Wind in complex terrain.
A comparison of WAsP and two CFD-models.

Abstract:

WAsP and the two CFD-models WindSim and 3DWind have been compared at a complex terrain site in western Norway for the two dominating wind directions south and north. One year of measurements from two 50 m masts and one 10 m mast were available. The paper analyses the mean absolute error, the vertical variations of wind speed and turbulence with height, and meso-scale wind variations across the wind farm. Despite the simplicity and known weaknesses of WAsP in complex terrain, no improvements of the average wind speed calculations were obtained by use of the CFD-models. Meso-scale wind variations of the order 2-3 m/s during a particular weather situation were encountered for a case study by use of a meso-scale model.

Keywords: Complex terrain, WAsP, CFD-models.

1 Introduction

Large wind energy developments are at the planning stage in Norway. Many of the planned wind farms will be located in rather complex coastal sites where wind resource assessment is difficult.

Wind models are potentially important at complex terrain sites in the wind resource assessment since measurements can only be afforded at selected positions, and the wind variations may be large over short distances.

For micro-scale flow (spatial scales of 1 m to 2 km), the WAsP model [1] is most commonly used in the wind resource analysis, but in areas with flow separation the model is not very well suited for resource assessment. However, simple terrain corrections (so called RIX-analysis see [2]) have been applied with success to the WAsP simulation for quite complicated terrain [2,3].

CFD-models are also utilized in micro-scale wind resource assessment. Most commonly, the CFD-models develop a steady-state time-independent solution for the wind and turbulence fields. Thus, a physically more realistic picture of the flow field can be obtained compared to WAsP. Examples of such models applied to Norwegian wind resource assessment are WindSim [4] and 3DWind [5]. Still, these CFD-models avoid the inclusion of the energy equation, thus stratified flow cannot be realistically handled. Also, the assumption of a steady state turbulent field may be doubtful since the turbulence actually often is very intermittent and transient.

Nested models that handle real-time meteorological data from the synoptic scale down to the micro-scale, including buoyancy effects on the micro-scale flow, have also been developed and tested [6]. Such models still require weeks of computational efforts on today’s most powerful computers [6], in order to generate a wind resource map for a wind farm. Thus the temporal and economical costs of such models may still be too high for practical applications.

In complex terrain, meso-scale wind variations within a wind farm area may as well be anticipated (spatial scales of 2 km to 200 km). Meso-scale models, that solve the coupled equations of dynamical and thermo-dynamical processes in the atmosphere, may be needed together with the micro-scale models to achieve a complete resource analysis. Examples on such models are the WRF-model [7], the MC2-model [8] and the RAMS-model [9].

The aim of the present study has been to validate the two CFD-models WindSim and 3DWind and to compare with the WAsP model at a complex terrain site in Norway. In addition, examples on meso-scale wind variations based on the WRF-model are given. One year of measurements from one 10 m and two 50 m measuring masts have been made available from a Hydro Oil & Energy site in western Norway. Both average mean wind and turbulence conditions have been analyzed. An important issue has been to determine whether or not the CFD-models could improve the confidence in the wind map at the complex terrain site.
2 Measuring program

2.1 The Gurskøy region

Hydro Oil & Energy initiated in 2000 a field measuring campaign at Gurskøy in western Norway. The area is located about 25 km east of Stadt, one of the windiest regions in Norway. The Gurskøy island has a complicated local terrain structure with mountaintops of about 600 m with steep edges down to local valleys and fjords (see Figure 1). Considerable local flow separation is expected in this type of terrain. From the sectors W to N open ocean flow modified by the local terrain may be expected. Toward S and E high mountains of 800-1500 m are encountered at distances of approximately 15 km or more, with associated meso-scale wind effects.

2.2 Description of the measuring sites

The measurements were collected from April 2002 to May 2003 for the sites 1 (z=424 m), 2 (z=390 m) and 3 (z=352 m) (see Figure 1). At site 1, the measurements were carried out with a 10 m steel tube mast, while 50 m steel tube masts where employed at sites 2 and 3.

