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THE NUMERICAL WIND ATLAS
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THE KAMM/WA^{S}P METHOD

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ABSTRACT

This paper will describe the method of combining the Karlsruhe Atmospheric Mesoscale Model, KAMM, with the Wind Atlas Analysis and Application Program, WA^{S}P, to make local predictions of the wind resource. This combines the advantages of meso-scale modeling — overview over a big region and use of global data bases — with the local prediction capacity of the small-scale model WA^{S}P. Results are presented for Denmark, Ireland, and Northern Portugal.
Keywords: Wind resource assessment, meso-scale modeling, WA^{S}P, KAMM

INTRODUCTION

The Wind Atlas Analysis and Application Program WA^{S}P (Mortensen et al., 1998, 1993) is a tested tool to make predictions of the wind energy potential from high quality wind measurements. It estimates the local influences on the wind by small hills, roughness changes (see e.g., Mortensen and Petersen, 1998) and obstacles like trees or buildings to generate a wind atlas of "cleaned" measurements. This wind atlas is used to make predictions at other sites with a similar wind climate (see e.g., Troen and Petersen, 1989).

Unfortunately, in many parts of the world there is only poor or no wind data available. On the other hand, global weather models make analyses also in these areas, e.g. the re-analysis projects at NCEP/NCAR (Kalnay et al., 1996), ECMWF (Gibson et al., 1997), or NASA (Schubert et al., 1993). These analyses are too coarse to be used directly for wind power applications. However, they can provide boundary conditions and external forcing for atmospheric meso-scale models.

Meso-scale models make wind prediction for larger regions of several ten thousand square kilometers. To cover a similar area with measurements would require many stations. This is costly, and it takes a long time to obtain climatological estimates. Therefore, meso-scale models promise to be good tools to obtain an overview of the wind resource of an entire region. However, they can not be used for the siting of wind turbines because the grid resolution of these models is too big.

This paper presents a method of combining both types of models employing the wind atlas concept as used in WA^{S}P. The Karlsruhe Atmospheric Mesoscale Model KAMM (Adrian and Fiedler, 1991; Adrian, 1994) is used to simulate the wind field for a region. It is forced by data from the global NCEP/NCAR reanalysis (Kalnay et al., 1996). The simulated wind fields are processed into wind atlas files which can be read by WA^{S}P to make local predictions of the wind resource. The combination of KAMM and WA^{S}P was first used by Landberg and Watson (1994). Further calculations for Ireland are presented in Frank and Landberg (1996, 1997, 1998).

The concept is described in the next section. The main part presents a comparison of observations and predictions for sites in Denmark, Ireland, and Northern Portugal. The conclusions are presented in the last section.

THE KAMM/WA^SP METHOD

The KAMM/WA^SP method is the connection of the meso-scale model KAMM and the small scale model WA^SP to make local predictions of the wind resource at a site. It combines advantages of the meso-scale model, coverage of a larger region and the possiblity to use globally available data bases, with the high resolution necessary to make local predictions.

First, the meso-scale simulations are performed. We use the statistical dynamical approach of regionalization of large-scale climatology (Frey-Buness et al., 1995) to calculate the regional surface wind climate. The simplifying assumption is made that the regional surface layer climate is determined uniquely by a few parameters of the larger, synoptic scale, and parameters of the surface. This parameter space is decomposed into several representative situations. Numerical simulations of these situations are performed with the meso-scale model. Then, the meso-scale climatology is calculated from the results of the simulations together with the frequency of the typical situations.

Important parameters for the surface wind climate in mid-latitudes are the strength and direction of the large-scale pressure gradient, or geostrophic wind, the stratification of the atmosphere, possible persistent inversions (Frank and Petersen, 1998), changes in terrain height, and surface roughness. Near coasts, the difference of the surface temperature between land and sea can be important for the development of sea breezes. For most wind energy purposes in mid-latitudes, when the interest is mainly in the moderate to high winds, the geostrophic wind together with terrain height and roughness are the dominant parameters.

As we combine the meso-scale simulations with WA^SP, we employ 12–16 equidistant direction sectors of the geostrophic wind. Each sector is divided in several speed classes of approximately equal frequency per sector. Usually, more speed classes are used in more frequent sectors. The stratification of the atmosphere does not change as much as the geostrophic wind. Its importance is measured by the inverse Froude number ${\mathrm{F_r}}^{-1} = NL/U$, where N is the Brunt-Vaisala-frequency, L a typical length scale of the terrain, and U a velocity scale. Hence, stratification is more important at low winds. Therefore, the lowest speed classes in a sector are further divided according to the inverse Froude number. Still, all representative situations with geostrophic wind from one sector have approximately the same frequency. Adrian et al. (1996) or Mengelkamp et al. (1997) used clustering to define representative classes.

