INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems
ANNEX XI

31st Meeting of Experts

State of the Art on Wind Resource Estimation

Risø, Denmark, October 29.-30., 1998

Organized by : RISØ National Laboratory

Scientific Coordination :

B. Maribo Pedersen
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31th IEA Experts Meeting

STATE OF THE ART ON WIND RESOURCE ESTIMATION

October 29. - 30. 1998, RISØ, Denmark

INTRODUCTORY NOTE

prepared by
Dr. Lars Landberg

With the increasing number of wind resource estimation studies carried out for regions, countries and even larger areas all over the world, the IEA finds that the time has come to stop and take stock of the various methods used in these studies. The IEA would therefore like to propose an Experts Meeting on wind resource estimation.

The Experts Meeting should describe the models and databases used in the various studies. It should shed light on the strengths and shortcomings of the models and answer questions like: where and under what circumstances should a specific model be used? what is the expected accuracy of the estimate of the model? and what is the applicability?

When addressing databases the main goal will be to identify the content and scope of these. Further, the quality, availability and reliability of the databases must also be recognised.

In the various studies of wind resources the models and databases have been combined in different ways. A final goal of the Experts Meeting is to see whether it is possible to develop systems of methods which would depend on the available input. These systems of methods should be able to address the simple case (level 0) of a region with barely no data, to the complex case of a region with all available measurements: surface observations, radio soundings, satellite observations and so on.

The outcome of the meeting should be an inventory of available models as well as databases and a map of already studied regions.

Wind resource estimation

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Abstract

This paper will describe the different ways a region's or a site's wind climate can be estimated. The set of possibilities is limited only by the imagination of the authors! The ways differ in mainly the complexity and detail of the input data. The paper will describe each of seven ways and comment on advantages and disadvantages of each of them.

1 Introduction

One of the first actions needed when interest in wind energy from a region appears is to establish an overview of the available wind resource. This overview should make it possible to identify areas of high and low winds. It should also quantify these, making it possible to evaluate whether wind energy is economically viable in the area. The problem is that different areas will have very different sources of information about the wind. This is not a problem if one has the option of establishing a dense measuring network, wait for 5 to 10 years, and then evaluate the wind resource. In practice this is not possible, of course, so other methods must be applied.

In the following seven methods for estimating the wind resource of an area will be described. First however, the term 'wind climate' will be defined.

2 Defining the regional wind climate

In Table 1 the definition of the regional wind climate is given. It is put into context by defining the wind resource and the wind atlas as well.

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Table 1: The definition of the three wind resource terms. For each term some comments are also given, relating to scale and/or scope.

Term	Definition	Comments
Atlas*	Collection of regional wind climates for a large area	Scope: 100 – 10,000 km Resolution: O(50 km)
Regional climate	Wind statistics, temporal and spatial variation. Reduced to standard conditions.	Scale: O(50 km) Regional validity Must be modelled
Resource	The actual long-term kinetic energy content of the wind at a specific location and height	Scale: O(1 m)

* 'Atlas' is also used as the term describing the WAsP .LIB-file.

The regional climate is calculated from measurements by removing the *local effects*. Local effects are all effects being specific only to the specific site, viz.

- shelter from near-by obstacles
- effects of roughness, and changes in roughness
- effects of the orography, on scales less than ≈10 km
- thermally driven effects

The main advantage of using this definition is that it is almost scale independent, ie small features in the landscape (hills, valleys, forests, lake etc) do not affect the regional wind climate.

3 Methods for wind resource estimation

In Table 3 the different methods are outlined and in the following sections each of the methods will be described and its applicability will also be discussed.

3.1 Method 1: Folklore

This method bases itself on interviews with local people, and the aim is to identify areas with high and/or low wind speeds. The method can be used if all else is not possible and has the advantage of being very cheap and fast. Of the large number of shortcomings this method has only two will be mentioned:

Table 2: The seven different ways of wind resource estimation. 'Measurements' refers to traditional on-site measurements taken at eg airports. An example of a data base of geostrophic winds could be the global one of NCEP/NCAR, and an example of a data base of land-use (ie the roughness of an area) as eg the CORINE data base.

