X=531.072; Y=4757.174; Z=556 / UTM 32).

The MM5 modelling was carried out by using meteorological input data from the AVN model (AVN analysis). A 2-way calculation has been carried out comprising 4 nested domains with the largest domain having a 27 km grid resolution and the smallest domain a 1 km grid resolution, using a 100 m terrain database. Two different planetary boundary layer schemes have been tested: MRF and Blackadar PBL schemes.

Two objectives have been set for these simulations:

- Analysis of the impact of changing grid resolution for the different MM5 domains on the modelling results
- Analysis of the influence of the parameterization of the PBL on the modelling results (two PBL Schemes: MRF and Blackadar)

Comparisons have been made for the following meteorological variables: wind speed, wind direction and temperature. The measurements carried out at the mast at a level of 43 m a.g.l. have been compared to the results from the MM5 calculations by taking into account the nearest grid point of the MM5 model (height of level 2 of MM5 model: 44 m).

Scenario 1: 02/02/03 12:00 to 03/02/03 24:00

Modelling of Strong Winds in the most frequent wind direction

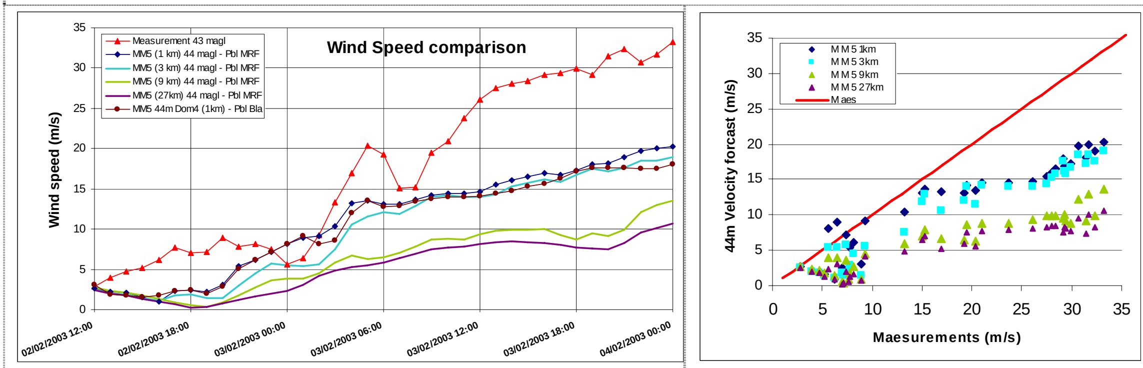


Figure 14: Evolution of wind speeds over the period 02/02/03 12:00 to 03/02/03 24:00

Concerning the wind speed, an improvement can be observed down to a 3 km grid resolution. The improvement with the 1km grid resolution is however modest. The speed up for high winds is difficult to model with a meso-scale model since the best possible resolution is 1 km which is not enough for taking into account local meteorological effects, such as a speed-up.

Differences in wind direction between the measurements and the MM5 results during the first 6 hours can be explain by looking at the measurement data: low wind speeds and high variability of the wind direction is occurring just before and at the beginning of this time period (2 hours before the beginning of this scenario, the wind direction measurement is 130 degrees with wind speeds of 2.7 m/s).

The model results of temperature is decreasing when the grid resolutions increases. The nested domain with 1 km grid resolution underestimates the temperature. The results obtained for the MRF and Blackadar PBL schemes are similar.

Scenario 2: 24/03/03 12:00 to 29/03/03 24:00
High wind speed variability

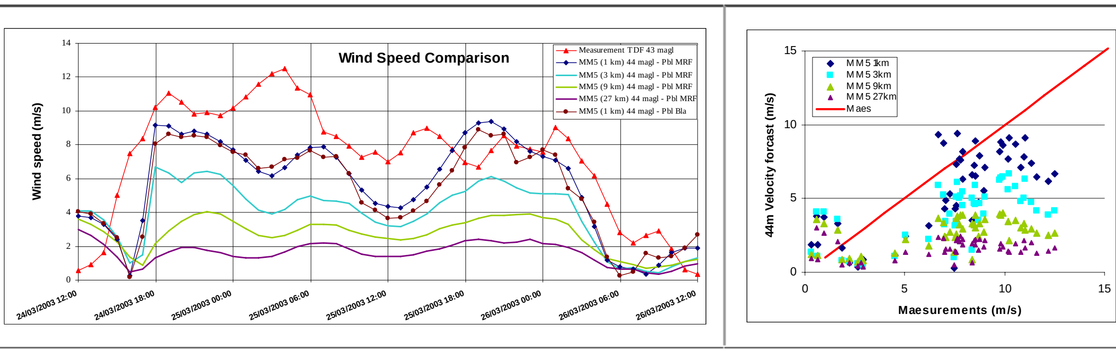


Figure 15: Evolution of wind speeds over the period 24/03/03 12:00 to 29/03/03 24:00

An improvement of the wind speed can be noted with increased grid resolution. The global evolution of the wind follows the measurements. The winds speed increases quickly in the beginning of the period to reach strong winds after a couple of hours and then slows down at the end of the scenario, similar to the measurements.

