



## WAsP engineering DK

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# WAsP Engineering DK

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May 2000**

**Abstract** This report summarizes the findings of the EFP project *WAsP Engineering Version 1.0 DK — Vindforhold for vindmølledesign*. WAsP Engineering is a series of experimental and theoretical activities concerning properties of the winds in moderately complex terrain with relevance for loads on wind turbines and other large structures. These properties include extreme winds, wind shear and turbulence. Most of the models have been integrated in a windows program prototype, also called WAsP Engineering.

The basic mean flow model LINCOM has been changed in several respects to accommodate the demands from load calculations. The most important change is the inclusion of a complex model for the roughness length on water bodies. This is particularly important for the estimation of extreme winds in the vicinity of sea shores. A second addition is the calculation of spatial derivatives of the mean flow to be used for the modeling of turbulence.

The turbulence structure on hills is modeled by perturbing the flat, homogeneous terrain turbulence using Rapid Distortion Theory. A simple model for the adjustment of turbulence to roughness changes is also applied. Second order turbulence statistics such as turbulence intensities, spectra and cross-spectra can be estimated at user-chosen positions in the terrain. A program for simulation of turbulence with the calculated statistics has been developed. However, it has not yet been integrated into the windows interface.

Climatological series of wind speed have been analyzed to establish the extreme wind climate over Denmark. The extreme wind climate contains directional information and is used for estimating the extreme winds at an arbitrary position in complex terrain. A net of high precision pressure sensors covering Denmark has been established in order to obtain a climatology of the geostrophic wind. A tentative conclusion from only one year of data is that, statistically, the geostrophic wind decreases when going from west toward east.

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# 1 Introduction

The outcome of WAsP Engineering DK is measurements, analysis and theories concerning properties of the wind which are relevant for the estimation of loads on wind turbines and other civil engineering structures situated in complex terrain. Most of the results of these activities are unified in the computer program WAsP Engineering, version 1 Prototype. The wind properties treated in this work are:

1. Extreme wind speeds, e.g. the 50 year wind. If a wind turbine is well situated on a hill the mean wind speed and thereby the energy production can be increased significantly compared to that over flat terrain. Unfortunately, the 50 year wind will increase correspondingly, maybe calling for increased strength of the wings or other parts of the turbine.
2. Wind shears and wind profiles. Strong mean wind shears (large differences of the mean wind speed over the rotor) give large fluctuating loads and consequently fatigue on wind turbine blades, because the blades move through areas of varying wind speed.
3. Turbulence. Turbulence (gusts of all sizes and shapes) causes dynamic loads on various civil engineering structures, including wind turbines. The strength of the turbulence varies from place to place. Over land the turbulence is more intense than over the sea. Also the hills affect the structure of turbulence. We model various terrain dependent properties of turbulence.

This report outlines the various subtopics of the project and presents the prototype software.

## 2 The linear flow model LINCOM

Within the concept of linearized flow models originally introduced by Jackson and Hunt (1975), Troen and de Baas (1986) developed a relatively simple model for neutrally stable flow over hilly terrain. The model was later named LINCOM, an acronym for LINearized COMputation. Several investigators extended and changed the model code in different ways until Santabárbara, Mikkelsen, Kamada, Lai and Sempreviva (1994) rewrote it completely. The base of this version of the code, giving the influence of the topography on the flow of a neutrally stratified atmosphere, has been extended by Astrup, Mikkelsen and Jensen (1997) with a model for the influence of varying surface roughness. This extension was based on the assumption that close to the ground the flow is in equilibrium with the local surface roughness, and on a complicated model for the vertical extent of this equilibrium zone.

Later the model has been extended to calculate spatial derivatives of the mean wind field, such as the vertical shear  $\partial U / \partial z$ , which is used in the turbulence modeling.

LINCOM is based on an analytical solution in Fourier space to a set of linear equations derived from the normal nonlinear mass- and momentum equations for incompressible fluid flows. The linear equations describe the perturbations in velocity and pressure which the real terrain induces in an equilibrium flow corresponding to a flat terrain with uniform surface roughness. The perturbations caused by horizontal gradients in ground elevation and surface roughness are determined separately and added as a first order approximation to the combined perturbation.

LINCOM is different from the flow model in WAsP (Mortensen, Landberg, Troen and Petersen 1993) in several aspects. WAsP uses a Fourier-Bessel expansion on a polar zooming grid and calculates the wind speed at the central point only. The zooming

grid resolves the landscape better the closer to the center, which is obviously appropriate. LINCOM calculates the wind vector by Fourier techniques in every mesh point of a rectangular grid, see figure 1. This is appropriate for WAsP Engineering for two reasons. Firstly, to model a wind speed (and fetch) dependent roughness at sea it is necessary to know the wind speed over the entire body of water. Secondly, the turbulence model described in section 3 uses the flow field upwind from the point of interest as input. Again, information on the flow in more than one point is essential.

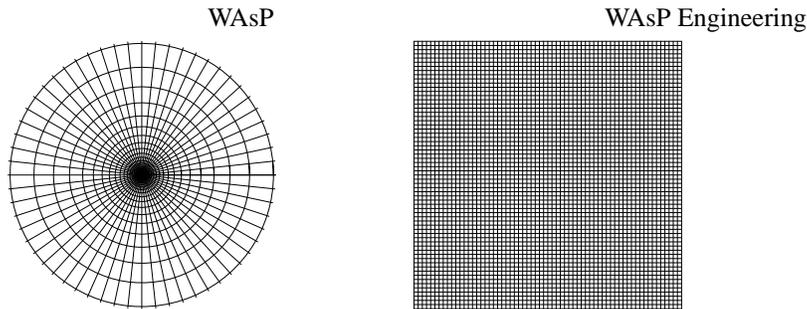


Figure 1. The calculation meshes of WAsP and WAsP Engineering

Another difference is that LINCOM has a more realistic treatment of the inner layer, i.e. the layer close to the ground where perturbations in the turbulent momentum transport is important.

Finally, thanks to Santabárbara et al. (1994) and later contributors the source code for LINCOM is well structured and easy to change.

## 2.1 The water roughness model

For WAsP Engineering, the best possible prediction of flow over water bodies is of great importance because at extremely strong winds the roughness of the sea is much larger than at average wind speeds. This in turn influences the calculated 50-year extreme winds whenever large bodies of water are close to the site of interest. For that reason a water roughness model i.e. a model giving the sea surface roughness height, has been interfaced with LINCOM. The modeled roughness depends upon the LINCOM-calculated velocity field which in turn depends upon the modeled roughness. Reasonably consistent fields of roughness length and wind velocity are therefore obtained by iteration.