The wind speed measurements were collected with the NRG Maximum #40 anemometer. Comparison with RISØ wind speed sensors have shown that the NRG sensor underestimates the wind speed for wind speeds lower than 2 m/s. For an annual average wind speed in the range 7-9 m/s the underestimation will be about 0.04 m/s, i.e. much less than the overall uncertainty of the measurements, including the uncertainties of long-term variability of the wind, of about 5% (see [3]).

The wind rose at site 1 is presented in Figure 2. We note the dominance of winds from S and SW and N and NE.

The sites 1 and 2 are situated on an east-west ridge with considerable speed-up for both southerly and northerly flow. The hillside to the south stretches all the way down to the fjord, while a mountain rises to about 400 m further to the south. Turbulence could be expected at all three sites north of this mountain for the dominating southerly flow. At site 1 there is some sheltering toward W and NW, but this is a wind...
direction with low frequency. Site 2 is partly sheltered for the direction NE. Site 3 is located in a SW to NE oriented hillside. Speed-up for SW flow can be expected at this site. The wind rose is consistent with observations from other stations in this region.

Figure 1: Location of the three measuring sites 1, 2 and 3 at the Gurskøy island. Height contours are for every 20 m.

Figure 2: Wind rose at site 1.

3 Micro-scale model set-up

3.1 WAsP

WAsP version 8.1 was employed in this study. Height contours for each 5 m were available for an area of about 3km*3km covering the met mast. Outside this area 20 m height contours were used. A background roughness of 0.03 m describing the bare mountain areas, was applied. Higher roughness values were applied to forests and small towns.

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<tr>
<th>Turbulent scheme</th>
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<tr>
<td>Table 1: Set-up of WindSim and 3Dwind for the simulation.</td>
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Although an as similar set-up as possible has been the intention, inevitably some differences are found.

Both WindSim (for a documentation of WindSim see http://windsim.com) and 3DWind [5], [10] are wind flow solvers based on the 3D Reynolds Averaged Navier-Stokes equations. The models solve the atmospheric flow for a “steady-state” case for a chosen wind direction. By “steady-state” it is meant that the model is run until the solution converges to one wind and turbulence distribution for the entire domain that do not vary outside a pre-set convergence limit. By simulating for several different wind directions (sectors) an annual average wind speed can be generated. The models are run for a given set of constructed boundary and initial conditions. The k-ε turbulence closure scheme is applied in both models.

Table 1: Set-up of WindSim and 3Dwind for the simulation.

An important advantage of a CFD-model compared to WAsP is that the CFD-model calculates the turbulent quantities of the flow, and thus gives information about high turbulence areas that should be omitted for wind power exploitation. Also, the direct effects of turbulence on the mean flow are calculated. Especially in complex terrain, where a complicated turbulence structure is encountered, benefits of a CFD-model are expected. However, any turbulence modeling will inevitable introduce new parameterization assumptions and constants, which also introduces uncertainty in the modeling (see for example [11]). Considerable uncertainty is therefore linked to the quantification of the turbulence and its effects on the mean flow.

Most CFD-models assume a neutral stratification of the atmosphere. For strong winds this is often a good approximation. But even for wind speeds up to 10-15 m/s stable stratification has been observed, at least in the coastal areas in central Norway [12]. Vertical wind shears, turbulent fields etc. may develop quite differently during stable (or unstable) conditions [12]. Thus, a limitation in the CFD-approach is encountered here. Another limiting factor is the finite number of directions applied in the derivation of the annual average wind speed. Since the long-term wind speed is composed of wind flows from all different directions (though with some predominant directions), a sample of for example 12 sectors may be too small to represent an annual average properly.
4 Results

