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APPLICATION OF THE WA^{S}P MODEL TO DETERMINE THE WIND RESOURCE IN NON-NEUTRAL CONDITIONS IN COASTAL AREAS

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ABSTRACT: Differences in stability conditions on- and off-shore mean that the coastal wind field is difficult to predict accurately. Using the default parameters in the WA^{S}P model gives good predictions of mean offshore wind speed profiles at Vindeby offshore wind farm, however, conditions at Vindeby are close to neutral on average. A number of scenarios are evaluated to test whether predictions can be improved in non-neutral conditions.
Keywords: Coastal sea areas, Models (Physical), Off-shore, Meteorology

1. INTRODUCTION

Coastal areas are frequently chosen as wind turbine sites because it is known that offshore wind speeds are typically higher than those onshore. However, accurate assessment of the wind resource in coastal zones is difficult since it depends on the parametrisation of both roughness and stability changes. Both these factors influence the development of the internal boundary layer and hence the wind speed profile moving away from the coast. The modification of atmospheric stability occurs onshore and offshore on different time scales. Diurnal variability is important on land, particularly in spring and summer, while sea surface temperatures change more slowly (Barthelmie et al., 1996). Unfortunately, relatively little is known about the stability climatologies of offshore areas. Stability in the coastal zone depends in part on the air-sea temperature difference and hence on a number of factors such as the orientation of the coastline, the prevailing wind speed and direction, water depth and the latitude influencing the magnitude of seasonal and diurnal changes of net radiation. To date, there have been few measurements in these offshore coastal areas with which models can be developed and evaluated.

In order to predict the wind resource of the Baltic Sea area, a number of approaches have been used which are described in Højstrup et al. (1996). As part of the Baltic Sea Wind Atlas project, stability analyses have been undertaken using data from a number of coastal, island and offshore sites. These show that atmospheric conditions offshore are frequently non-neutral tending towards stable in this area (in agreement with analyses detailed in Joffre, 1985 and Smedman et al., 1996).

2. WA^{S}P

The Wind Atlas Analysis and Application Program (WA^{S}P) (Mortensen et al., 1993) has been used successfully for siting wind turbines both on-shore and offshore. In offshore areas, away from the influence of the coast, it gives good predictions in comparison with observed mean wind speeds and the wind speed profile (Petersen, 1992). However, if conditions offshore are predominantly stable, WA^{S}P will tend to over-predict wind speeds in the near-coastal offshore zone (Barthelmie et al., 1996). This is because the internal boundary layer grows more slowly in stable conditions and, in the range of heights of interest for wind energy (i.e. 30-100m), the increase in wind speed will be smaller than in near-neutral conditions.

Without undertaking a detailed stability analysis for each offshore area, more comprehensive modelling (e.g. using a mesoscale meteorological model) is not possible. However, with a generalised climatology, a number of parameters can be easily changed in WA^{S}P which effectively allows different stability conditions on- and off-shore to be taken into account. Data from the Vindeby offshore wind farm are used to assess how WA^{S}P predicts the modification of wind field moving offshore in different stability conditions.

3. VINDEBY DATA

Meteorological data have been collected at Vindeby wind farm since 1993. The site is shown in Figure 1 and has been described in detail in Barthelmie et al. (1994, 1996). There are three masts - one at the coast LM, and two offshore SMS and SMW at distances of 1400 and 1600m respectively.

Stability conditions at Vindeby have been classified according to the Richardson number (Arya, 1988) and the frequency of different classes are shown for each of the three masts in Table 1. Thus, on average, conditions are shown to be close to neutral, with near-neutral conditions occurring more frequently at LM than at the sea masts.

Table 1. Percentage occurrence of stability classes at Vindeby based on Richardson numbers.

Ri		LM	SMS	SMW
Ri>0.1	Stable	19	26	25
-0.1<Ri<0.1	Near-neutral	66	48	51
Ri<-0.1	Unstable	15	26	24

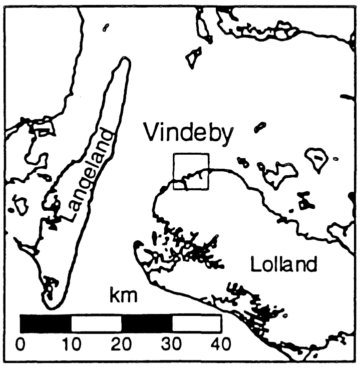

Figure 1. Location of the Vindeby wind farm, Denmark.