The basis of the model is the well known formula of Charnock (1955) for surface roughness of the sea, stating that roughness increases with increasing wind speed. This has been modified to take into account finite fetch lengths (Astrup and Larsen 1999, Astrup, Larsen, Rathmann and Madsen 1999). An example of calculated water roughness for strong winds is shown in figure 2.

## 3 Turbulence

A lot is known about turbulence over flat terrain. The purpose of this part of the project is to develop models that take into account the influence of roughness changes and gentle hills on the turbulence statistics. This is described in more detail below. In section 3.2 we outline how this model of the turbulence statistics is used to simulate fields of turbulence suitable as input to dynamic load calculations on wind turbines and other structures.

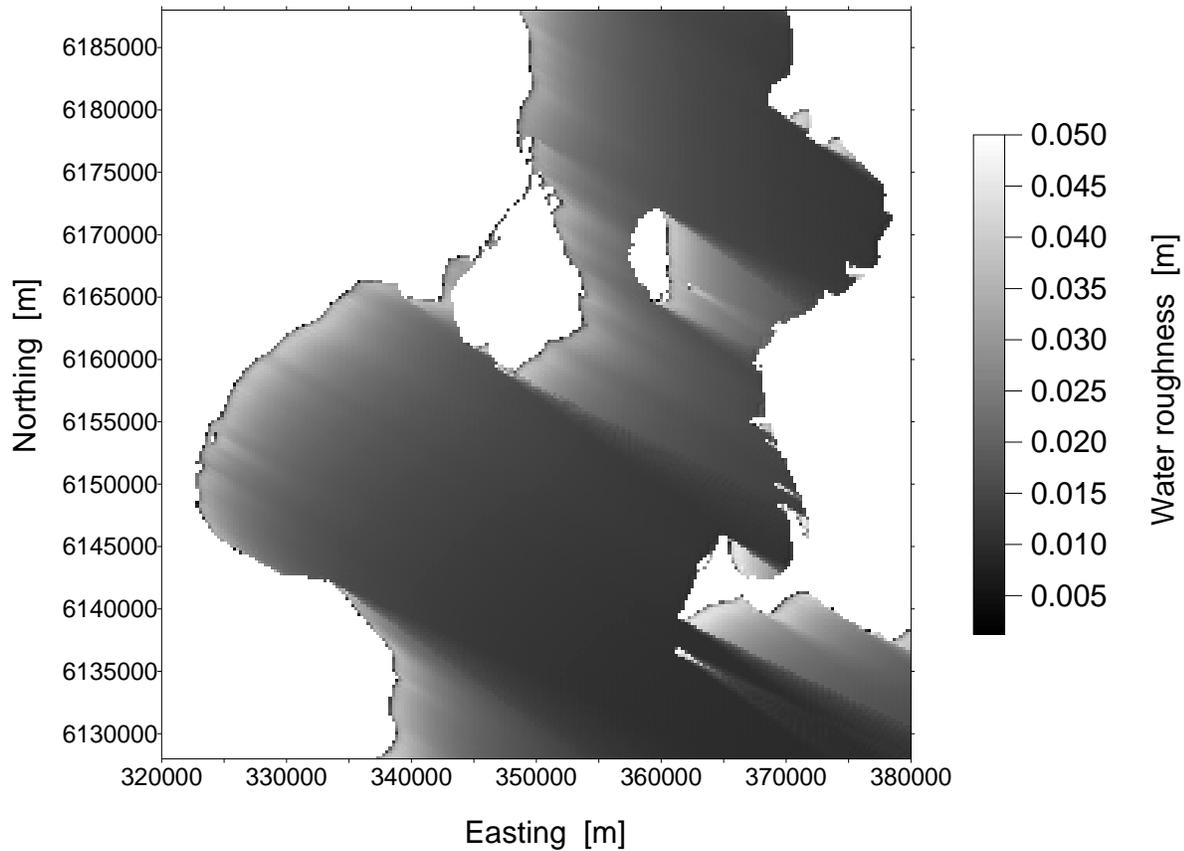


Figure 2. Calculated roughness lengths at sea for 24 m/s winds coming from 300°.

### 3.1 Turbulence statistics model

The modeling of the turbulence structure is divided into two parts: Orography and roughness variations. For the former rapid distortion theory (RDT) is used.

Effects of both on the turbulence are treated as perturbations to the flat and homogeneous terrain turbulence model of Mann (1994), which encompasses many well known properties of atmospheric surface layer turbulence. The model assumes neutral atmospheric stratification. This may be a serious restriction in cases of moderate wind speeds over the sea, where stable stratification may suppress turbulence. Also at low wind speeds both stable and unstable atmospheric stratification may alter the mean flow and the turbulence and hence the structural loads drastically. A prominent example of this is a steel chimney, which may experience the largest dynamic loads at light stably stratified (turbulence free) winds, where vortex shedding occurs.

The modeling of the change of turbulence due to orography is limited to the so-called outer layer. For a simple isolated hill the height  $\ell$  of the inner layer is estimated by

$$\frac{\ell}{L} \ln^2 \left( \frac{\ell}{z_0} \right) = 2\kappa^2, \quad (1)$$

where  $z_0$  is the roughness length,  $L$  the upwind distance where the elevation is half the hill height and  $\kappa \approx 0.4$  the von Kármán constant (Jensen, Petersen and Troen 1984). At heights lower than  $\ell$  there is approximately local equilibrium between production and dissipation of turbulent kinetic energy, and above  $\ell$  the perturbations caused by the hill are approximately inviscid. The inner layer height is also approximately equal to the height above which the travel time over the hill is shorter than the Lagrangian time scale or the eddy ‘turn-over’ time scale.

Inner scales derived from (1) compare well with measurements from Askervein, a nice “Gaussian” hill on the Outer Hebrides (Walmsley and Taylor 1996). Examples of calculated inner scales are shown below:

Hill dimension $L$ [m]	Roughness length $z_0$ [m]	Inner layer height $\ell$ [m]
100	0.03	2
100	0.3	4
1000	0.03	10

The lower limit of the applicability of the model thus depends on the terrain.<sup>1</sup> However, most wind turbine rotors are in the outer layer.