The MM5 result of temperature for the domain with the smallest resolution (1 km) underestimates the temperature. The results using Blackadar PBL and MRF PBL scheme look similar.

Conclusions:

These scenarios (one not shown here) were selected because of their meteorological complexity (scenario 2 & 3) related to the topography of the site and the proximity to the coastal Mediterranean sea. In these cases, the time period of simulation permits to analyze the influence of the nesting and PBL scheme of a meso-scale model.

Globally, the trend and the evolution are well accounted for with a meso-scale model like MM5. Using AVN analysis data, the nesting enhanced the results down to a resolution of 3 km. For the resolution of 1 km, the model wind speeds are further improved but the temperature is underestimated. The MM5 results for the smaller domain (1 km resolution) could probably be improved by using a larger grid with more horizontal points but this is quite expensive in CPU time. The calculation time is rather short – a calculation with a 1 km resolution is approximately 3 times longer than a calculation with a 3 km resolution. It could permit to account for local effects with more accuracy. In this case, a resolution of 3 km seems to be sufficient as a first approach. The MM5 results with regard to the two PBL schemes are very similar for these scenarios.

However, in order to further improve the mesoscale model results it is necessary to integrate local meteorological effects and to improve the grid resolution. This can be achieved by nesting with other meteorological models like ARIA WIND (MINERVE) taking into account local topography and land use or by using statistical combinations with pre-established calculations such as the MERCURE code (this methodology is explained in the following chapter).

3.3 ARIA: Nesting MM5 and MINERVE (Aria Wind)

Corsica is an island with complex topography making meteorological modelling difficult. The ARIA WIND (MINERVE) model can use topographic and land use data with high resolution (100 m), thus making the calculating of turbulence fields more precise; this is particularly important in the presence of discontinuities of ground conditions (such as land/sea interactions).

