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Wind resource estimation in complex terrain: Prediction skill of linear and nonlinear micro-scale models.

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1 Wind Atlas methodology

The wind atlas methodology [2] was designed for horizontal and vertical extrapolation of mean wind conditions for use in wind power resource estimation. That is, if one has long term measured wind data (speed and direction) from some point (met mast location) at some height above ground, the method is used to estimate the wind conditions (wind speed frequency distributions per direction sector) at some other point of interest (hub height of wind turbine). The method assumes that winds in the points considered are governed by the same large- (meso-) scale wind forcing (thus the term micro-scale)

The methodology involves two distinct parts: The “Wind Atlas Analysis” in which the measured wind data are transformed using micro-scale models to estimate the local influences at the measuring point, subtracting these and using Rossby number similarity theory (“ Geostrophic drag law”) [5] to give a “Wind Atlas data set” , figure 1.

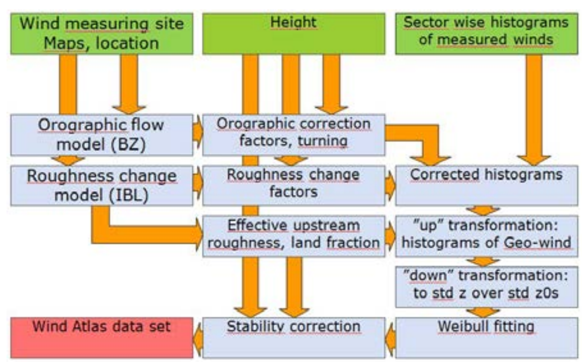

Figure 1: Wind Atlas Analysis, adapted from [2]. The user input is indicated in green, the internal machinery as light blue blocks and orange arrows, results in red.

The second part is the “Wind Atlas Application” in which the same micro-scale models are used to introduce the flow perturbations at the location and height of interest (e.g. the real or prospective location and hub height of a Wind Turbine) (figure 2).

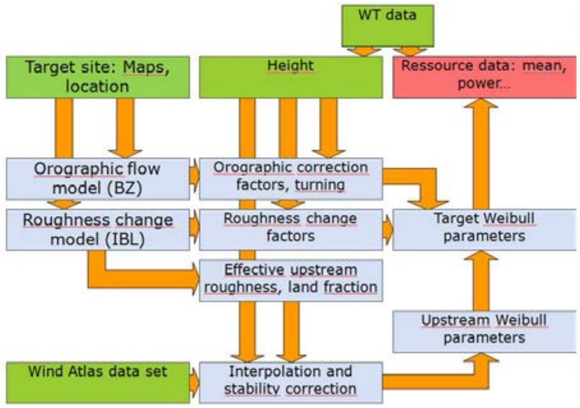

Figure 2: Wind Atlas Application, adapted from [2]

The “Wind Atlas Analysis and Application Program” (WAsP) contain these two parts with the built-in orographic flow model (BZ) [2, 6] and the simple “internal boundary layer” (IBL) model for surface roughness inhomogeneities [2, 7]. Recently the WAsP has been modified to allow these internal (essentially) linear models to be replaced by external models, e.g. nonlinear models based “Reynolds Averaged Navier-Stokes” (RANS) equations. Such models require considerable more computing resources than standard WAsP and therefore these model simulations must currently be run on a remote cluster, figure 3. The terrain maps are transferred via the web (the clouds in the figure) together with specification of the target area to the remote cluster where grid generation and the running of the Ellipsys model takes place. The results (flow perturbations relative to specified far upstream inflow logarithmic profile) are returned via the web as a “result volume” giving the calculated flow corrections per upstream wind direction in a regular horizontal grid and at several levels above the ground. Within WAsP the internal models are thus replaced with interpolation within the result volume.

The purpose of this study is to compare the skill in making cross predictions in very complex terrain of the two WAsP configurations, which we will denote WAsP-IBZ for the “standard” version with the linear internal flow models, and WAsP-CFD for the configuration using the remote Ellipsys model.