The frequencies of the classes are only approximately the same because they are determined locally for each point of the large-scale analysis, and interpolated to the grid points of the meso-scale simulations. This accounts roughly for inhomogeneities on the larger scale.

KAMM is forced by the large-scale pressure gradient and temperature distribution and run to an approximately steady state. The simulated surface winds are processed similar to measured wind to produce wind atlas files for WA^SP.

The combination of KAMM and WA^SP is illustrated in Figure 1. The simulated wind is corrected for roughness changes and orographic perturbations on the KAMM grid as in WA^SP. The orographic correction is calculated for neutrally stratified, non-rotating flow. Stratification and rotation effects are not accounted for in WA^SP. Therefore, they must remain in the “cleaned” data like they remain in “cleaned” observations. The roughness change model of Sempreviva et al. (1990) is used to calculate perturbations relative to an upstream roughness which is determined as in WA^SP. The upstream roughness is used to transform the “cleaned” wind

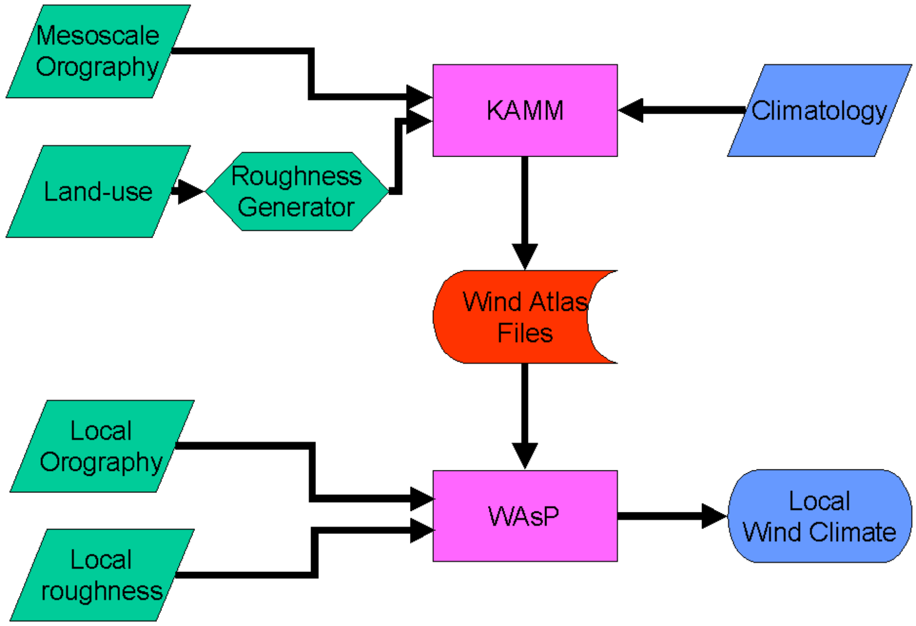

Figure 1: The combination of KAMM and WAsP to calculate the local wind climate.

to the roughness classes of a wind atlas file using the geostrophic drag law (see e.g. Blackadar and Tennekes, 1968).

Extra care must be taken to sample the simulated wind in several wind direction sectors, which is required for wind atlas files. The geostrophic wind classes have a width of some tens of degrees. Hence, on average, a simulated surface wind represents a sector of the same width. If it falls near the boundary of a sector of the wind atlas direction classes, it must be accounted for in both sectors of the wind atlas. Therefore, each simulated wind is split up in a number of wind vectors; typically in 5 values. The split-up winds are obtained by interpolation with the surface wind from the neighboring geostrophic wind class which is “most similar” to the geostrophic wind class which is split. The “most similar” wind class is the one in which the inverse Froude number, determined from the geostrophic wind and the mean stratification, is closest to the inverse Froude number of the split-up geostrophic wind class. The neighboring surface wind is also scaled to the same geostrophic speed with the help of the geostrophic drag law before the interpolation is done. After the simulated winds have been split up, there are enough values (¿500) to calculate frequencies and fit Weibull distributions for different sectors.

DATA

Topography

WAsP uses maps which contain lines of constant height and/or roughness change lines. The maps can be generated by digitization of topographic maps or exported and reformatted from GIS data sets. The resolution can vary from very high in areas with complicated topography to low in smooth, homogeneous terrain.