4. APPLICATION OF THE WA^{S}P MODEL

4.1 Standard application of WA^{S}P

Wind speed and direction data from 20m height at LM are used to predict wind speed profiles at SMS and SMW using the default parameters of WA^{S}P. Predicted and observed profiles at the three masts are shown in Figure 2. With the exception of the wind speed at 7m at SMS, WA^{S}P predicts the profiles reasonably accurately (within ±0.2m/s or ±3%). The data are then sub-divided according to the stability classes given in Table 1. Data from LM are used to define stability and wind speeds at 20m at LM are used by WA^{S}P to predict wind speed profiles at each mast for each stability class. Note that WA^{S}P uses climatological averages to describe the stability conditions in which conditions over land are slightly unstable and those over sea are slightly stable (see Troen and Petersen, 1989). Wind speed profiles are plotted in Figure 3 as normalised differences (percentages):

$$\textit{Normalised differences (\%)} = \frac{U_{obs} - Upred}{U_{obs}} * 100$$

As shown in Figure 3, in stable conditions WA^{S}P tends to over-predict wind speeds below 20m and underpredict wind speeds above 20m. In near-neutral conditions, wind speeds are slightly underpredicted at all three masts. (Note that differences of up to 2% can be caused solely by rounding errors). In unstable conditions, wind speeds at the sea masts tend to be under-predicted.

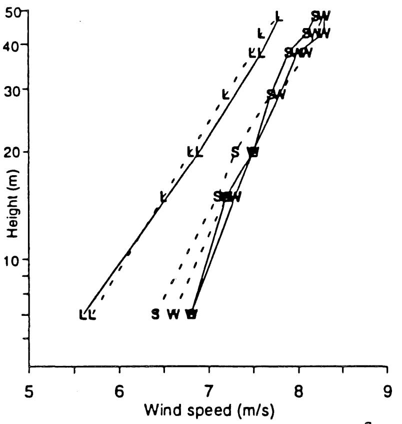

Figure 2. Mean observed (solid line) and WA^{S}P predicted wind speed profiles (dashed line) at the three masts (L=LM,S=SMS,W=SMW).

4.2 Changing WA^{S}P parameters

Within WA^{S}P stability differences between land and water surfaces are incorporated by treating 'stability modifications as small perturbations to a basic neutral state' (Troen and Petersen, 1989). There are 74 parameters in the initial set-up of WA^{S}P, of which 29 can be used to account for deviations of the atmosphere from near-neutral conditions. Since the model is generally shown to model atmospheric responses to roughness changes well (Troen and Petersen, 1989), analyses presented herein concentrate on parameters which deal specifically with changes between land and water surfaces. There are three groups of relevant parameters:

1. Width of the coastal zone.
2. Differences between stability parameters which affect the wind speed profile on- and off-shore.
3. Differences in the heat flux and heat flux variability on- and off-shore.

In order to modify WA^{S}P correctly, it is necessary to calculate appropriate values for each parameter. Data from Vindeby are used below for this purpose. Each set of predictions is based on data from 20m height at LM.

4.3 Changing the width of the coastal zone, *c*

The width of the coastal zone is the distance on either side of a discontinuity over which the discontinuity has an impact on the predicted wind speed. In stable conditions, since the internal boundary layer grows more slowly, it could be assumed that the wind speed reaches the same equilibrium offshore value but over a longer distance from

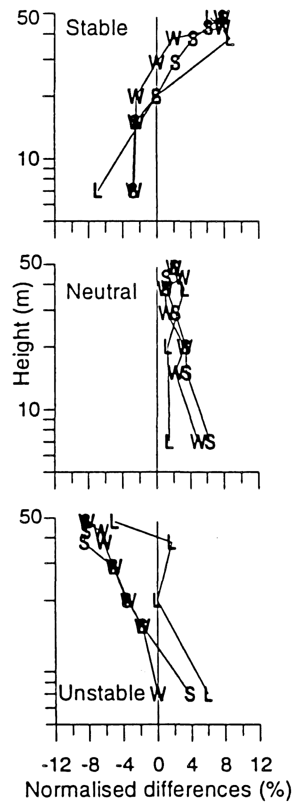

Figure 3. Differences between predicted and observed wind speed profiles at the three masts in different stability conditions (L=LM,S=SMS,W=SMW).