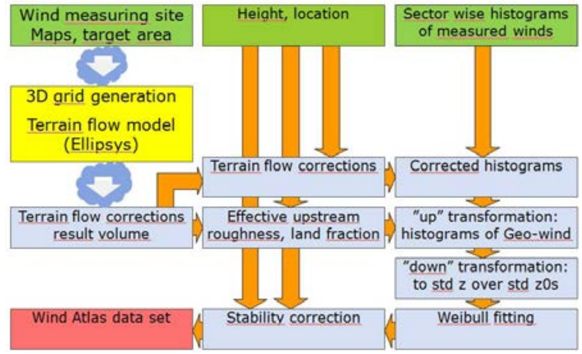

Figure 3: Wind Atlas Analysis using the Ellipsys RANS model, replacing part of the left blocks in figure 1. The corresponding Wind Atlas Application uses the same replacement of the two left column blocks (but in figure 2).

2 The BZ model

The linearized flow model in WAsP-IBZ [2,4] has been shown to compare well with other similar models for flow over hills [4,6] when applied to model flow over isolated hills.The linearized models tend to fail where full or partial/intermittent flow separation may occur e.g. in the lee of steep hills [8].

When the terrain is flat or with only very moderate slopes the surface drag is governed by the surface roughness (viscous drag). With substantial terrain relief the additional drag introduced by the pressure forces on the terrain slopes (form drag) can become much larger than the viscous drag [9]. In addition this drag force acts on the atmosphere in a deeper layer and not as a surface force like surface roughness [12]. The IBZ model does not include this drag.

3 The Ellipsys model

The Ellipsys3D code [11, 13 and 14] is used in the WAsP-CFD configuration. As explained above the model including grid generation is done externally to WAsP with input maps and the resulting flow corrections communicated via web links. The EllipSys3D code is a multiblock finite volume discretization of the incompressible Reynolds Averaged Navier-Stokes (RANS) equations in general curvilinear coordinates.In

WAsP-CFD configuration the model is setup for purely neutral atmospheric stability (as BZ), making it Reynolds number independent, meaning that flow perturbations will be independent of the inflow wind speed scale and only one simulation needs to be done per inflow direction.36 CFD simulations with different inflow directions are conducted for each WAsP-CFD result. Turbulence is modeled using two equation k-ε (turbulent energy and dissipation) closure [15]. The adaptation to the specific (automated) application used here will be detailed in an upcoming publication [10]. The model has been shown to well reproduce the Askervein experimental data [11] and was among the best performing RANS models in the Bolund model blind comparison (described in [1, 8]). As a fully dynamical model it does model highly disturbed flow situations including flow separation and should also model the form drag.

For the below validation of WAsP-CFD we use as input the exact same maps, wind data and site specifications as for the linear WAsP-IBZ configurations. The results from the Ellipsys simulations are returned as mentioned above in the form of a 3D grid of flow corrections over a square "tile" of size 2km by 2km with 20m horizontal resolution. The actual computational area is of course much larger but the limit of the size of the result volume is intended to ensure that the quality of the results is quasi constant within the tile. Here we use only the minimum number of tiles: If two or more locations can fall within one tile that tile is used for these locations. When locations are further separated, tiles are used with the location at the tile center.

4 Validation data

The validation is intended to document the skill of these model setups for use in real world wind resource estimation. We have used data from 9 sites with a total of 26 mast locations, most masts with several levels instrumented. The data was mainly provided by wind power developers, and the masts and sites were therefore chosen at or near potential wind energy installations.