ARIA WIND SIMULATION: Nesting MM5/ARIA WIND on the Corsica site

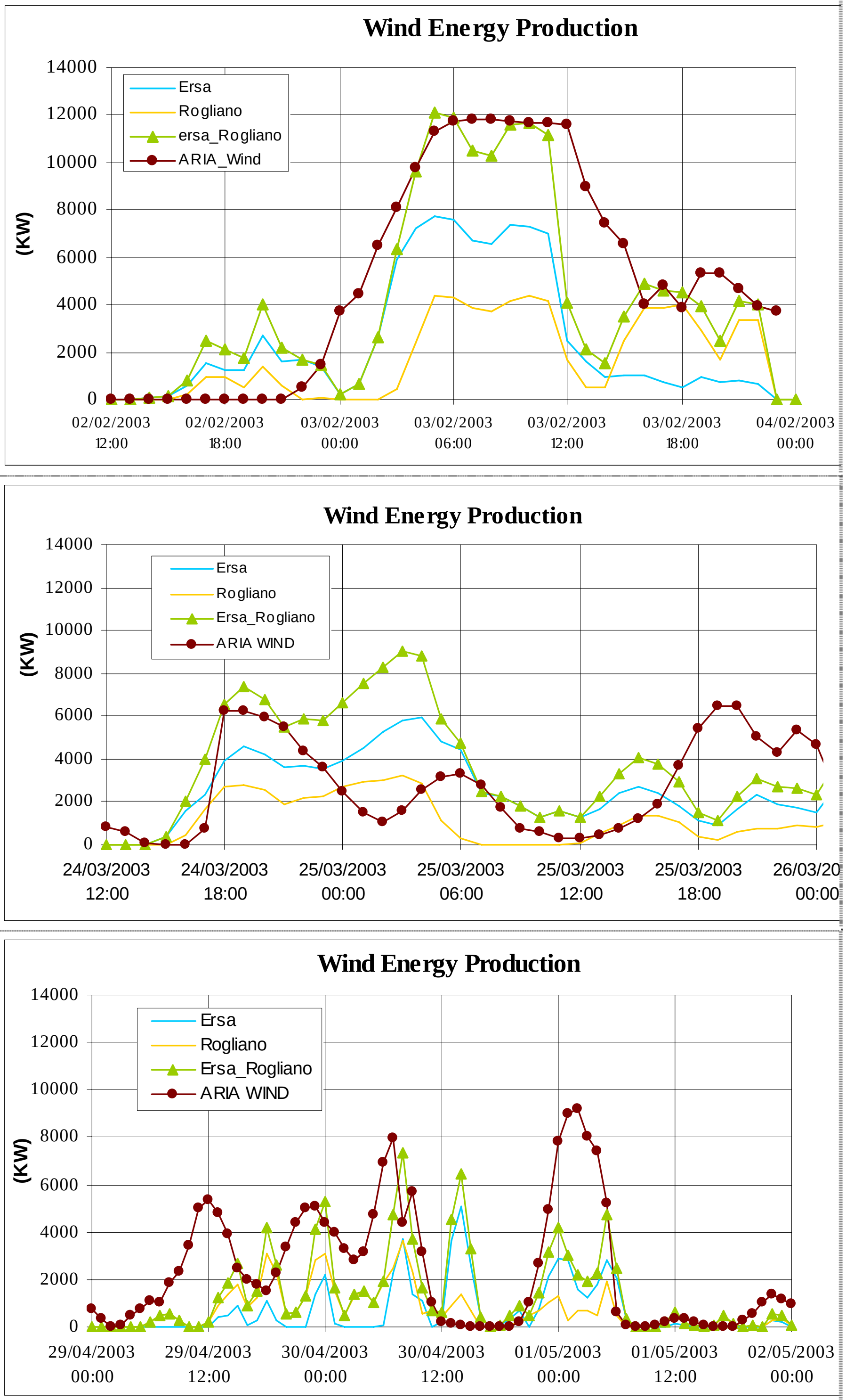


Figure 16: Time series of wind energy, nesting MM5/ARIA WIND.

Nesting of MM5 with ARIA WIND (MINERVE) is realized in order to compare wind energy production with measurements. The ARIA WIND nesting domain has a resolution of 100 meters. The meteorological data provided by MM5 and used for the nesting is presented in the previous chapter (Figure 14 and Figure 15).

The best results were obtained for scenario 1: Thanks to the use of topographical data with a high resolution (100 m) the increase of wind speed has been better accounted for than in the case of using only MM5 meso-scale nesting. The ARIA wind modelling of the “cut off” of the wind turbine corresponds to the measurements.

The two other scenarios are more difficult to model because of the variability of meteorological conditions. It’s difficult to draw any conclusions from these cases regarding the improvements with nesting MM5 with the ARIA WIND model; the meteorological scenarios selected were difficult to model and the time series were too short.

4 Results for Crete

The main wind farm for the Anemos comparison in Crete is the farm at Rokas, in the eastern mountains of the island. Additionally, three more wind farms were chosen for comparison, the Plastika, Iweco and Aeolos wind farms.
The agreed dates for the modelling were chosen as follows. Note that the corrected power (the blue line) is the measured power of Rokas, divided by the number of turbines actually running, and times 22. Thereby, the effects of technical failures are taken out of the power signal. The details of this are not so relevant, as both CIEMAT and IASA only modelled the local wind speed in the farm.

4.1 MM5 (CIEMAT)

CIEMAT has also applied MM5 to the Crete cases, using the same inputs as in the Corsica cases. The topography used (GTOPO30, by the U.S. Geological Survey’s EROS Data Center) in the last domain does not give any change in the level above the ground, in the surroundings of the mast. Therefore, a priori very good results cannot be expected in the downscaling. An increase in resolution should be possible with the new data from the Shuttle Radar Topography Mission (SRTM), though this has not been tried here. Only land-sea effects are taken into account.

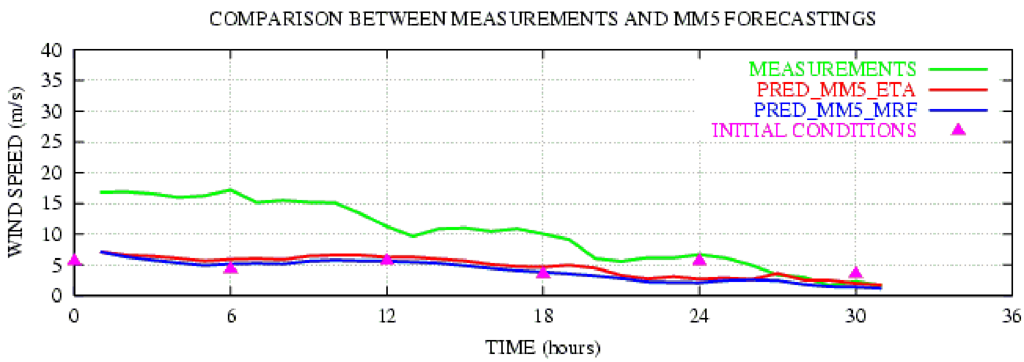


Figure 17: Comparison between measurements (in green), first interpolations of the NCEP data (in pink) and results of the two MM5 parameterizations (MRF and ETA in blue and red) for the period 15/1/2003 18:00 – 17/1/2003 17:00.

The MM5 results always underestimate the measurements (except the MRF ones during some hours of the second analysed period), giving high values for the bias. The coefficients of determination are different depending on the period, but in general they are not very high. The two MM5 parameterisations show very similar results in all the cases.