the coast than in near-neutral conditions. The weighting factor, w, is applied to stability corrections where:

$w=min(x,c)/c$

and x is the distance from the coast. Reducing c means that close to the coast weighting factors will be larger but applied over a shorter distance (as in unstable conditions), while increasing c means that the factors will be smaller but applied over longer distances. The effect of varying c on the predicted wind speed profile at SMS is shown for different stability conditions in Figure 4. Reducing c gives a better prediction for the wind speed profile in near-neutral conditions, while increasing c improves the predictions below 40m in stable conditions. Differences between the observed and predicted wind speeds appear to arise mainly from the deviation of the observed profile from the near-logarithmic profile predicted by WA^{S}P rather than from variations in the weighting factor.

4.4 Changing the shape of the wind speed profiles

WA^{S}P can apply small changes to the wind speed profile (relative to a logarithmic profile) due to stability effects which are set using three parameters (these are only applied if default parameters are changed). The first is a height parameter, dy - 'the height above ground where differences between stable and unstable profiles are smallest' (Mortensen et al., 1993). The default value is 100m. The second is a stability root mean square (r.m.s.) factor which accounts for stability variations in near-surface wind speeds e.g. at 10m. Mortensen et al. (1993) report that this value is close to the r.m.s. of the diurnal variability of wind speeds. The default value is 0.12. The last factor is an offset (the increase in wind speed) due to stability. The default value is 0.11. The equivalent parameters for over water situations can also be changed - these have default values of 50m, 0 and 0 respectively. Values for the first parameter are difficult to determine without measurements to 100m height. However, examination of wind speed profiles in different stability conditions (Figure 3) suggests that dy is set correctly. To calculate the second parameter, r.m.s values are determined for the whole Vindeby data set at 20m height at LM and SMS. The data set is then divided into stability classes (as given in Table 1) and the r.m.s value for the near-neutral class calculated. The difference between this r.m.s and the r.m.s. for the whole data set is assumed to be equivalent to the second parameter. For LM this value is 0.29 and for SMS it is 0.33. To determine the offset, the difference between the WA^{S}P predicted profiles at 48m and the observed values are used. For LM and the sea masts the factors are 0.12 and 0.08 respectively (positive in stable conditions, negative in unstable conditions). These are close to the WA^{S}P default. The effect of changing these parameters on the WA^{S}P predicted wind speed profiles is very slight (Figure 5). The improvements in the predictions occur near the top of the wind speed profiles.

4.5 Changing the offshore heat flux

In the standard application of WA^{S}P there are differences between the heat flux, H_0, and heat flux variability over land and sea. The values used are climatological averages with variability introduced by the r.m.s. value, where:

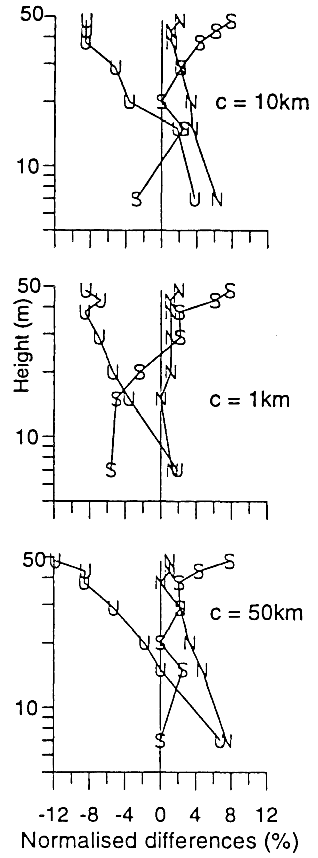

Figure 4. Differences between predicted and observed wind speed profiles at SMS for different values of the width of the coastal zone, c (U=unstable, N=near-neutral, S=stable).