The CFD-models are initialized based on assumptions about higher level (~500m) and lateral boundary level wind speed and profiles. A logarithmic wind profile (corresponding to neutral stability conditions) is employed at the boundaries in both models. Thus, in order to compare the output of the CFD-models with any measurements, the modeled wind speed fields have to be scaled by use of the measurements. For example, for a specific annual wind speed from sector S at 50 m at one of the sites, the output of the CFD-model will be assumed equal to the measurement at this site. It is then further assumed that the wind field can be scaled linearly based on the scaling at this particular site. By employing this method model simulations of the wind speed at all the measuring sites can be obtained. Thus it is assumed that the ratio of the modeled and measured values at one site will apply to the whole modeling domain. This assumption may not be valid everywhere in the modeling domain, but it is quite commonly applied to modeling. In the following section we assess the model simulations by using this method. The CFD-models are scaled to yield correct wind speed at the 50 m level at Site 2 and Site 3 respectively, then the results at the other measuring sites are extracted from the CFD-models.

The WAsP model work differently. In order to make the results from WAsP comparable to the CFD-models, the measurements at 50 m from Site 2 and Site 3 are inserted in the model and the wind speed of the other measuring mast are obtained for the same sectors as utilized by the CFD-models.

Note that the CFD-models were run only for the two sectors north (N) and south (S) to save computational efforts. Each sector covers 30° centered around 360° and 180° respectively. According to the wind rose (see Figure 2), the directions N and S represent ca. 13% and 18% of the wind data respectively.

4.1 Annual average wind speed

In Figure 3 the vertical profiles at site 2 have been obtained based on a “true” solution at 50 m height at site 3. For the southerly sector the wind direction is nearly perpendicular to the steep slope to the south of site 2 and a strong speed-up is encountered. Both WindSim and WAsP yield only small differences from the observations, while 3DWind yields a large overestimation of the wind speed. For the northerly sector, the wind speed actually decreases from 10 m to 50 m at site 2. All three models underestimate the wind speed for this sector, still WAsP yields the best results in this particular case.

A further comparison of the output of the model simulations with the observations has been carried out. The three models are all scaled to fit the observations at 50 m height at either site 2 or site 3.

Based on the scaled values of each of the two sites, the annual average wind speed is estimated at the other levels of the same mast (10m and 30m) and
at the three measuring levels of the other 50m mast and finally at 10 m at site 1. The results are summarized in Figure 4 and Table 2. The total number of data points to be verified are 12, thus any statistical analysis has to be interpreted with care since the data points are few. For the sector S, WAsP and WindSim show similar behavior, while the errors are somewhat larger for 3DWind. For sector N, WAsP gives somewhat surprisingly the best correspondence, while WindSim has the lowest correlation. Based on the results of Figure 3 and 4 and Table 2 we conclude that the errors are as large (and actually a little larger) for the CFD-models compared to WAsP for the two sectors analyzed. This is an important finding, although we lack insight into the reasons why the CFD-models are unable to improve the simulations at Gurskøy. In the following sections we present a discussion aiming to give a better understanding of the modeling results.

A RIX-analysis was carried out for the three sites to check if the WAsP results could be improved. The RIX-values using a radius of 2 km were 24.2%, 20% and 17.2% for the site 1, site 2 and site 3 respectively. In contrast to [3] no relationship between the differences in RIX-values and the prediction error was found. For example, employing the 10 m measurements at site 1 gave an over prediction of the wind speed at site 2 and 3, while an under prediction could be expected from the RIX-analysis. These results underline that a RIX-correction should always be supported by empirical data, and a generalization of the method from one area to another is not recommended.

### 4.2 Turbulence and the directional dependence

In Figure 5 the turbulence intensities at site 3 is presented. While 3DWind overestimates the turbulence for sector S WindSim gives too low values. For sector N both models are closer to the observations, but still 3DWind over predicts while WindSim under predicts. The same pattern is encountered for site 2 (not shown), and in other similar model experiments using 3DWind. Our conclusion from these investigations is that the over prediction of the turbulence in 3DWind at site 3 most probable is linked to an underestimation of the average wind speed at the same site. This also leads to the overestimation of the predicted average wind speed level of 3DWind at site 2 based on the wind field scale to site 3 (upper panel of Figure 3). In Figure 6 the turbulence pattern derived from 3DWind is presented for the wind directions 180° and 190°. Separated flow and strong turbulence is developed on the lee side of the mountain to the south of the ridge where the three meteorological masts are located. At both sites 2 and 3 it is likely that the turbulence intensities could be rather sensitive to the exact wind direction.