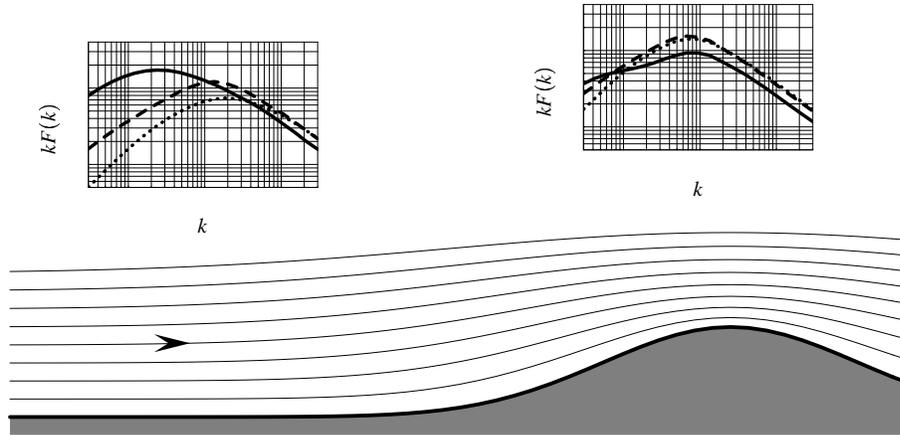


Figure 3. Qualitative sketch of the action of a ridge on the turbulence according to the RDT model. The fluctuations in the  $u$ -component of the turbulence are attenuated, as seen from the  $u$ -spectrum (solid curve), the  $v$ -fluctuations are not changed much (dashed curve), while the  $w$ -fluctuations are amplified (dotted curve).

To simplify the RDT equations various approximations are applied (Mann 2000), and although the results have been tested against the Askervein data, the limit of applicability in terms of the complexity of the landscape remains to be fully understood. An illustration of the modification of the turbulence spectra is shown in figure 3.

The modeling of turbulence changes due to roughness variations is not limited to the outer layer and should apply all the way down to the roughness sub-layer which is very close to the ground. The flow disturbances produced by roughness changes are by nature viscous and thus much “slower” than those due to RDT. We use and modify the idea that eddies respond to roughness changes on the order of “the eddy turn-over time scale” (Panofsky, Larko, Lipschutz, Stone, Bradley, Bowen and Højstrup 1982, Højstrup 1981). A consequence of this is that the low frequency end of the spectrum responds very slowly to roughness changes while small eddies quickly get in equilibrium with the underlying surface.

The basic model result is the so-called spectral tensor (Mann 1994). From this mathematical quantity more familiar statistics, such as spectra, cross-spectra, variances, turbulence intensities and coherences, can be derived. The calculation does not use information about the landscape directly, but indirectly through the mean flow field calculated by LINCOM.

<sup>1</sup>It should be pointed out, however, that the mean flow model LINCOM does not have this limitation.

### 3.2 Turbulence simulation

The spectral tensor produced by the model discussed above is very well suited for simulation of turbulence fields, which can be used for time domain simulation of dynamic loads on turbines and other structures. The simulation algorithm is described in detail in Mann (1998) for turbulence fields over flat terrain, and central parts of the algorithms can be used unchanged in complex terrain. As opposed to the turbulence statistics part the simulation part has not yet been integrated in the Windows program prototype.

## 4 Extreme winds in Denmark

Wind-speed data from four sites in Denmark have been analyzed in order to obtain estimates of *the basic wind velocity* which is defined as the 50-year wind speed under standard conditions, i.e. ten-minute averages at the height 10 m over a uniform terrain with the roughness length 0.05 m. The sites are, from west, Skjern (15 years), Kegnæs (7 years), Sprogø (20 years), and Tystofte (15 years). The data are ten minute averages of wind speed, wind direction, temperature and pressure. The last two quantities are used to determine the air density  $\rho$ . The data are cleaned for terrain effects by means of a slightly modified WASP technique where the sector speed-up factors and roughness lengths are linearly smoothed with a direction resolution of one degree. Assuming geostrophic balance, all the wind-velocity data are transformed to friction velocity  $u_*$  and direction at standard conditions by means of the geostrophic drag law for neutral stratification. The basic wind velocity in 30° sectors are obtained through ranking of the largest values of the *friction velocity pressure*  $1/2\rho u_*^2$  taken both once every two months and once every year. The main conclusion is that the basic wind velocity is significantly larger at Skjern, close to the west coast of Jutland, than at any of the other sites. Irrespective of direction, the present standard estimates of 50-year wind are  $25 \pm 1$  m/s at Skjern and  $22 \pm 1$  m/s at the other three sites. These results are in agreement with those obtained by Jensen and Franck (1970) and Abild (1994) and supports the conclusion that the wind climate at the west coast of Jutland is more extreme than in any other part of the country. Simple procedures to translate in a particular direction sector the standard basic wind velocity to conditions with a different roughness length and height are presented.

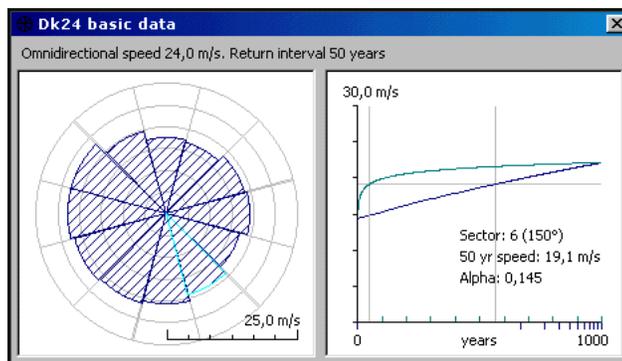


Figure 4. The extreme wind atlas for all of Denmark with exception of the West Coast. Clicking on a sector in the left panel displays the wind speed for that sector as a function of return period in the right panel.

A central outcome of this analysis, which is described in detail in Kristensen, Rathmann and Hansen (2000), is the sectorwise extreme winds for Denmark. An example of this so-called extreme wind atlas is shown in figure 4, which is valid for the most of Den-

mark except from the western part of Jutland. The left panel shows the 50-year storm as a function of direction in twelve sectors of 30°. It is no surprise that the strongest winds come from the West and Southwest. The right panel shows the extreme wind as a function of return period for sector 6 on a logarithmic (the almost straight line) and a linear scale. The results on the extreme wind climate have influenced the Danish code for loads on buildings and other structures.