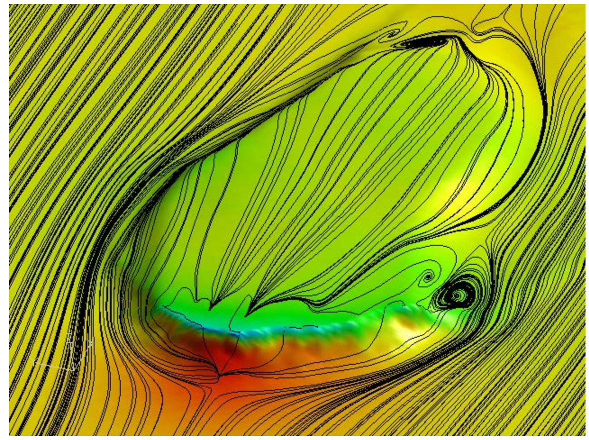

Figure 4: Surface streamlines from Ellipsys modeling of the flow over Bolund illustrating the models ability to produce flow separation upwind and downwind of steep slopes. Reproduced from [1].

.This means well exposed hills and ridges in general windy settings in complex terrain. The sites are located in Europe (5), Americas (2), and Southeast Asia/Australasia (2). The data and site descriptions are covered by Non-Disclosure-Agreements, so the individual cases cannot be discussed. We present a purely statistical analysis of the errors in cross predictions between wind observation locations based on the digitized maps, mast locations, anemometer/wind-vane heights and wind data (frequency distributions) provided to us. Most (6) sites were chosen by EMD international A/S among data held in their archives for which concurrent measured data could be extracted for several masts and covering at least a period of approximately one year, and for which the linear WAsP-IBZ was known to be beyond its "comfort-zone" because of very steep slopes and with the aim of testing the improvement offered by the WAsP-CFD configuration

The data from the 27 masts allow the selection of a total of 310 data pairs. The measuring heights vary from 10m to 100m. Most heights in the 40-80m range. Mast distances vary from approximately 1 km to 15km, with most distances a few km (overall average: 5km).

5 Prediction errors for the WAsP configurations

When considering the model prediction errors in complex terrain one should first realize the important difference between this situation and the more classical model validation (e.g. [4], [8]), where the inflow reference is generally well defined and undisturbed, and in addition one looks at single flow cases. Here we have several differences: We have in general to use input data, which are in the complex terrain and thus “disturbed” and predict at another “disturbed” site; we use climatological data that are truncated in sectors (here we use 12 sectors) and we predict over relatively large horizontal distances (km).

In the following the prediction error in percent is defined as

$$error = 100\left(\frac{predicted - observed}{observed}\right)$$

Where the predicted mean speed value is obtained by using WAsP as illustrated in figure 1 and 2 (with the linear IBZ model used) or with the Ellipsys CFD model used as illustrated in figure 3. Mean values are calculated from the observed or predicted sectorwise histograms of wind speed occurrence.

The somewhat complicated figure 6 shows a comparison of the prediction errors of the WAsP-CFD (red curve) versus the linear WAsP-IBZ (blue). In this case we have taken all cases with measuring heights above 40m, prediction target at same or higher level, and mast distances less than 4km, corresponding to very common conditions. The figure shows that there is some correlation between the model errors from case to case (R=0.5), that the skill appears to be not very different and that (for either model) no clear dependence on mast distance. For larger separations (and same height range) the dataset unfortunately only includes one site and involves for each case one particular mast.