KAMM needs grid maps with a constant grid spacing. Terrain heights for the meso-scale simulations are

Table 1: The classes of the US Geological Service, which occur in the GLCC data base, and the assigned roughness length z_0.

z_0 cm	class	description
40	100	Urban and Built-Up Land
10	211	Dryland Cropland and Pasture
10	212	Irrigated Cropland and Pasture
10	213	Mixed Dryland/Irrigated Cropland and Pasture
7	280	Cropland/Grassland Mosaic
15	290	Cropland/Woodland Mosaic
5	311	Grassland
7	321	Shrubland
6	330	Mixed Shrubland/Grassland
7	332	Savanna
40	411	Deciduous Broadleaf Forest
40	412	Deciduous Needleleaf Forest
50	421	Evergreen Broadleaf Forest
50	422	Evergreen Needleleaf Forest
40	430	Mixed Forest
0.02	500	Water Bodies
03	620	Herbaceous Wetland
10	610	Wooded Wetland
02	770	Barren or Sparsely Vegetated
05	820	Herbaceous Tundra
15	810	Wooded Tundra
10	850	Mixed Tundra
3	830	Bare Ground Tundra
0.1	900	Snow or Ice

derived from the GTOPO30 global data base (GTOPO30, 2000), which has a horizontal resolution of 30 arc seconds, i.e. lless than one kilometer. The original heights are averaged with a weak Gaussian filter to the resolution of the model grid.

The roughness length of land surfaces is derived from the Global Land Cover Characterization (GLCC) data base (GLCC, 2000) using the classification of the US Geological Service. It is shown in Table 1 together with assigned roughness lengths. Some roughness values are different for some regions. The classification is derived from AVHRR data. It has a resolution of 1 km^2. A roughness length z_0 is assigned to each land use class. The coordinates are transformed from the Lambert Azimuth Equal Area projection to system used in KAMM (UTM, Irish National Grid). Then $\log z_0$ is averaged to the grid size of the simulation to obtain roughness maps for KAMM.

The CORINE land-use database (CORINE = Coordination of Information on the Environment) of the European Community was available for Northern Portugal. It has a much higher resolution, and we think it is more accurate. Therefore, it was used for that region.

The roughness length of the water surfaces is calculated from the friction velocity using Charnock's relation (Charnock, 1955). This predicts increasing roughness with increasing wind speed. However, for low wind speeds the roughness increases with decreasing speed. This is described using the roughness length for a smooth surface following Smith (1988).

Atmospheric data

The large-scale forcing for the meso-scale modeling is determined from several years of data from the NCEP/NCAR-reanalysis (Kalnay et al., 1996). In most cases the geopotential height of the 1000, 850, 700, and 500 hPa level and temperature and humidity at 850 and 500 hPa are used. The data is inter- and extrapolated to constant height above sea level and a geostrophic wind is calculated at these heights. Representative classes of geostrophic winds and stratification are determined from the reanalysis data set.

Rick Watson from University College, Dublin, provided the observed wind data for Ireland. Most of the data analysis for the Danish sites was done within the project "Vindressourcekort for Danmark", contract 51171/97-0002 of the Danish Energy Research Program. Data in Portugal was collected within the JOULE project "Measurements and Modelling in Complex Terrain", contract JOUR-CT90-0067. For one site in Portugal data was provided by Scite-Peristyle, S.A.

RESULTS

Here, we shall present results for Denmark, Ireland, and Northern Portugal. They can be roughly categorized as orographically simple terrain (Denmark, though roughness changes are complicated), slightly complex terrain (Ireland, some mountains), and complex terrain (Northern Portugal, very mountainous). Approximately 150 simulations were performed for each region.

Figure 2 shows the wind rose and Weibull distribution of wind atlas data for height 50 m above roughness length 3 cm processed from measured winds at Risø and from simulations for the grid point nearest to Risø. The agreement is good. The frequency of westerlies is over-predicted and that of southeasterlies is under-predicted. In general modeled wind roses are too narrow.

Model wind atlas data as shown in Figure 2 is used by WAsP together with high resolution maps to predict the local wind at a site. Observed energy flux densities, E,[1] are compared with modeled values in Figure 3 and 4. Observations are on the abscissa. The predicted values are shown on the ordinate. The vertical and horizontal dotted lines are the means of the observations and the predictions. The dotted diagonal would be perfect agreement.