These relatively bad results could be expected, taking into account the bad topography and temporal resolution used as input data, as was mentioned above. Nevertheless, in all cases the model (MM5) improves the initial conditions used in this set-up, interpolated to 135 km from the 2.5° NCEP analysis data, which always underestimate the actual values, as it was concluded in the Corsica cases.

4.2 IASA: Rams

IASA has contributed to the high resolution modelling of WP4 by providing data with the RAMS model of down to 0.5 km for the wind farm of Rokas in Crete for a period selected in 2003. In particular, RAMS runs for the testing period proposed for wind energy forecasting purposes between 4 and 6 September 2003. Five two-way nested grids were used for the particular application with the largest one to cover the whole Mediterranean Region with 48km resolution; the next grid of 12km resolution included the whole Greece, the third grid of 6km resolution contained Crete, the fourth grid of 1.5km resolution included the east part of Crete, while the smallest grid included the edge of the east part of Crete with 0.5km resolution where the Rokas wind farm is located (c.f. Figure 18). Three different runs were performed in order to investigate the effect of the initial conditions, i.e. time of initialisation and use of only analysis data or addition of assimilated observations, on the predicted wind:

- With initialisation at 00UTC on 04/09/03 with ECMWF gridded analysis fields for a period of 90 hours, hereafter called "Run1".
- With initialisation at 00UTC on 04/09/03 with ECMWF gridded analysis fields and observations assimilated for a period of 48 hours, hereafter called "Run2".
- With initialisation at 12UTC on 04/09/03 with ECMWF gridded analysis fields for a period of 48 hours, hereafter called "Run3".

The wind farm of Rokas as well as other wind farms sited at the east part of Crete at an altitude of 480m, located in a mountainous area with varying topography.

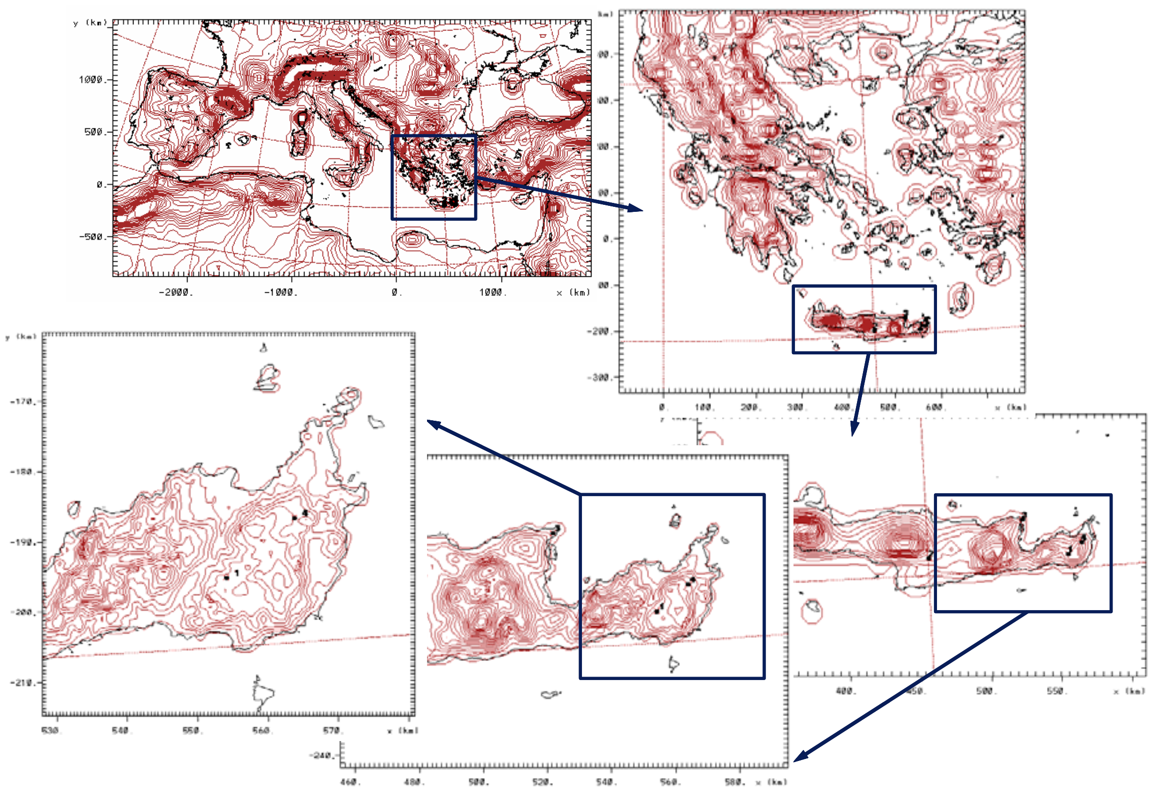


Figure 18: The five two-way nested grids used for the RAMS application for the case of Crete wind farms.