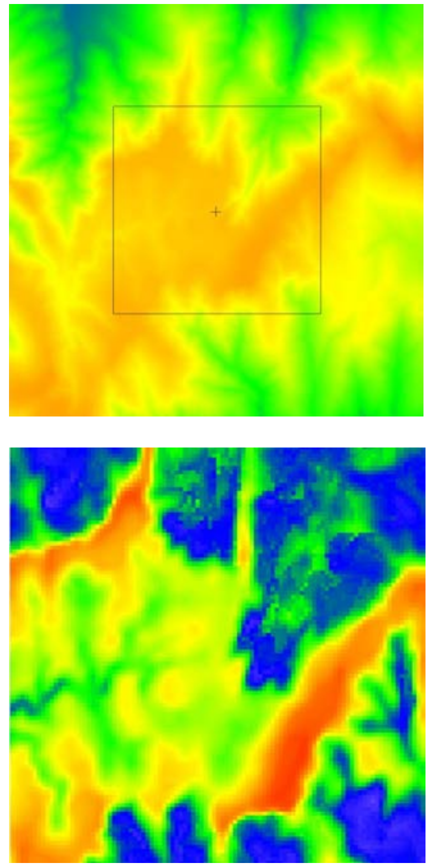

Figure 5: Illustration of a validation site. The top frame is a 4 by 4 km square showing the terrain height (bluegreen to orange approx 100m to 1000m) with the met mast indicated in the center. Below is the central 2 by 2 km tile from the CFD run with the predicted mean wind speed at 10m a.g.l. (blue to red approx. a factor 7 in mean wind speed).

Figure 7 show the same data as in figure 6, but plotted as cumulated probabilities. The absolute value of the errors for each WAsP configuration is plotted versus case numbers sorted by the absolute error. The plot shows that the CFD gives lower errors in general and that using the mean of IBZ and CFD lowers the error of the estimation. The root-mean-square errors and biases are given in the legend.

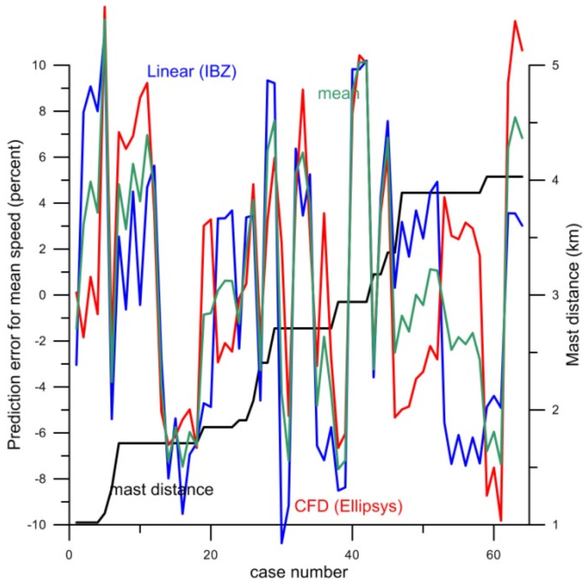

Figure 6: The relative mean speed prediction errors (y-axis) for measuring pairs with same anemometer heights above 40m and mast separations less than 4km.The dark blue is the standard WAsP-IBZ, The red curve shows the WAsP-CFD performance. The x-axis is an case number sorted by mast distance (from approx 1km left to 4 km right)

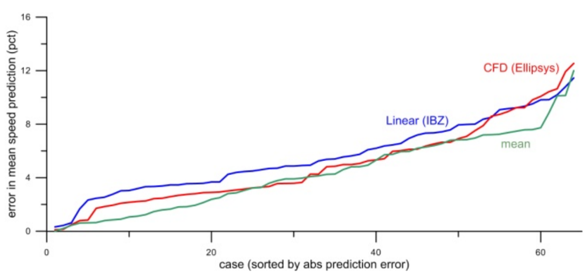

Figure 7: Same data as in figure 6, but sorted in order of absolute prediction error for each WAsP configuration (thus the case numbers do not necessarily correspond). The bias for IBZ is -0.6pct, for CFD +0.8pct, the rms values 5.7pct and 5.3pct respectively. For the mean the bias is 0.13pct and the rms error 4.7pct.

As mentioned above the data available includes only one site with mast separations larger than 4km (and measuring heights above 40m), furthermore all measurement pairs (17 in all) involve one particular mast in these cases. This makes it more uncertain obviously to draw any conclusions. Nonetheless, we note that for these data the skill of using WAsP-CFD is systematically better than using the linear configuration (bias and rms for CFD: 1.9pct and 10.8pct, for IBZ: 4.8pct and 19.0pct).