From Figure 7 it is also noted that the annual average wind speed varies largely for different wind speed directions. The variability at site 2 for the direction 170°, 180° and 190° is quite well captured by 3DWind. It is also observed that the outcome of
the CFD-model is largely dependent on the selection of sectors. In the present case with complex terrain 12 sectors yield inevitable course resolution. Ideally at least 36 sectors should be utilized, which on the other hand increase the computational demands.

5. Comparison of the CFD model data

In Figure 8 the differences between WindSim and 3DWind for southerly flow are presented. The wind fields of the two models have been scaled in order to minimize the differences between the two models. Note that during the scaling linearity is assumed, although this may not strictly be the case. From the figure we see quite much higher wind speeds in WindSim than in 3DWind especially in the turbulent lee wakes. This is consistent with the findings in section 4.2 where a higher turbulent level is encountered in 3DWind. This will reduce the horizontal wind speed, since a larger part of the available kinetic energy of the flow is consumed by turbulent processes. Although the two models employ the same turbulent scheme we encounter a large difference in the resulting wind field and turbulence field. This emphasizes the importance of the turbulent processes in rough terrain and the complexity of a proper modeling of the turbulence.

The frequency distribution of the wind speeds covering the domain of Figure 8 is presented in Figure 9. The wind speed of each single grid-point at 50 m in the modeling domain has been included in this distribution. The data are not scaled and thereby not strictly comparable, still a good picture of the behavior of the two models is given. We immediately observe the much higher frequency of low wind...
speeds in 3DWind compared to WindSim, which is consistent with the results of Figure 8 and the higher turbulence level in 3DWind. WindSim also has a notable higher frequency of high wind speeds (above approximately 15 m/s). A comparison of the two models is also carried out for a potential wind farm area. The RMS differences of the two models in this area become 1.54 m/s and 1.51 m/s for southerly and northerly sector respectively. For the total area of Figure 8 the corresponding numbers are 1.87 m/s and 2.20 m/s. We can conclude that the differences are large also for a restricted wind farm area and large differences in energy production may be expected. Based on the above results it is difficult to establish any more confidence in the wind map generated from the CFD-models compared to the WAsP model.

Figure 9: Frequency distribution of wind speeds from the area of Figure 8 for WindSim (left) and 3DWind (right).

6. Meso-scale simulations

Two meso-scale case studies were conducted by use of the WRF-model (WRF-Weather Research and Forecasting, see http://www.wrf-model.org, [7] and [13]). The model was set up for our region in the following way: Global meteorological data with 1 degree resolution were available from the National Centers for Environmental Protection (NCEP) with 8 time-frames per day. The global data were interpolated to a WRF-grid covering western Norway. The WRF-model was further set up with terrain and land-use data of a resolution down to approximately 1 km based on data accessible from the WRF-home page. The set-up of the model domain for Gurskøy is shown in Figure 10. The outer domain has 5 km resolution employing a horizontal dimension of 80*80 and 31 layers in the vertical, while the inner domain has 1 km horizontal resolution with the corresponding grid-resolution of 80*65 and 31 layers in the vertical. The domains are rather small in order to save computational efforts, still we believe that they are sufficiently large for illustrating the variability of the meteorological parameters across the island.

The case presented is from 1 January 2005. A strong SW flow dominates the wind pattern over southern Norway and the adjacent seas. The wind veers slightly more toward S over our area of interest compared to the SW wind outside the coastline (Figure 11). We encounter wind speeds varying from about 15 m/s to above 20 m/s. Effects of the fjords and sheltering from the mountains to the south are apparent.