The modelled horizontal wind was extracted at the location of Rokas for the nested grids of 12 km, 6 km, 1.5 km and 0.5 km. In this way, the effect of the grid resolution on the predicted wind was investigated. At the same time the modelled wind was taken from the two model levels adjacent to the observation level (40m above ground), in order to examine also the best fitted modelled level to the measuring level values. Figure 19 shows time series and scattered diagrams of the predicted horizontal wind at the two modelled levels for all three runs as one example of similar plots for all four chosen grid resolutions.

For the nested grid of 12 km horizontal grid resolution, RAMS follows the evolution in time of the data fairly well with the higher model level being closer to the observations. An underestimation of the predictions for the second level is observed for winds stronger than approximately 20 m/s. It seems that there are small differences among the results of the three runs that mostly involve the predictions during 00UTC and 15UTC on 5/9/2003, when the highest winds are observed. The corresponding results for 6 km horizontal grid resolution show similar behaviour. However, the underestimation seems to have been reduced with the upper threshold being approximately 22 m/s. The differences among the results of the three runs start to appear after the 00UTC on 5/9/2003. Also the 1.5 km horizontal grid resolution results are similar. However, in this case the third run, namely initiation at 12UTC on 4/9/2003 with only ECMWF gridded analysis fields compares better with the observations (c.f. Figure 19). Finally, the predicted wind resulted from the 0.5km grid resolution is closest to the observations. However, the model still cannot capture exactly the high peak observed between 00UTC and 12UTC on 5/9/2003, hence an underestimation still exists only this time the upper threshold is approximately 25 m/s.

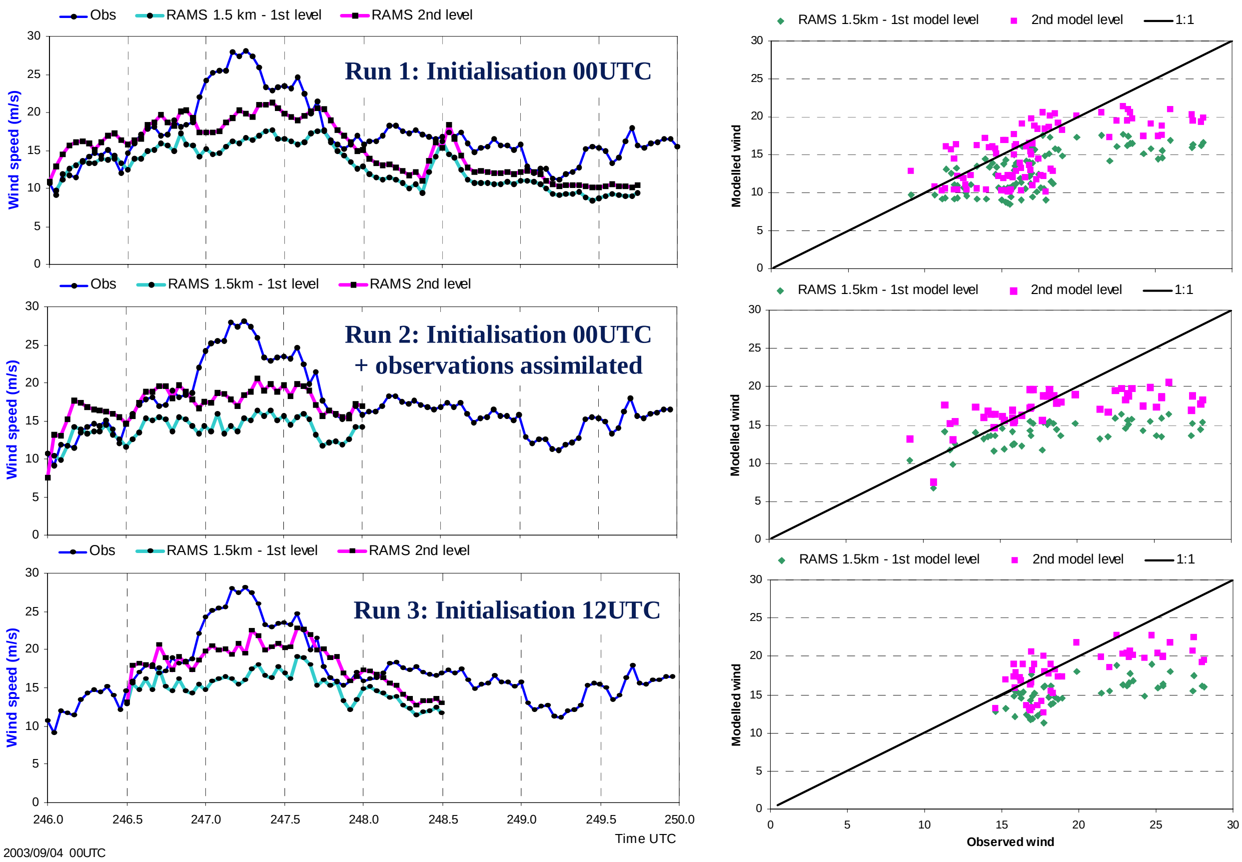


Figure 19: Comparison of wind speed observations and RAMS predictions at the first and the second free level resulted by the three different runs with the grid of 1.5 km resolution. The accompanying smaller plots show the scattered 1:1 diagrams between observations and predictions for both levels.