Method	1	2	3	4	5	6	7
Measurements		√	√		√		√
Data base geostrophic winds				√		√	√
Data base land-use						√	√
Data base orography						√	√
WAsP terrain					√		√
Meso-scale model						√	√
Micro-scale model					√		√
Geostrophic drag law				√			
Statistical models			√				
"Folklore"	√						

there is almost always a tendency to overestimate the wind in windy areas, mainly – we speculate – because of the chill factor: when it is cold even moderate winds feel strong. The other problem with this method is that it is not certain that the entire area in question is traversed by humans. The reasons for this can be many, one could be high winds! another inaccessibility. In conclusion this method should be used only if no other is available and important decisions should not be based on this evidence alone.

A derivative of this method is onomatology where areas with potentially high winds are located by finding geographical names indicating this. An example is 'Windy Standard' in Scotland.

Another related method is locating high wind areas by studying the local vegetation; eg trees in very windy areas tend to take shape after the prevailing wind, the so-called 'flagging' of trees.

3.2 Method 2: Measurements only

Basing a regional study on measurements only is indeed possible. However, great risk exists of either severely over- or under-determining the resource. The resource will be under-determined if the study is based on mainly observations in build-up (or other high roughness) areas. Conversely the resource will be over-determined if the observations are mainly from low roughness, very exposed areas.

3.3 Method 3: Measure-correlate-predict

A method often used in micro-siting is measure-correlate-predict (MCP) . The idea is that the resource at a potential site can be determined using a short measuring campaign at the site and then correlating these measurements with an overlapping but climatologically representative (ie containing measurements over a 5–10 year period) time series. This method could also in principle be used for regional wind resource estimations, but it suffers from the same drawbacks as method 2: risk of either severe under-/over determination of the resource.

3.4 Method 4: Global databases

Using global databases of winds has first been possible within the past 2–5 years with the appearance of databases like the ones from NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) and ECMWF (European Centre for Medium-range Weather Forecasting) (cf Figure 1). These databases are the result of the huge reanalysis effort carried out by these institutions. The databases typically contain wind at several heights, temperature, pressure etc. To ensure that local effects on the measurements are avoided to the greatest extend wind in the free atmosphere are used. To extrapolate these winds to the surface the geostrophic drag law is employed. The geostrophic drag law connects the geostrophic wind to the friction velocity at the surface according to

$$G = \frac{u_*}{\kappa}\sqrt{\left(\frac{u_*}{fz_0} + A\right)^2 + B^2} \tag{1}$$

where G is the geostrophic wind (ie the wind derived from the balance between the pressure force and the Coriolis force), u_* is the friction velocity, κ (=0.4) the von Karman constant, f the Coriolis parameter, z_0 the surface roughness, and A and B are constants, equal to 1.8 and 4.5, respectively.

The geostrophic drag law is used to extrapolate the wind to different roughness and landscape conditions.

This method has several advantages. Firstly, since the databases are global-spanning the method can be applied to any area. Secondly, since high-level winds are used the local effects are not introduced in the first place, Thirdly, since the database contains typically around 10 years or more of measurements the estimates are climatologically stable. This, potentially, makes the estimates very close to the actual wind resource. The method has also some drawbacks, the main one is the resolution, typically on the order of degrees (ie 100's of km).