The vertical profiles from the SW and SE corner of Gurskøy (see Figure 12) show quite large differences in wind speed and temperatures from the western to the eastern side of the island. The wind speed at 100m varies with about 2-3 m/s while the temperature drops with about one degree. A statically stable layer is found below 100 m on the western side, while a thicker stable layer is seen on the eastern side. We also observe that the wind shear is strongest for the height intervals with highest vertical stability. Clearly, in a neutrally stratified atmosphere (no change of potential temperature with height) less vertical wind shear could be expected.

A second case with unstable cold northerly wind was also examined. Smaller differences across the island in both wind speed and temperature were encountered in this case (not shown).

7 Summary and conclusions

The micro-scale models WAsP, WindSim and 3DWind have been compared and evaluated for a complex terrain site in western Norway of Hydro Oil & Energy. Previous analyses of the wind measurements at this site had shown large deviations between WAsP simulations and measurements (of the order of 1 m/s within 1 km horizontal distance). Thus it was difficult to establish confidence in the wind map.
The present analysis shows that, despite the complex terrain, WAsP compares better than the CFD-models to the observations when results for the sectors south and north are considered. This conclusion is valid both for the vertical wind profiles and the annual average wind speed levels. The mean absolute error for sector south is 11%, 10% and 28% for WAsP, WindSim and 3DWind respectively. For sector north the corresponding numbers are 14%, 24% and 24%. The RMS-differences in the wind speeds between the two CFD-models have been calculated for an area where wind energy exploitation is realistic. For both sector south and north an average RMS-difference of about 1.5 m/s is found.

Meso-scale simulations with a complete meteorological model indicate large wind variations within the island due to the mountains to the south. For one particular case with southerly flow, wind speed variations of 2-3 m/s at 100 m height are encountered moving from the western to the eastern side of the island. A dependence of the vertical wind profile on vertical stability is also found in the meso-scale model simulations. One disadvantage of WAsP and the two CFD-models is that meso-scale wind variations are not taken into account in the modeling. In particular, the effects of the vertical stability on both the meso-scale and the micro-scale flow may be anticipated to be important (see for example [8]), but it is not accounted for in the micro-scale models. This becomes a limitation of the three models when applied to a complex terrain site such as Gurskøy.

An advantage of the CFD-models compared to WAsP is the explicit calculation of the turbulence field. The comparison of the measured and modeled turbulence intensities shows that 3DWind overestimates the turbulence while WindSim tends to give too low values. The directional classification uses 12 sectors of 30°. The model runs show that large variation in the turbulence level may occur within a 30° sector when the terrain is complex. Thus smaller sectors should be employed, although this increases the computational efforts of the CFD-models. Through the analysis of the modeled turbulence fields a better understanding of the measurements at Gurskøy is obtained. For example, the 3DWind runs clearly indicate an influence of the first mountain to the south on the turbulence level (and consequently also the average wind speed level) at the measuring sites. This mountain is of the same height as sites 2 and 3 and located about 3 km to the south.

The results of this study emphasize the importance of high quality measurements in complex terrain for a reliable wind resource mapping. Still, both micro- and meso-scale models are important for the interpretation of the measurements and for an investigation of the turbulence and speed-up effects in complex terrain. The data material of this report is limited, and therefore further validations of the micro- and meso-scale models in complex terrain are recommended. This is anticipated to give increased insight into the potential and limitations of the models for wind farm development.
Figure 11: Wind speed at 50 m height at 03 UTC 01.01.2005. WRF-run with 1 km horizontal resolution. Height contours (black lines) are drawn every 30 m. The vertical profiles are from the positions 1 (SW) and 2 (SE).

Figure 12: Vertical profiles of wind speed and potential temperature at the SW corner (red lines) and SE corner (blue lines) of the island Gurskøy. Height represent the heights above sea level.

References


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