The behaviour of RAMS is further examined applying statistical analysis to the data series. The Bias and RMSE values were calculated for all cases. Here, we focus on the common period of the three runs, i.e. up to 00UTC on 6/9/2003, for consistency. **Error! Reference source not found.** includes the values of the average bias and RMSE for each 12-hour forecasting period together with the corresponding mean value of the wind speed for comparison with the RMSE. In this way, the first 12 hours correspond to the period between 00UTC and 12UTC on 4/9/2003 and hence it appears only in the case of Run1 and Run2.

The fact that the addition of observations assimilated in the initial conditions (Run2) does not offer improvements in the predicted wind that may have been expected is probably related to the limited number of measuring meteorological stations available in the area of Crete. On the other hand, Run3 provides the most accurate predictions as the initialisation time is closer to the change (increase) in the wind conditions.

The discrepancy of the model results of all three runs from the observations may be subject to different aspects such as:

- errors in the initial and lateral boundary conditions provided by the global model,
- possible errors in the observations, e.g. instrumental errors, influence of the wind generators due to their location with respect to the monitoring tower, etc.
- representativity of the terrain surrounding the wind farm measuring point.

The representativity of the terrain is an important aspect for the accuracy of the forecasts. If the terrain is not sufficiently uniform to allow comparison to the scale of the grid cell, the models will average the flow characteristics. For this reason, higher resolution modelling may provide more accurate wind predictions. The existing tools (two-way nesting atmospheric models) are considered mature for wind potential forecasting applications. However, such applications are computationally expensive. In particular, the CPU time required for a 48-hour run with 5 two-way nested grids in 3 nodes (6 CPUs) was approximately 48 hrs. Therefore, the answer to the necessity of performing such runs using expensive computational facilities to get this level of information for operational purposes is dependent on the requirements and the purpose of the case study itself.

5 Summary and Conclusions

This section first summarises the individual institutes own findings, and then tries to bind the WP together into some cross-cutting conclusions.

Conclusions from the studies with RAMS

The representativity of the terrain is an important aspect for the accuracy of the forecasts. If the terrain is not sufficiently uniform to allow comparison to the scale of the grid cell, the models will average the flow characteristics. For this reason, very high resolution (> 10 km) modelling may provide more accurate wind predictions. The existing tools (two-way nesting atmospheric models) are considered as mature for wind potential forecasting applications. However, such applications are computationally expensive. Therefore, the answer to the necessity of performing such runs using expensive computational facilities to get this level of information for operational purposes is dependent on the requirements and the purpose of the case study itself. One way to avoid using such expensive resources and at the same time to obtain accurate meteorological forecasts is the application of Kalman filtering onto less high resolution forecasts (~10 km), which may lead to improved wind power predictions (c.f. Deliverable report D3.1).

Conclusions from the offline KAMM mesoscale modelling studies

While it has been seen that qualitative wind flow characteristics of the wind farm sites have been captured in the mesoscale modelling work, it has been found that there are several issues that need to solved in order to fully exploit advantages that the offline mesoscale modelling may be able to offer for short term predictions.

The first problem is that the information needed for selecting the most appropriate mesoscale model run to be used for the correction matrix is not information given in the typical NWP output for wind farm short term prediction. Typically, NWP values for wind speed and direction at a couple of heights above ground level for neighbouring grid points have been used in short term prediction systems. However the mesoscale model needs to have information covering the vertical and horizontal extent of the modelling domain. For a very simple site it would be possible to create a function to convert the NWP wind at the site to some kind of large scale wind. However for these cases the flow is too complicated to allow this to be done.

The second problem is that since stability plays a role in the regional flow, stability information is needed for the mesoscale integrations. So far the prediction system described here has used a look up table based on wind speed and direction alone. Even though it was seen that stability alters the regional flow, there was no clear way of including it from the NWP output. The sectorwise MOS had the same dimension number as the KAMM corrections and for this reason the inclusion of the KAMM corrections did not improve forecast skill.

The results of this study have provided very helpful suggestions towards the next steps that need to be taken for offline mesoscale modelling to be used in short term prediction. For example NCEP/NCAR reanalysis data covering the same time period as the Alaiz test case period is being used to provide information about the geostrophic wind and temperature profiles. With this information the KAMM modelling can be done taking into account the large-scale winds and stability. The NCEP/NCAR reanalysis data will be replaced by the appropriate meteorological fields from NWP models for more realistic testing. This work is ongoing and should be the subject of subsequent publications.