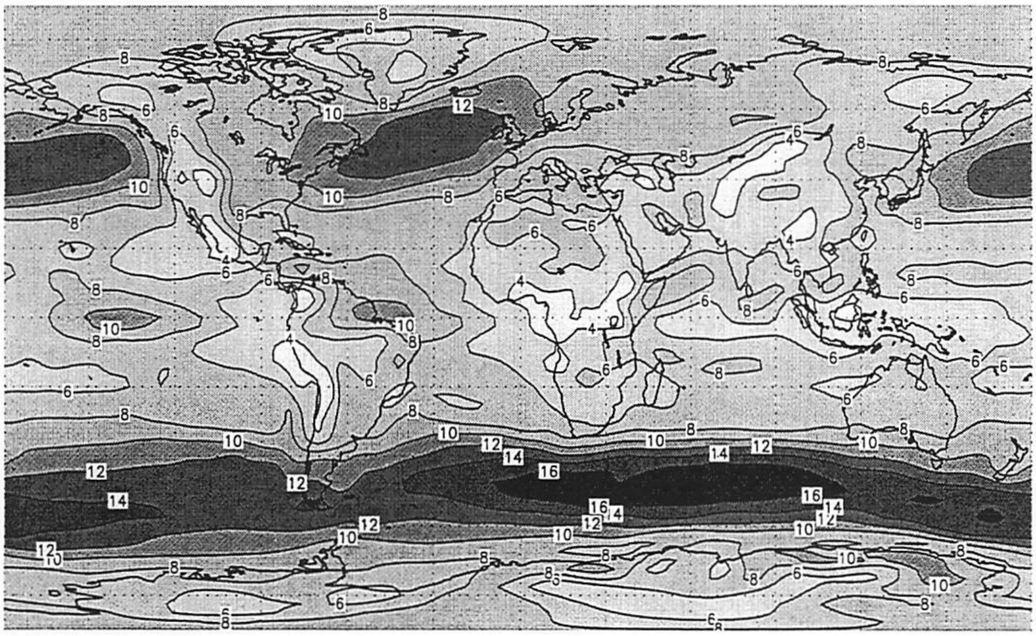

Figure 1: Mean wind speed at 850 mb for the years 1976-1995 from the NCEP/NCAR reanalysis.

3.5 Method 5: Wind Atlas Methodology

For countries with a tradition of long records and dense networks of observations of the wind, the wind atlas methodology (Troen and Petersen, 1989) is the preferred method for wind resource studies. The method has been applied to a large number of counties (all of EU-Europe, Russia, countries in northern Africa) making it the de-facto standard, see Figure 2. The method directly corrects existing long-term measurements for three of the four local effects listed in Section 2 (cf Figure 3). The fourth is not very dominant in many areas of the world. In areas where thermally driven winds do occur the wind atlas methodology can be applied – as long as care is taken to only use wind climate files for areas of similar thermal influence.

The advantages are many: firstly, by being the de-facto standard different wind atlases can be compared and understood directly by a large community. Secondly, by using the method in reverse (the so-called application part) makes it possible to determine the specific winds at a site to a very high accuracy.

3.6 Method 6: Meso-scale modelling

With the increasing speed of computers it became possible during the last years to use atmospheric meso-scale models to estimate the wind resource of a region. The grid size of the models is of the order of a few kilometres. A region

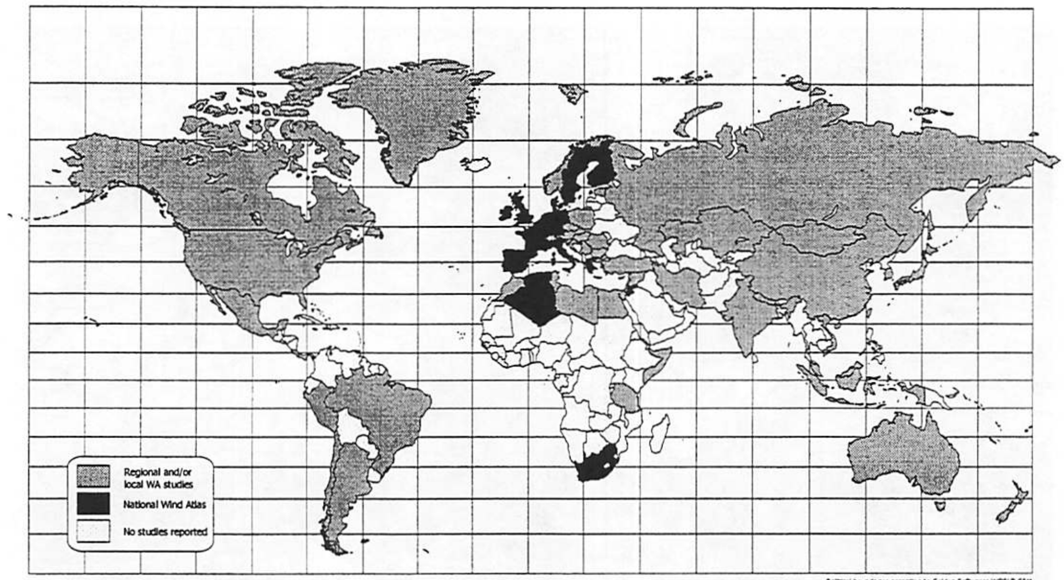

Figure 2: World-wide status of the Wind Atlas methodology by the end of 1998. National wind atlases have been published for the countries marked in black and regional and/or local studies exist in the countries marked in dark grey. No wind atlas studies have been reported so far for countries marked in light grey.

of a few hundred by hundred kilometres is modelled, see Figure 4.