The extreme wind atlas is the basis for estimating extreme winds in complex terrain, where it is very important to know the directional distribution of strong winds relative to directional features in the terrain. How the user of WAsP Engineering does this calculation is shown in section 6.

For more information on uncertainties and analysis on extreme winds see (Mann, Kristensen and Jensen 1998, Kristensen, Rathmann and Hansen 1999, Kristensen et al. 2000).

## 5 Pressure measurements and geostrophic winds

The basis for the methods used in WAsP Engineering (and WAsP) is a relation between the ‘free’ wind kilometers above the surface and near surface winds. This idealized relation is called the geostrophic drag law, and the purpose of this part of the project is to obtain and analyze data to investigate this relation in more detail.

Therefore, high-precision barometers have been deployed at six sites in Denmark, four west and two east of the Great Belt (see figure 5). The purpose is to establish long climatological records of the geostrophic wind as a supplement to the records of tens of years of duration of surface observations of wind, temperature, humidity etc., which have been obtained by Risø at many sites in Denmark. Three of these sites are in principle sufficient to determine an average of the magnitude and direction of the geostrophic wind inside the triangle formed by the three sites. Ten, out of twenty possible, triangles have been selected as suitable for studying the geographical variations of the geostrophic wind. A tentative conclusion from about one year of data is that statistically the geostrophic wind decrease in magnitude when going from west toward east. The data also showed that the largest mean values of the geostrophic mean wind speed are in a direction sector from 285° to 315°. The Weibull parameters were calculated for all ten triangles. The curvature of the isobars were determined by using simultaneous pressure measurements at all six sites and the geostrophic and gradient winds were calculated and compared to the geostrophic wind based on three pressure measurements in one particular triangle. Combining the geostrophic wind with the surface wind measured at Tystofte in southern Zealand, the two dimensionless constants  $A$  and  $B$  in the geostrophic drag law were determined as functions of the surface friction velocity. These data suggest that  $A = 0.5$  and  $B = 3.5$ . The surface data at Tystofte and at Børglum in Vendsyssel in northern Jutland were used to predict the geostrophic wind by applying the geostrophic drag law with these constants and the predictions were compared to the observed geostrophic wind.

Ultimately, we want to carry out an extreme-wind analysis on the geostrophic wind and the geographical variation of the 50-year event, similar to the analysis by Kristensen et al. (1999). However, the records we have so far are too short in duration to make such an analysis meaningful. From that point of view, we hope that the measurements will continue for at least 10 years.

More information on geostrophic winds and pressure measurements in Denmark may be found in Kristensen and Jensen (1999).

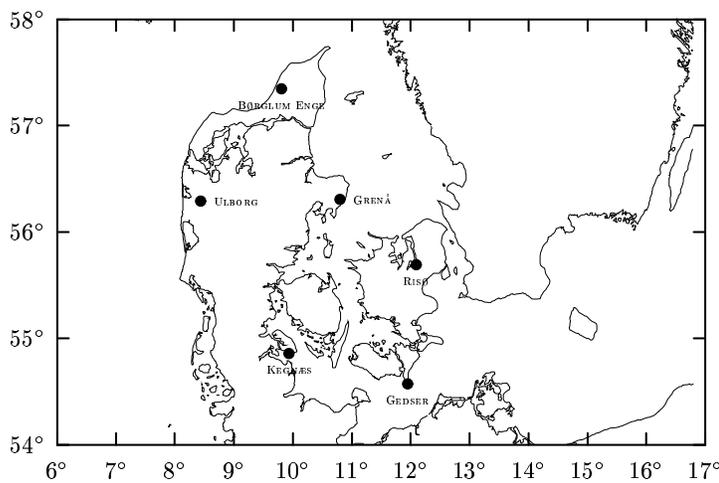


Figure 5. High precision pressure stations in Denmark installed early 1998.

## 6 The graphical user interface

Most of the models described in this report have been integrated into a computer program called WAsP Engineering. The program is a prototype implying that the architecture and the user interface may be altered drastically in response to the first experiences with the product. The program has been distributed to a limited number of potential end-users.

In the following we shall describe the functionality of the program and show various screen dumps. This is not intended to be a complete user manual.

The GUI (graphical user interface) is organized as follows. To the left three trees organize the user input and control which results are displayed to the right.

To start a project the user selects a map file, which has the format also used in WAsP. The calculation area, which may not be the entire area, is then selected and the program produces grid files of height and roughness to be used in the subsequent calculations. The various maps can be viewed by clicking the icons in the top left panel (see figure 6).

Before starting the mean flow calculations the user has to specify some wind speeds and directions together with one or more heights above the terrain. The user may also specify some points of interest (e.g. wind turbine sites) that are going to be investigated in more detail or where turbulence statistics is going to be calculated. The user entered wind speed is an unperturbed wind speed at a given height over a given roughness over flat terrain. In a future version of WAsP Engineering we intend to have the option of entering the wind speed at some user chosen point and to do the mean flow calculation over the entire domain from that.

An alternative way of entering wind speeds and directions is to import an extreme wind climate. This is a collection of 50-year speeds for the twelve 30° sectors as shown on the lower left panel or on the lower right window in figure 7. Also seen on the 'Map' window on the same figure is a flag indicating a user chosen site of interest.

Once the heights, winds and sites of interest are entered the calculations of the mean flow can be started. The results to display is controlled by the two lower left panels. For example, by selecting the wind '270° 22.8 m/s' and 'Fetch' the upwind fetch over water will be displayed in a window to the right as shown in figure 8. The wind speeds at the height  $z = 70$  m are displayed similarly. The calculated grid fields, which all are available under the node 'Result grid maps' in the 'Sites and heights' panel, are listed below:

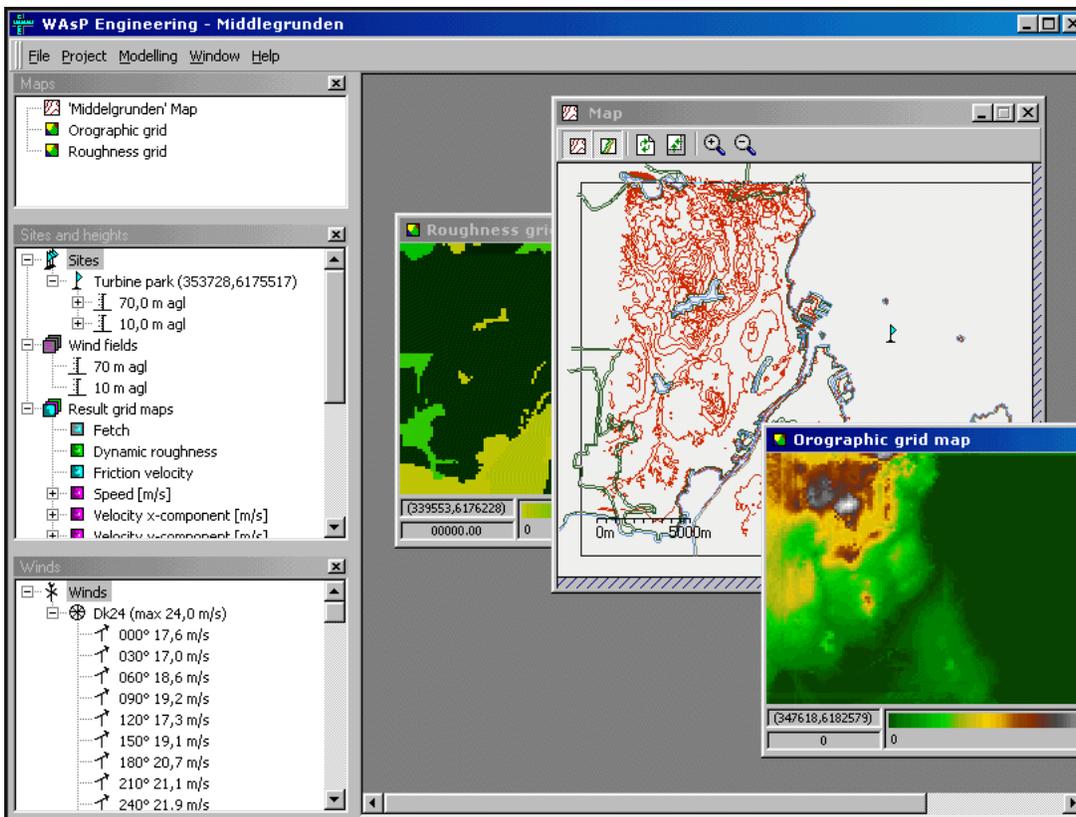


Figure 6. The graphical user interface of WASP Engineering.

Quantity	Description
Fetch	The length of the up wind water fetch. This is used in an iterative calculation of the roughness of the water surface.
Dynamic roughness	The aerodynamic roughness of the surface. It is variable over water depending on fetch and wind speed.
Friction velocity	The surface friction velocity $u_*$ .
Terrain inclination	Inclination of the terrain in the direction of the unperturbed mean wind.
Speed	The length of the mean wind vector.
Velocity components	Components in the coordinate system defined with $x$ -axis in the direction of the unperturbed wind, $y$ in the other horizontal direction and $z$ the vertical.
Derivatives $\partial U / \partial x$ , $\partial U / \partial y$ , etc.	Various shears.
Wind tilt angle	Tilt angle of the mean wind flow.

The upper four are not dependent on height, the lower ones are.

As soon as the user selects an other wind in the 'Winds' panel, e.g. '330° 19.8 m/s', the windows will show the quantities pertaining to the new wind, as seen in figure 9.

An alternative way of displaying the wind fields is by a vector plot as shown in figure 10. The small white rectangle at the upper left of the window controls which subarea to display.

By selecting a wind in the 'Winds' panel and a site under the 'Site' node the program displays a lot of variables of interest to load calculations (see figure 11. Also, at the point

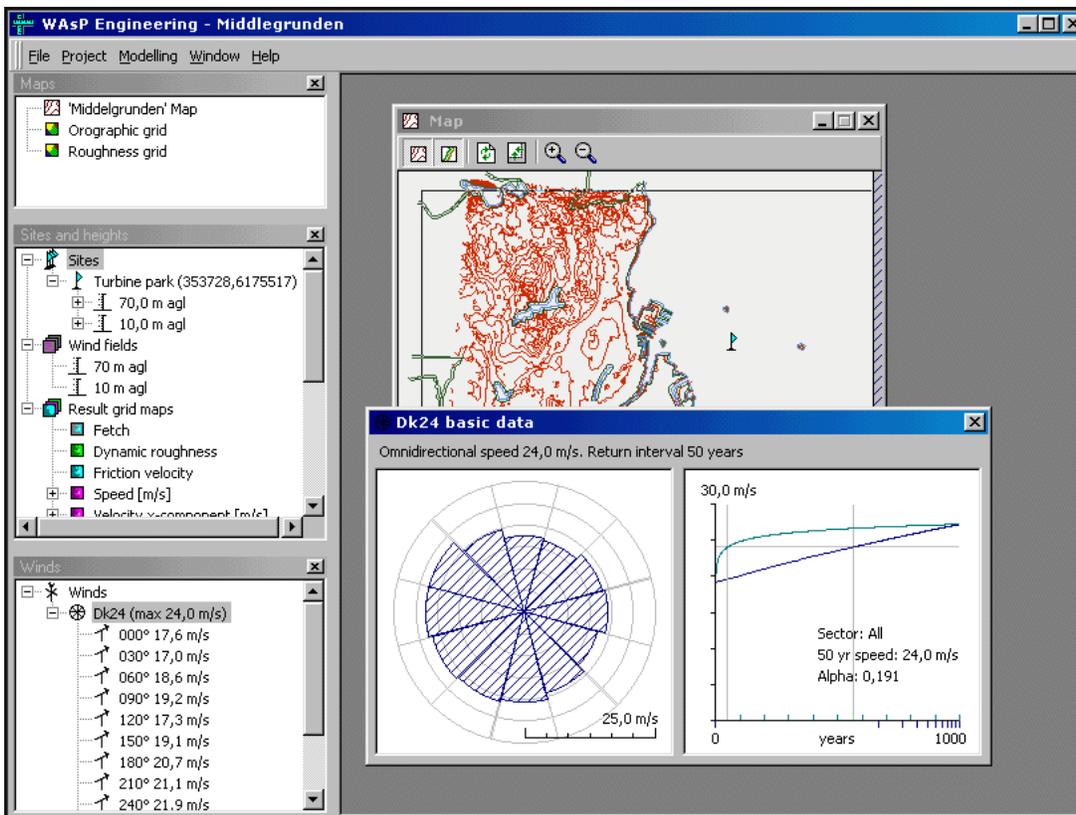


Figure 7. GUI with extreme wind climate.

of interest the terrain distorted extreme wind atlas can be displayed giving, for example, the 50-year storm at the complex terrain site.