The 4 times daily NCEP/NCAR reanalysis data for 2001 has been used to construct approximately 100 different wind and stability situations, called wind classes, for the Alaiz case study. The mean wind farm measured wind and power production have been calculated based on the occurrence of each wind class. Interestingly it has been found that for wind classes with the same wind speed and direction but different stability, the high stability cases show an increased measured wind speed and farm power production. This is consistent with the studies described earlier in this report.

For each wind class a KAMM simulation has been performed. It is then possible to relate the wind speed at the wind farm site from the simulations with the wind measurements for a given time when that wind class is valid. If no MOS is used, the mean error on the wind speed is -1.4 m/s and mean absolute error is 3.8 m/s. This compares to a mean error of –1.0 m/s and a mean absolute error of 4.6 m/s if the NCEP/NCAR geostrophic wind is used directly. The reduction in the mean absolute error that comes about with the use of KAMM indicates that the mesoscale model when used with the wind classes is adding skill to the forecast. If MOS is used with the output of KAMM, then the mean error becomes –0.3 m/s and the mean absolute error becomes 3.1 m/s. This compares well with the Hirlam-MOS results with mean error of -1.2 m/s and mean absolute error of 2.8 m/s seen earlier in the report. Considering the coarse resolution of the NCEP/NCAR model compared to the Hirlam model, the KAMM wind class method performance is encouraging.

MM5 nesting (meso scale modelling) and MM5+MINERVE (local approach)

Using NWP data (GFS data made by NCEP in the US), MM5 nesting improves significantly the wind speed results down to a resolution of 3 or 2 km for the Alaiz and Corsica cases. MRF PBL scheme is designed for wind speed prediction.

The MM5 outputs can be very different depending on the inputs that are used (topography, PBL parameterisation, way of nesting, number of domains, etc.). In all the analysed cases the model (MM5) improves the initial conditions used in the Ciemat set-up, interpolated to 135 km from the 2.5° NCEP analysis data, which always underestimate the actual values.

It is not easy to get general conclusions from the errors analysis, especially when there is variation in the quality of the different error parameters between the different cases. From the Ciemat runs, It cannot be concluded that one parameterisation is better than the other. There are some cases in which further investigations are needed in order to remove some bias effects.

The differences between the results obtained during different periods in the same place can be quite large. It is possible that the main reason is the impossibility of MM5 to take into account some synoptic atmospheric features, especially in complex terrain. The relatively bad results could be expected, taking into account the bad topography and temporal resolution (6 hours) used as input data.

A nesting from MM5 to MINERVE (for wind energy production as ARIA WIND), a mass consistent model, improves the forecast of wind speed. MINERVE can take into account influence of atmospheric stability on flow, the topography and surface roughness with a highest horizontal resolution until 100 meters. MINERVE permit to improve the first solution of MM5 taking into account more local effects.

An automatic forecast system based on a MM5 configuration of one way nesting permits to forecast each day with less 8 hours of calculation time 48 hours horizon on a standard computer. The results are respectable. The nesting from MM5 to MINERVE for local approach improves the wind speed results.

Combination of CFD and mass consistent model

ARIA has applied MINERVE (ARIA WIND) and MERCURE (ARIA LOCAL) nesting to the Alaiz and Corsica cases. The aim was to improve the first solution with a simple model (MINERVE) by nesting it with a CFD code (MERCURE).

The method developed for a stationary case permits:

- Reducing the CPU time needed by the CFD code.
- Integrating all available data on the site for a 3D calculation with MINERVE, not only a vertical profile (3D meteorology fields and 2D topography and land use files).
- Improving the first solution provided by a simple code (errors made with a simple code/local meteorological effects on a complex terrain)

The combination of a mass consistent model (MINERVE) and a CFD (MERCURE) model improves the results for the complex site at grid resolutions inferior or equal to 100 meters. Local effects like wake effect or roughness effects are simulated with better accuracy.

The automation of the process could be made with MM5 + MINERVE + MERCURE. For such applications, we would need to define a classification for the meteorological conditions. Some cases would need a more complex tool (MERCURE) but most cases would be treated with a simpler tool. The definition of this limit needs a sensitivity study on different sites: coastal sites, other complex sites and offshore sites. This kind of modelling by associating MM5 + MINERVE + MERCURE with a statistical method would be especially suitable in complex terrain.

Cross-cutting conclusions

The work presented here consisted of different approaches applied to several distinct problems. This makes it hard to compare fairly the results obtained by each group. Weather modelling is a game with extremely many degrees of freedom, not all of which can be analysed in detail. However, the results as such using high-resolution modelling in complex terrain were encouraging. While the “rule-of-thumb” for when to use finer scale modelling remains elusive, it is clear that more effort in improving the NWP predictions can pay off in many cases with complex terrain. It is difficult to say a priori what constitutes complex terrain, but high RIX values indicating non-attached flow are one way to figure out the complexity of the terrain. Low horizontal resolution from the NWP input also is a factor to take into account when deciding.