Mostly, a statistical dynamical approach of regionalization of large-scale climatology [4] is used to calculate the regional surface wind climate. It is assumed that the regional surface layer climate is determined uniquely by a few parameters of the larger, synoptic scale and parameters of the surface. Representative combinations of the parameters are found and 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.

Required input data are orographic and land-use grid maps. The surface roughness is determined from the land-use. The external forcing of the model are boundary conditions from the larger scale, e.g. the large-scale pressure gradient or geostrophic wind. It is either determined from radio-soundings [7], or from large-scale models, e.g. re-analysis data [6, 5].

In principle, the method can be applied worldwide as global data coverage is now available.

Major problems are the determinations of the important external parameters and the definition of the most representative situations. Also, a resolution of several kilometres cannot resolve the micro-scale terrain features which influence the surface wind. Resolutions of one kilometre or less require a tremendous amount of computing.

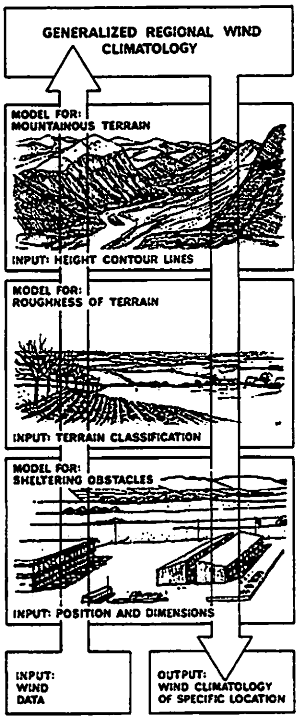

Figure 3: The Wind Atlas Methodology. From Troen and Petersen, 1989.

3.7 Method 7: Combined meso-/micro-scale modelling

A slightly different use of meso-scale modeling is done in combining a meso-scale model with a micro-scale model like WAsP. Instead of trying to resolve all small-scale terrain features the meso-scale modeling stops at a resolution of approximately 5 km. Local predictions are made with a micro-scale model like WAsP using output from the meso-scale model as input for the small-scale model. This approach is followed by [2, 3].

The method produces wind atlases like method 5 making it comparable for different regions. Also, many people, who gained experience in wind resource estimation with WAsP, can readily use the output from the meso-scale model. An example of the application of the method is shown in Figure 5.

4 Estimating the global wind resource

In this section a sketch plan is laid out, describing one approach to attacking the rather large task of estimating the wind resource world-wide.

The first step is to realise that it will be impossible to apply the same method to all areas of the globe: the data coverage and the availability will vary considerably from region to region. Therefore, an approach must be taken where

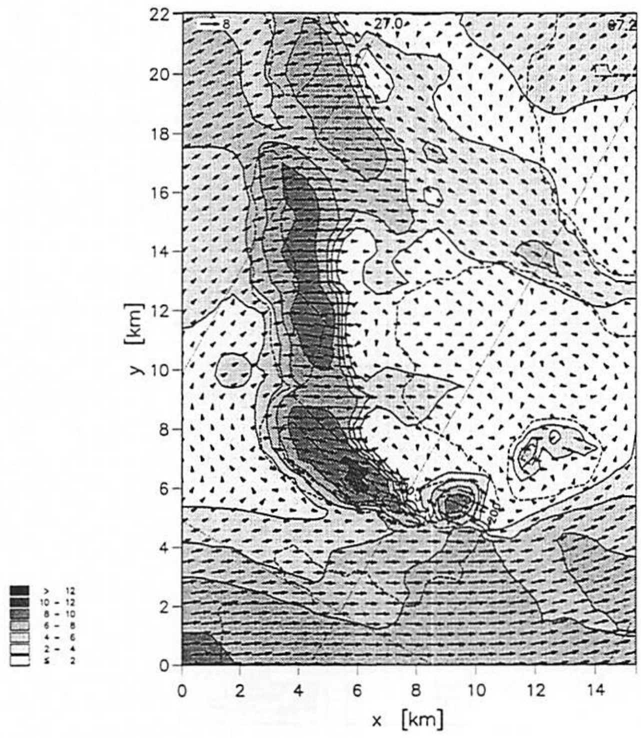

Figure 4: Simulated wind field at 61 m a.g.l. around Pyhätunturi Fell in northern Finland for a geostrophic wind of 10 m s^{-1} from the left under conditions of a very strong inversion. The contours show wind speed. Height lines are dashed. Note the eddies in the wake of the mountains which are approximately 300 m higher than the surroundings.

different levels of sophistication can be applied.