Finally, at the points of interest various aspects of the turbulence statistics can be calculated. The complexity of the input window (figure 12) reflects the wide range of second-order statistics that can be calculated by the program.

Starting from the upper left the user first has to check a box indicating which standard code spectrum is preferred, either Kaimal, Wyngaard, Izumi and Coté (1972), Simiu and Scanlan (1996) or ESDU International (1986). Parameters of the spectral tensor of Mann (1994) are adjusted to fit either of these spectral models (Mann 1998). The type of output can be variances/turbulence intensities, one point spectra, and cross-spectra. The spectral range of wavenumbers has to be set, and for the (two-point) cross-spectra the separations in a plane perpendicular to the mean wind ( $\Delta y, \Delta z$ ) has to be chosen.

The results are displayed as shown in figure 13.

## 7 Future developments

In this section we list possible future developments. Some of the items have got support from the EFP project WASP Engineering 2000.

- The windows program is a prototype. This means that many features have to be rewritten in order to obtain a robust product, which can be distributed to a large group of engineers. Also, the program lacks essential features such as a help menu.
- We have only obtained a detailed extreme wind climatology for Denmark. We would like to investigate the possibility of extending the climatology to Europe or a larger

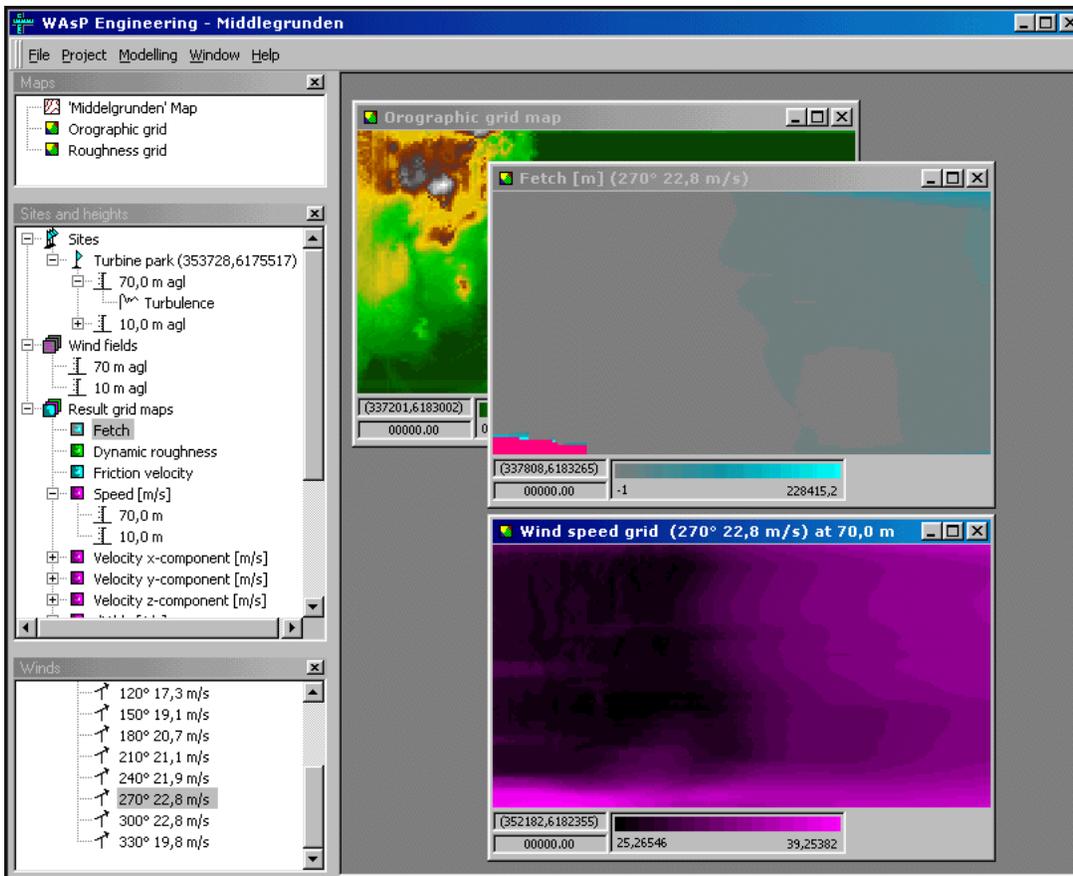


Figure 8. Results display with a wind direction of 270°.

part of the Globe by use of the meteorological reanalysis data covering the last 50 years available from National Center for Atmospheric Research (NCAR) or elsewhere.

- We would like to compare the predictions of the turbulence model with data from more complex terrain in order to get a better understanding of the limitations of the model and, ultimately, improve the turbulence model.
- A continuation of the high precision pressure measurements may one day lead to a better understanding of the connection between geostrophic winds and surface winds.
- A very powerful source of turbulence is the wake of wind turbines. When turbines are situated very close to each other wake turbulence may be the largest source of fatigue. We would like to include wake turbulence models into the program.
- An utility program in WASP called OWC (Observed Wind Climate) takes measured wind series and calculates the wind climate. We would like to make a similar program for the estimation of the extreme wind climate from measurements.
- The extreme wind climates reported here have been calculated with WASP with a constant sea roughness. Detailed analysis of the hurricane of December 3rd, 1999 shows that the varying sea roughness modeled by WASP Engineering/LINCOM is in fact very important (Mann and Hansen 2000). We would like to make a reanalysis of the climatological time series with WASP Engineering.