The full line is a regression line which accounts for errors in both data sets. Probably, the biggest observation errors are periods of missing data. For the cross predictions it was assumed that the prediction errors are twice as big as the observations errors. For the other predictions the ratio between observation and prediction error was three.

Four different ways of modeling are compared in Figure 3. The first is the typical wind atlas application with WAsP, where data measured at one site is used to predict the wind at another site. Prediction between sites up to a distance of 25 km apart are shown in the plot.

In addition to surface observations WAsP can use upper air winds. Here, we used the wind at 850 mbar from the NCEP/NCAR reanalysis. Wind atlas files were made for each 2.5° with the reanalysis data. The wind atlas files were interpolated with the LibIntLT-program (Nielsen, 1999) to the exact locations of the

[1] Actually, the third moment of the wind speed distribution multiplied by a standard air density

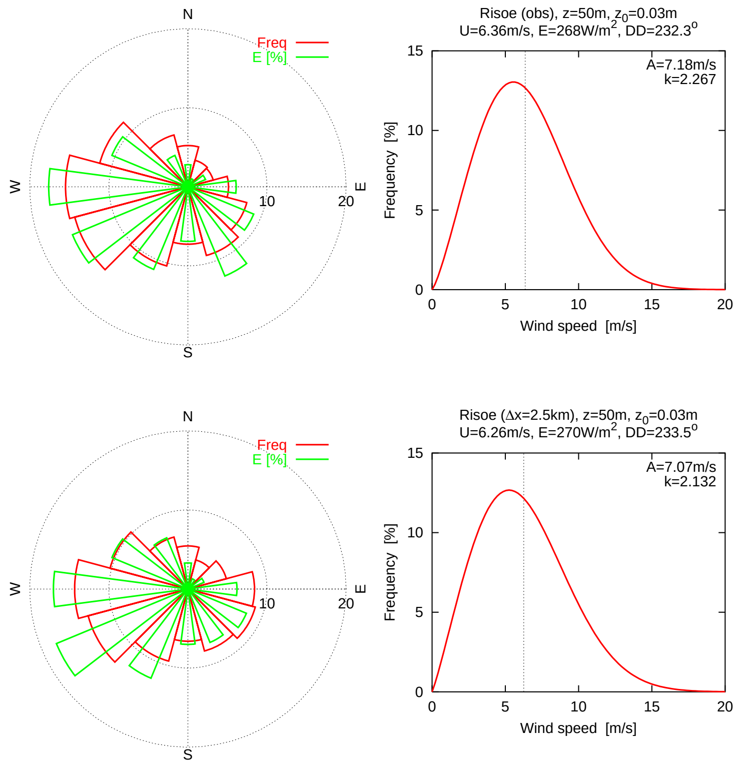

Figure 2: Wind distribution of the wind atlas data for 50 m height above roughness 3 cm from measurements at Risø (left) and from simulations (right).

Irish sites. Then, the surface wind was calculated using these "local" wind atlas files. These predictions overestimate the actual wind resource (Figure 3, top right).

One could use the KAMM results directly without any post-processing by WAsP. The simulated mean energy flux densities at the observation heights are interpolated from the nearest grid points to the exact position of the sites. With a simple interpolation no correction for differences of the local roughness and the roughness used in KAMM is made. We compare simulation on a grid with 2.5 km resolution with observations (Figure 3, bottom left). The model cannot see small moutains or hills below the grid resolution, which yield important speed-up effects. Therefore, the performance is bad for the good wind energy sites. Much higher resolution would be necessary to resolve the small-scale speed-up. However, then the simulation could cover only a smaller area with the same amount of computation.

Finally, the last plot in Figure 3 shows the predictions using KAMM and WAsP. It yields the best results (see also Table 2).

WAsP cross predictions and predictions of KAMM and WAsP for Northern Portugal are shown in Figure 4. The cross predictions look very bad. However, the triangles and crosses show predictions with high differences of the ruggedness index. In such cases WAsP is used outside its operational envelope. Large over- or under-predictions must be expected (Bowen and Mortensen, 1996; Mortensen and Petersen, 1998). If these sites are excluded the errors are only half as big.

The combination of KAMM and WAsP performs well. The prediction errors are bigger than for Ireland. But, this must be expected in more complex terrain.