The lowest level is to use data bases of the geostrophic wind and then project the wind down to different roughness and landscape classes (method 4). Next step up is the wind atlas methodology (method 5) and the final step is the combined meso-/micro-scale modelling (method 7).

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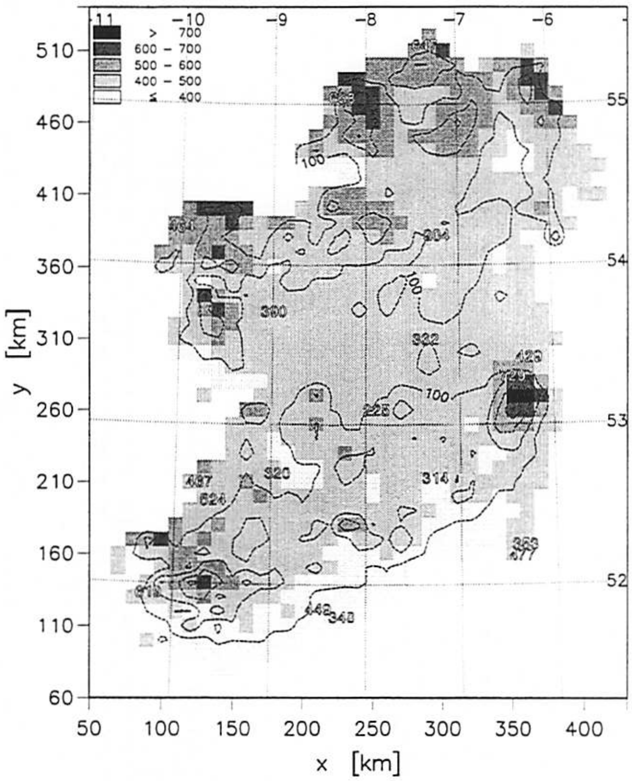

Figure 5: Simulated mean wind power density E in W m^{-2} at 50 m above a surface with roughness length z_0 = 3 cm for Ireland. Numbers show values determined from observations with WA^{S}P. Height lines are dashed.

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State of the art of wind resource estimation in Norway.

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1 Introduction

The first modern wind turbine in Norway was installed on the island Frøya in 1986. Shortly after, a 'demonstration programme' was initiated. Ten wind turbines were installed along the Norwegian coast, to get some practical experience with installation and operation of wind turbines. A utility oriented research programme allowed development of siting tools for complex terrain along with studies on the wind resource.

The energy sector was re-organised towards a market based system from 1991. Over-capacity in the hydro-power based system and limited export capacity diminished the interest for wind energy. The research programme and demonstration programme was discontinued, and funding was instead aimed at development of industrial products.

The two last years, Norway has become net importer of electricity. The remaining hydro-power projects are controversial, and gas power projects have been postponed due to the greenhouse debate. The interest for wind energy among developers re-emerged in 1997, and the land rush has led to significant siting and wind monitoring activity.

The first commercial windfarm came on line 21. August 1998. It is located at Lindesnes, at the southern edge of Norway. It is a small group of 5 x 0.75 MW Windworld machines. It is owned by the local utility companies.

A 1.65 MW Vestas V66 was connected to the grid 22. October 1998 at Hundhammar-fjellet in the county Nord-Trøndelag. The utility company Nord-Trøndelag Elektrisitetsverk owns this turbine.

The proposed national budget for 1999 contains tax incentives for wind energy. It is partly a cut in taxes, and partly an investment subsidy of up to 25 % of the cost. This makes wind energy on the best sites interesting for commercial developers.

This paper gives a short overview of the methods used so far in Norway and some main results from studies on wind energy resources.