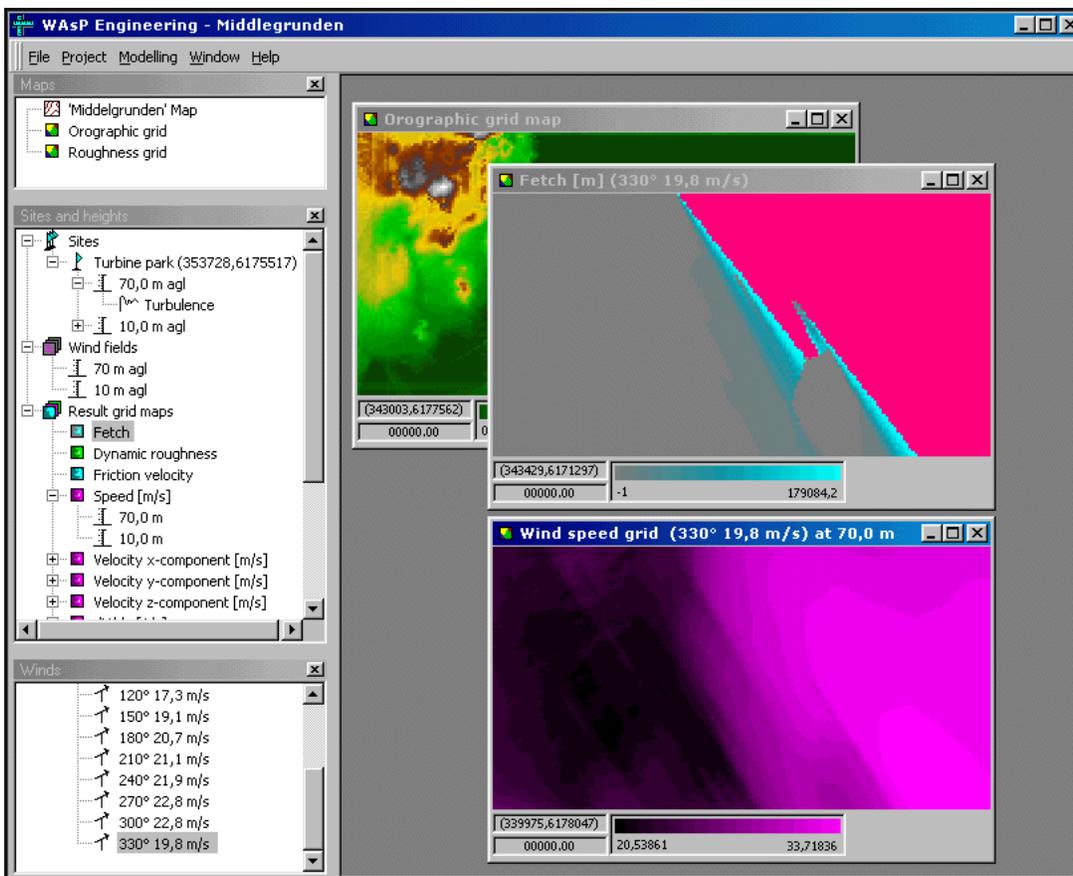


Figure 9. Results display with a wind direction of 330°.

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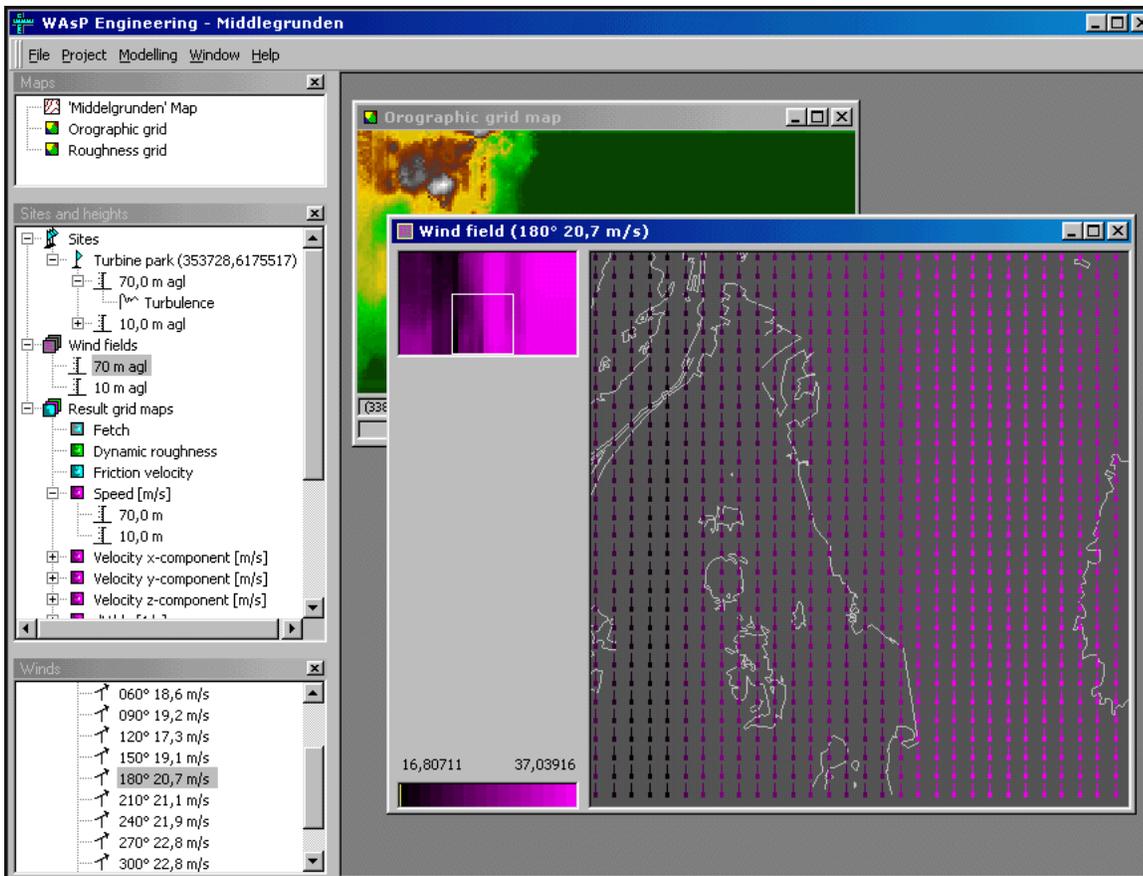


Figure 10. Wind field display.