H_0 land -40Wm^{-2}	r.m.s H_0 land 100 Wm^{-2}
H_0 sea 15Wm^{-2}	r.m.s H_0 sea 30 Wm^{-2}

Analysis of Richardson numbers at Vindeby suggests that stability conditions at SMS are frequently different to those at LM. Here, a number of scenarios are tested in which the default offshore H_0 is varied. The r.m.s. value is unchanged in all cases. The wind speed predictions are improved slightly by setting H_0 to -100 Wm^{-2} in near-neutral conditions, and to +100Wm^{-2} in unstable conditions. Predicted wind speeds are increased at the lower heights if H_0 is negative, and increased at all heights if H_0 is positive. If H_0 is set to -100Wm^{-2} the predictions can be improved at some heights in stable conditions. These results are shown in Figure 6. It should be noted that stability conditions at Vindeby may not be typical of offshore areas due to the low water depths. Further analysis is required to quantify H_0 and r.m.s. H_0 for different offshore areas.

5. DISCUSSION

WA^{S}P is used here to predict wind speed profiles at two offshore masts between 1 and 2km from the coast using data from a land - based mast. In this coastal zone,

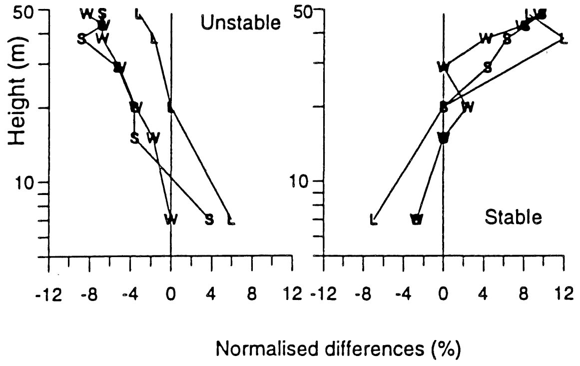

Figure 5. Differences between predicted and observed wind speed profiles for different values of the stability parameters in the wind speed profile on- and off-shore (L=LM,S=SMS,W=SMW).

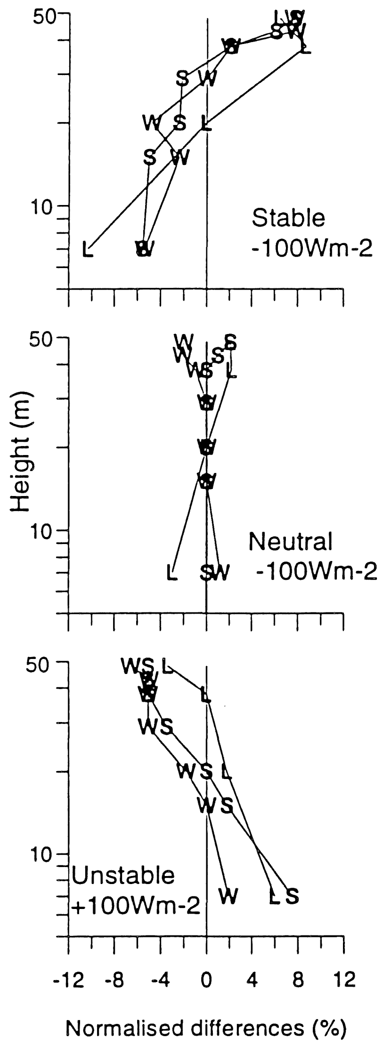

Figure 6. Differences between predicted and observed wind speed profiles for different values of the offshore heat flux (L=LM,S=SMS,W=SMW).

the wind field is modified by changes in both roughness and stability. The standard WA^{S}P application predicts mean wind speed profiles at the sea masts with a good degree of accuracy (within ±0.2m/s or ±3%).

In order to examine WA^{S}P's performance in different stability conditions, the data are subdivided into stability classes. This introduces two errors - those due to stability deviations and the problems of using a small data set. Accurate predictions within WA^{S}P rely on a the fitting of a Weibull distribution which may no longer be valid for short time-series. Even when the data are subdivided by stability class, the maximum difference between observed and predicted wind speeds is ±0.5m/s or ±12%.

WA^{S}P's default parameter settings can be changed to account for different stability conditions. Here three scenarios are evaluated:

1. Width of the coastal zone.
2. Stability parameters in the wind speed profile
3. Heat flux and heat flux variability on- and off-shore.

Predictions of wind speed profiles at the sea masts can be improved slightly by altering these parameters based on data from Vindeby. Further improvement may be obtained by combining changes in the default settings which will allow varying stability conditions to be taken into account more effectively. This requires further investigation, together with detailed examination of stability in different offshore environments. This approach may improve implementation of the WA^{S}P model in offshore areas such as the Baltic where conditions are frequently stable.

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