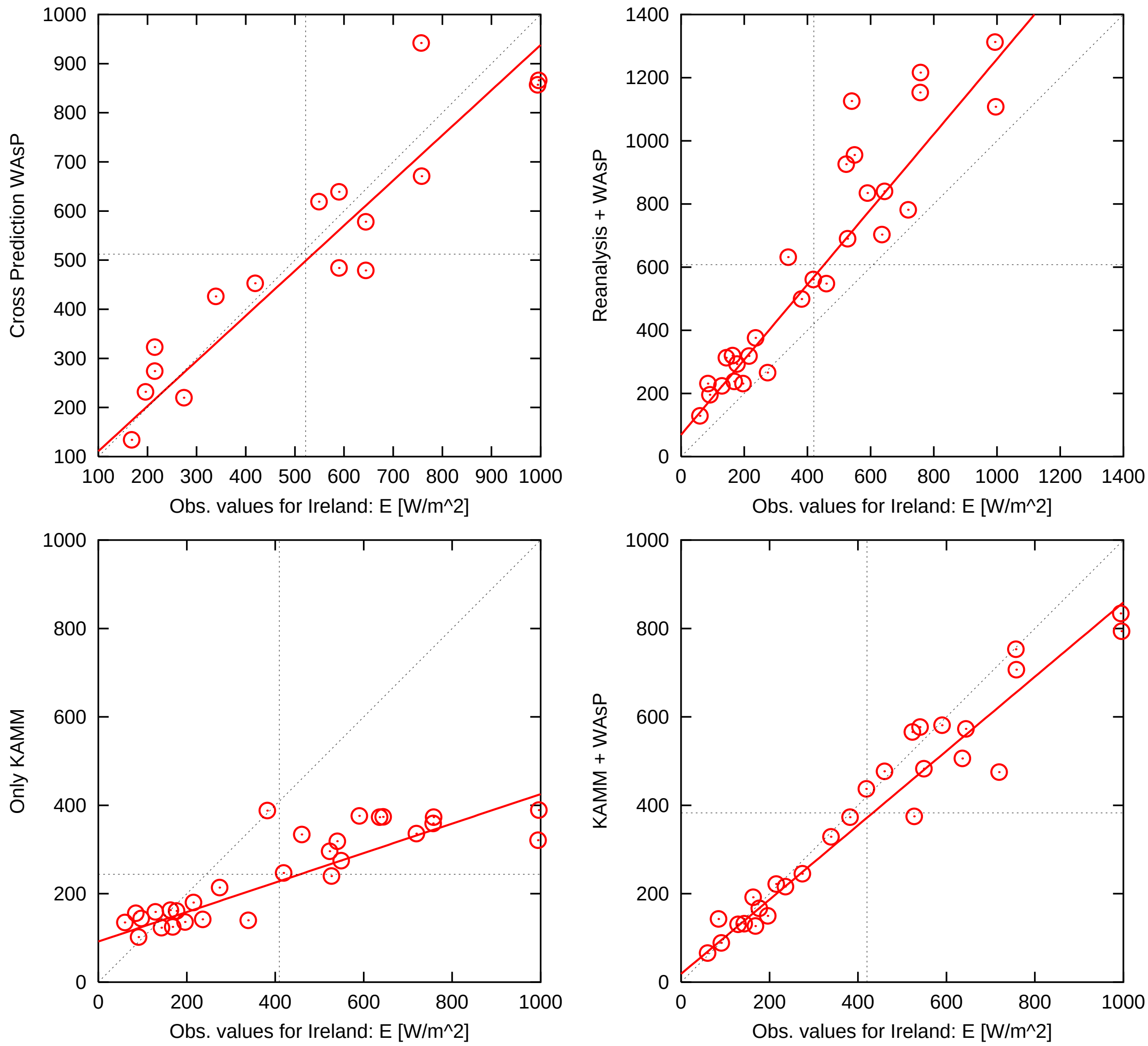

Figure 3: Measured and modeled energy flux densities at sites in Ireland. Cross predictions between sites with WAsP (top left), predictions with WAsP using wind at 850 hPa from the NCEP/NCAR reanalysis (top right), predictions using KAMM (bottom left), and predictions of WAsP using wind atlas files from KAMM (bottom right).

The random-mean-square (RMS) value of the difference of observations, E_o, and predictions, E_p, and the RMS of the relative difference, $2(E_o - E_p)/(E_p + E_p)$, are listed in Table 2. We can see that cross predictions with WAsP work well in simple to moderately complex terrain. The direct use of reanalysis data in WAsP is good for Denmark, but bad for Ireland and Northern Portugal. Using KAMM without post-processing is bad. The combination of KAMM and WAsP yielded good results in all regions.