Generally, there are two approaches: the look-up table approach and the nested model approach. Both approaches can be coupled with a MOS, refining their results using actual measured data. If such data is available, it can replace some of the highest resolution modelling steps. In all cases, we have seen that there seems to be a natural limit to accuracy – going from 9 to 3 km horizontal resolution does not necessarily help, if the prediction is coupled to a MOS, and even without a MOS can the result of 1.5 km and 500 m resolution be comparable. In the latter case, we could track down the problem to be a terrain database resolution of only 1 km. Also in other cases it seemed that exceeding the resolution of the terrain DB is a waste of resources. On the other hand, increasing the vertical resolution in the lowest 200 m above ground increased the accuracy of the result. The model also has to encompass a large enough area to capture all the important properties of the airflow. This can require domains as large as 400x400 km^2.

Most of the effort expended in this work package was used on MM5. Despite the many different results, not everything became clear in the end. There was no clear winner for PBL parameterisation, although more often than not, if there was one, it was MRF. Also, one has to distinguish between use of MM5 in analysis mode (ARIA, CIEMAT) and forecasting mode (CENER). In forecasting mode, the quality of the predictions is soon limited by model physics, and not by the horizontal resolution employed. Also, phase errors (errors in the timing of changes) are only amplified by going to very high resolution in forecasting mode. This might be the explanation why ARIA finds improved results down to 2 km resolution, while CENER finds no improvement beyond 9 km resolution. On the other hand, the latter result was achieved with MOS. Two-way nesting seems to perform more reliably than one-way nesting, but under the right circumstances, one-way nesting can be an alternative. Care has to be taken at the boundaries of the domain, not to choose the last domain with the highest resolution too small, since there could be irregular conditions creeping in from the domain boundary.

The look-up table approaches did improve the quality of the forecasts, but were surpassed by the use of MOS. This is fairly self-evident, if one considers that the MOS usually employs as many variables as the look-up table, which in itself is linear. Only when a MOS is not possible, or when the meso-scale, micro-scale or CFD models are using more parameters for their look-up table than the MOS can there be a significant improvement at all. An advantage though was that the computational burden placed on the forecast provider is much less for a look-up table than it is for a nested model. The computing time scales mainly with the number of points calculated by the model, while the accuracy does not necessarily follow.

Recommendations

If you have a site in complex terrain, where you even after using an advanced MOS are not happy with the forecasts, then try to use higher resolution modelling. In many cases and with a large number of approaches, the models can improve the NWP results. When setting up a model yourself, make sure to use the best terrain DB available (e.g. SRTM data), and try to get good NWP input data. Set up the model to have good vertical resolution, and reasonable horizontal resolution. Find out for yourself what “reasonable” means in this context. Use a MOS. Use insights gleaned from high-resolution modelling to decide which parameters to employ in the MOS. In any case, setting up a model from scratch will take a long time before one is familiar with the model and its quirks, so do not plan on having a solution up and running immediately.

6 Acknowledgements

Thanks go to Energia Hidroelectrica de Navarra, Spain, for providing the measurement data and to National Meteorological Institute of Spain for providing the HIRLAM forecast data. Thanks goes also to EdF, France, for the data from the wind farms in Corsica. Also, PPC is acknowledged for their data from the wind farms on Crete. And a great thanks to our sponsor, the European Commission, funding the Anemos project (ENK5-CT-2002-00665).

7 References

1 G. Giebel (ed.), et al, *Model Results.* Anemos project Deliverable D4.1b, 2006. See Anemos.cma.fr.

2 G. Giebel (ed.), J. Badger, P. Louka, G. Kallos, C. Lac, G. Descombes, A-M Palomares, I. Martí Perez: *Description of NWP, Mesoscale and CFD models*. Anemos project Deliverable 4.1a, 2005. See anemos.cma.fr

3 Louka, P., G. Kallos, C. Lac, I. Martí, A.M. Palomares, P. Katsafados: *Evaluation of purely meteorological forecasts with emphasis to high-resolution systems.* Deliverable report D2.2 for the anemos project. See anemos.cma.fr.

4 Louka, P., P. Katsafados, G. Kallos: *Long term wind resource predictability*. Deliverable report D4.3 for the Anemos project. See anemos. cma. fr

5 Adrian, G. and F. Fiedler, 1991: *Simulation of unstationary wind and temperature fields over complex terrain and comparison with observations*. Beitr. Phys. Atmosph. 64, 27-48.

6 Mortensen, N. G. Mortensen, L. Landberg, I. Troen, E. L. Petersen, 1998: *Wind Atlas Analysis and Application Program (WAsP). Vol. 1: Getting Started.* Risø National Laboratory, Roskilde, Denmark, Risø-I-666(v.1)(ed.2)(EN).