2 Models

2.1 Measure-Correlate-Predict (MCP)

To evaluate proposed sites, short term measurements with 30-50m tilt-up towers and correlation techniques have been used since 1987. Since many sites are in complex fjord/island areas with significan channeling of the wind, the MCP method was extended in 1992 to account for direction changes. The following procedure is used (Nygaard 1992), (Tallhaug and Nygaard 1993):

Treat the velocity vector at the reference station (R) and site (S) as stochastic variables V (velocity) and D (direction class).

Use short-term measurements and linear regression to establish relationship for velocities for each direction class d_{Ri} at the reference station. Extrapolate long term data from reference station to site.

$$E(V_S \mid d_{Ri}) = \mu_{Si} + \frac{\rho_i \sigma_{Si}}{\sigma_{Ri}}(E(V_R \mid d_{Ri}) - \mu_{Ri})$$

$E(V_S|d_{Ri})$: Estimated long-term seasonal mean at site, by reference direction class

$E(V_S|d_{Ri})$: long-term seasonal mean at reference station

μ_{Si} : Measured mean velocity at site

μ_{Ri} : Measured mean velocity at reference station

ρ_i : Measured cross-correlation coefficient

σ_{Si} : Measured standard deviation at site

σ_{Si} : Measured standard deviation at reference station

The measured joint probabillity $p(d_{Ri},d_{Sj})$ during the short-term period can be used to estimate the long term directional distribution at the site $p(d_{Sj})$ from the long-term directional distribution at the reference station $p(d_{Ri})$:

$$p(d_{Sj}) = \sum_{i=1}^{12} p(d_{Ri}) p(d_{Ri}, d_{Sj}) / \sum_{i=1}^{12} p(d_{Ri}, d_{Sj})$$

An estimate of the long term seasonal mean at the site can now be given in terms of the direction at the site:

$$E(V_S \mid d_{Sj}) = \sum_{i=1}^{12} E(V_S \mid d_{Ri}) p(d_{Ri}, d_{Sj}) / \sum_{i=1}^{12} p(d_{Ri}, d_{Sj})$$

A preliminary report is given after three winter-months of measurement, and a final report after one year. This method has been used on around 50 sites along the Norwegian coast, and has been the workhorse so far in Norwegian siting activities. Figure 1 shows cross-correlation coefficients as function of distance for some projects.