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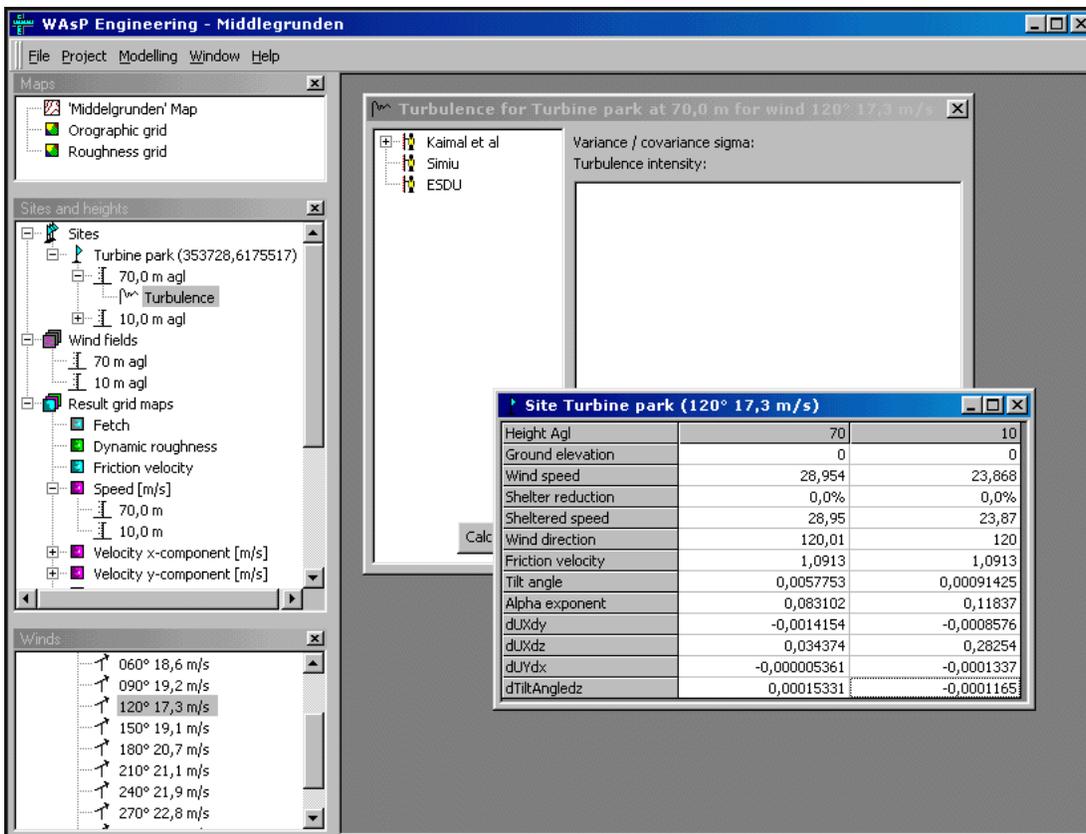


Figure 11. Table of variables at a site of interest.

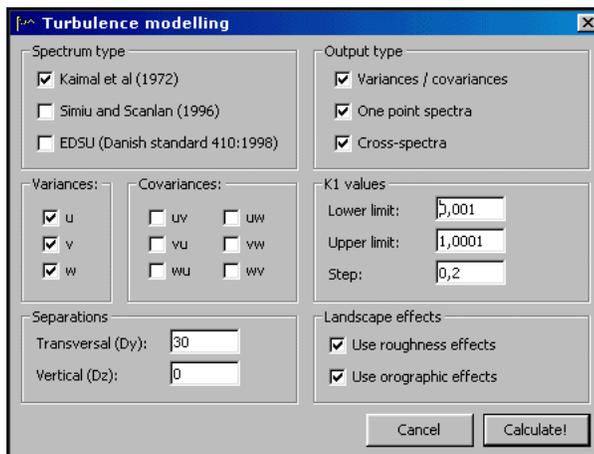


Figure 12. Input window for turbulence statistics calculations.

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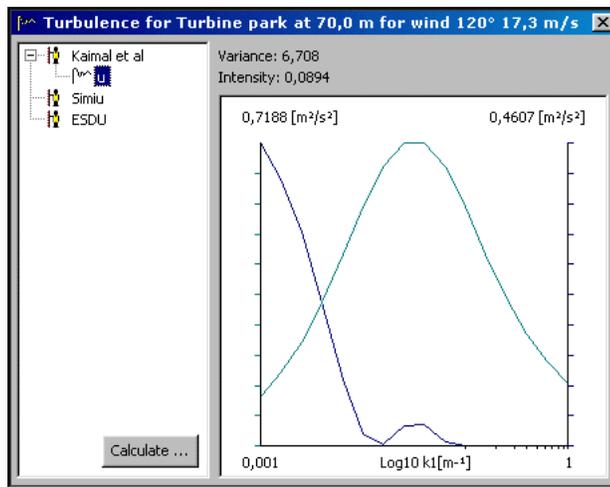


Figure 13. Variance, turbulence intensity, spectrum and cross-spectrum of the  $u$ -component for the site 'Turbine park' at the chosen wind.

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WAsP Engineering DK

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Abstract (Max. 2000 char.)

This report summarizes the findings of the EFP project *WAsP Engineering Version 1.0 DK — Vindforhold for vindmølle design*. WAsP Engineering is a series of experimental and theoretical activities concerning properties of the winds in moderately complex terrain with relevance for loads on wind turbines and other large structures. These properties include extreme winds, wind shear and turbulence. Most of the models have been integrated in a windows program prototype, also called WAsP Engineering.

The basic mean flow model LINCOM has been changed in several respects to accommodate the demands from load calculations. The most important change is the inclusion of a complex model for the roughness length on water bodies. This is particularly important for the estimation of extreme winds in the vicinity of sea shores. A second addition is the calculation of spatial derivatives of the mean flow to be used for the modeling of turbulence.

The turbulence structure on hills is modeled by perturbing the flat, homogeneous terrain turbulence using Rapid Distortion Theory. A simple model for the adjustment of turbulence to roughness changes is also applied. Second order turbulence statistics such as turbulence intensities, spectra and cross-spectra can be estimated at user-chosen positions in the terrain. A program for simulation of turbulence with the calculated statistics has been developed. However, it has not yet been integrated into the windows interface.

Climatological series of wind speed have been analyzed to establish the extreme wind climate over Denmark. The extreme wind climate contains directional information and is used for estimating the extreme winds at an arbitrary position in complex terrain. A net of high precision pressure sensors covering Denmark has been established in order to obtain a climatology of the geostrophic wind. A tentative conclusion from only one year of data is that, statistically, the geostrophic wind decreases when going from west toward east.

Descriptors INIS/EDB

ATMOSPHERIC PRESSURE; COMPLEX TERRAIN; FLOW MODELS; SEAS; TURBULENCE; VELOCITY; W CODES; WIND; WIND LOADS

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