CONCLUSIONS

It was shown that a combination of KAMM and WAsP yielded good predictions of the wind measured at several sites in Denmark, Ireland, and Northern Portugal. Model data is treated similar to observed data, i.e.

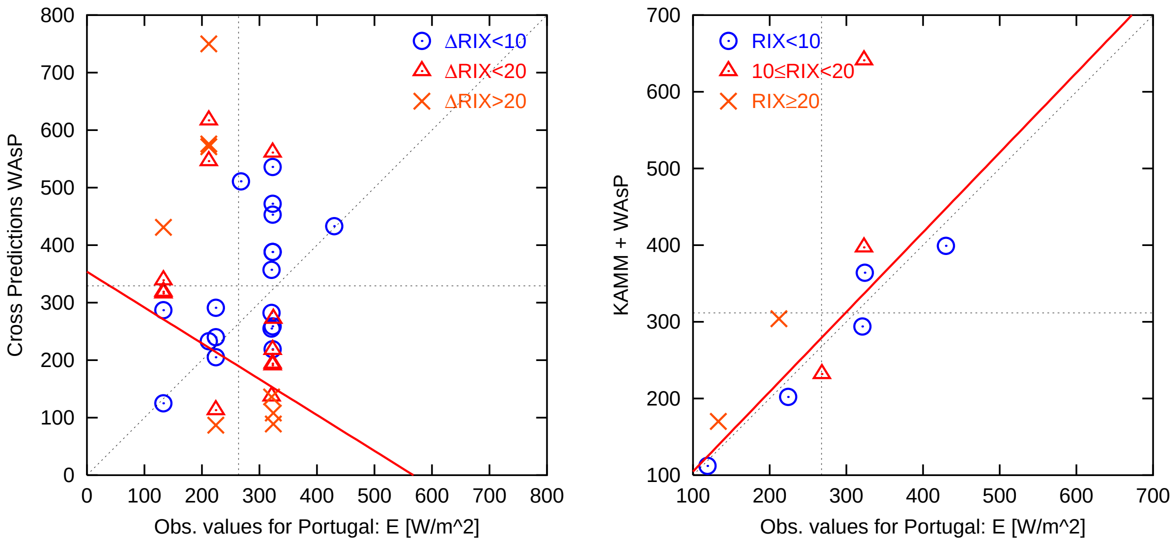

Figure 4: Measured and modeled energy flux densities at sites in Northern Portugal. Cross predictions between sites with WAsP, predictions with WAsP using wind at 850 hPa from the NCEP/NCAR reanalysis (left) and predictions of WAsP using wind atlas files from KAMM (right). The symbols depend on the difference of the ruggedness index, RIX, between predicting and predicted site, or on the ruggedness index of a site.

Table 2: RMS values of the relative and absolute prediction errors of energy flux density in % and W m^{-2}. Cross predictions means predictions with WAsP using observations at other sites. NCEP + WAsP employed the wind data at 850 hPa from the NCEP/NCAR reanalysis and WAsP.

Region	Cross predictions	NCEP + WAsP	KAMM	KAMM + WAsP
Denmark	7.5	23.5	47.5	21.9
	27	101	97	87
Ireland	20.4	47.5	53.9	18.3
	99	236	252	83
Portugal	64.0	47.6	82.5	26.9
	201	218	222	110

the variation of the wind on the grid-scale is removed to a large extent, to produce wind atlas files which are used by WAsP to make predictions of the wind at a specific site. The grid resolution of the meso-scale simulations is only of minor importance for the calculation of the local wind resource.

Cross predictions with WAsP work well in simple to moderately complex terrain. In very complex terrain the error depends on the sign of the difference in ruggedness index (Bowen and Mortensen, 1996; Mortensen and Petersen, 1998).

The direct use of reanalysis data in WAsP is good for Denmark. In Ireland and Northern Portugal it over-estimates the wind resource.

Using KAMM without post-processing is not good because the small-scale, local topography is not resolved with a horizontal grid size of 2.5 km. To obtain good results in complex terrain like Northern Portugal, probably, the resolution would have to be higher than 1 km. Then, the meso-scale simulations cannot cover greater regions, which is one of the advantages compared to small-scale models like WAsP.

Future work will be further improvements of the correction models applied to the meso-scale simulation results. The roughness change model of WAsP applied to the grid data of KAMM cannot totally remove roughness change effects at coast lines. Perhaps, the roughness change sub-model of LINCOM (Astrup et al., 1996) will agree better with KAMM. LINCOM is a linear flow model similar to WAsP's flow models, but operates on regular cartesian grids,

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