For larger mast separations we have one additional dataset only [3], which unfortunately has only one (low) measuring height for each of the 5 masts. The mast locations are in very complex settings also, with the measuring height at 10m agl. Mast separations are up to 15km. Apart from the low measuring height, we know that the data are of very good quality and cover approximately 5 years (one of these mast locations are illustrated in figure 5). The skill of WAsP-CFD/IBZ for these data, for all mast separations larger than 4 km is shown in figure 8.

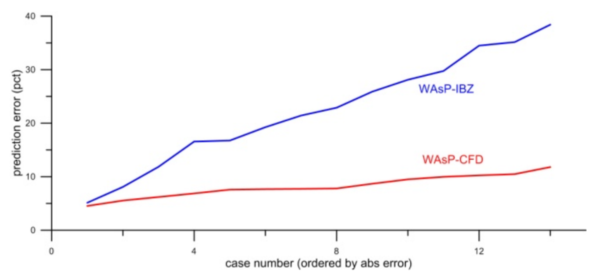

Figure 8: As figure 7, but for the 5 low (10m) masts. Mast separations larger than 4km.

It is clear that for the larger mast separations the linear model fails in particular for these low heights, while the CFD still exhibit useful skill.

6 Discussion

For very complex terrain with large terrain slopes near the measuring masts, as is the case for all sites discussed here, the prediction of wind conditions at a location some distance away from the measuring mast is difficult due to important distortion of the wind flow.

Here we compare the skill of two configurations of the “wind atlas method” (WAsP), one with the linear flow model (IBZ) and the other with the fully 3D nonlinear RANS model Ellipsys (CFD). Apart from the different flow models the treatment and transformations of the data within

WAsP is identical for the two configurations and the input (Wind statistics) and auxiliary (terrain maps) data are identical.

Theoretically the linear model should essentially fail for these cases as the linear approximations are clearly violated and the calculated flow distortions tend to be exaggerated. For relatively small horizontal mast separations (up to 4km) this deficiency is not very evident as the mast locations for each site in our validation data have a high degree of similarity (well exposed ridges and summits), thus avoiding the more distorted locations. In this case the exaggeration of the model response in the linear case tend to stem from larger terrain scales and these tend to affect nearly equally the input and target locations for the smaller mast separations. Also the effect of increased drag due to the terrain slopes (formdrag) , not modeled in IBZ, tend to be relatively constant over these distances.

For larger mast separations we have much less data available, but with this reservation notwithstanding, we see that the more complete nonlinear dynamics of the CFD model is necessary for useful predictions.We interpret this as the CFD is properly handling the partial absence of larger scale similarity in general (thus the loss of the compensating effects " needed" by IBZ), and that the CFD also more correctly includes the formdrag.

For the smaller mast separations we see a small but significant improvement in the skill in the CFD relative to the linear IBZ of between 1 and 2 pct, and also that having both estimates further reduces the uncertainty.

In addition to improvements in resource estimation offered by the WAsP-CFD the CFD also gives estimates of turbulence intensities and flow inclination angles at any target site (not discussed here).

The prediction errors may not solely be attributable to the flow models but may in part stem from anywhere in the data and model chain, including input wind data and site descriptions. However, here we have minimized the possible impact of this by using the models in exactly the same WAsP framework.

The development of WAsP-CFD was triggered by the desire to make CFD capabilities easily available to anyone in the wind resource micrositing field. This has been accomplished by adding a web fully automated service with a remote computational engine within WAsP. This allows the use of the standard IBZ configuration in setting up and running siting projects and then adding or switching directly to the CFD mode when needed. This facility has been essential for the present study.

In further model development and improvement it would be highly desirable to extend this analysis to many more complex sites with good quality data. Equally or more importantly large scale field experiments are needed in complex terrain

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