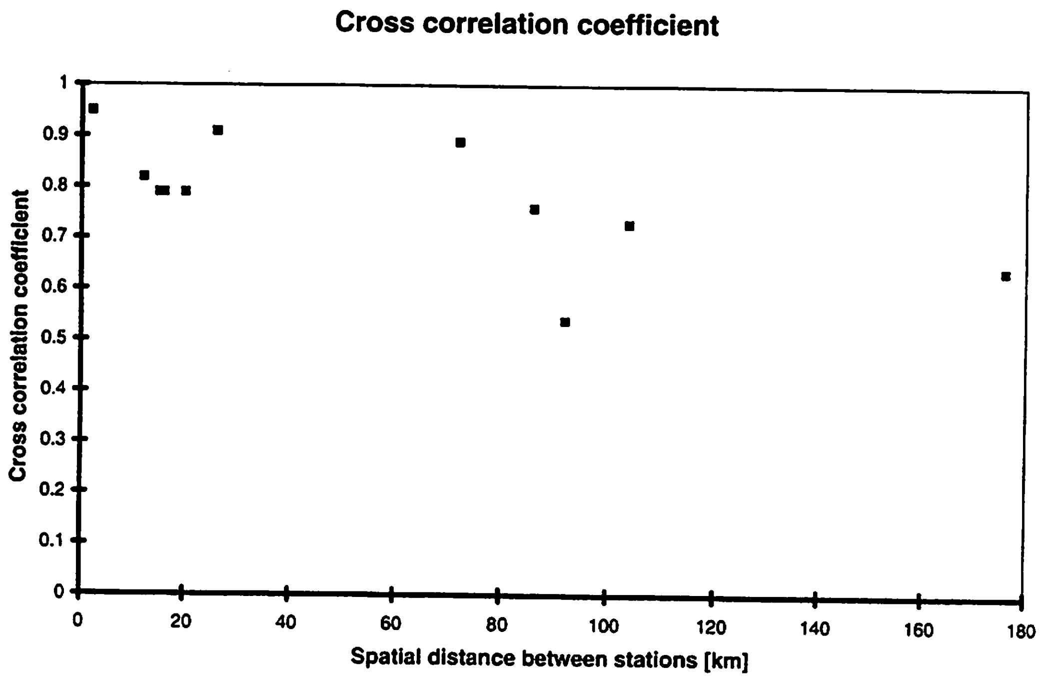


Figure 1: Cross-correlation coefficient as function of distance

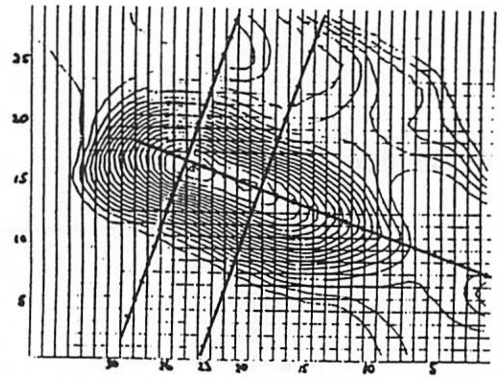
2.2 WASP

WASP (Troen and Lundtang Pedersen 1988) has been used extensively along with the MCP method. It is particularly useful for a relative comparison of sites on islands outside the fjord/valley systems. Inside the fjord/valley systems, channeling of the wind and significant direction changes from reference to site calls for caution when using linearised models. It is not recommended to use WASP with data from well exposed light-houses to evaluate sites inside the coastline.

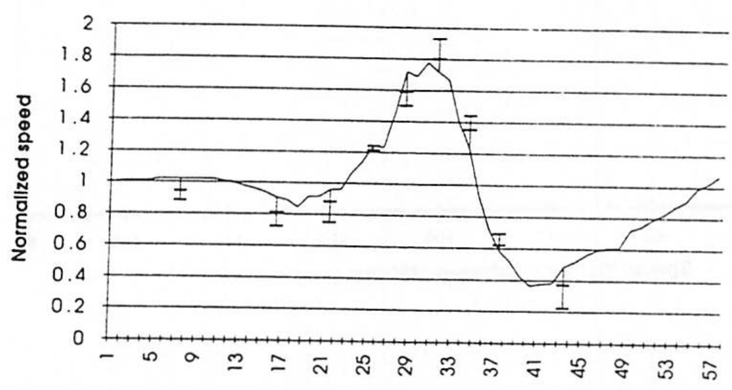
2.3 Three-dimensional Navier-Stokes model.

A non-linear, non-hydrostatic model for complex terrain has been developed (Alm and Nygaard 1995). It is based on the general-purpose Navier-Stokes solver PHOENICS (Spalding 1991). It is intended for the micro-scale, with model domain up to a few km.

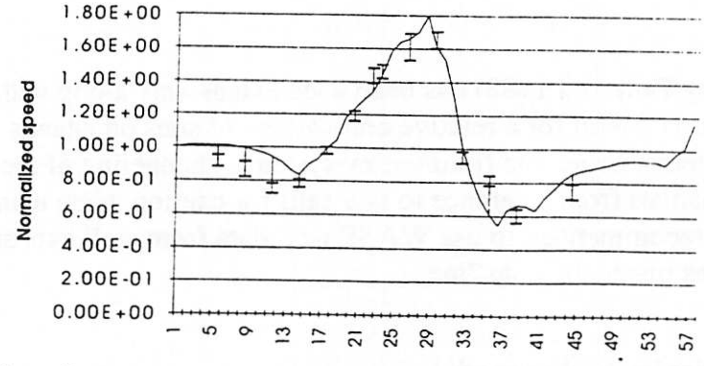
It has been tested for Askervein Hill, where extensive measurements have been done. It agrees relatively well also for the lee-side of the hill, where linearised models overpredict the wind-speed.



Computational grid and contour map of the 3D Askervein Hill model.



Normalised speed at 10 m above ground level (a.g.l.) at the SW–NE measurement line through the hilltop (HT).



Normalised speed at 10 m a.g.l. at the SW–NE measurement line through the central point (CP).

Figure 2: Comparison between model and measurement at Askervein Hill.

2.4 Meso-scale models

With the increasing capacity of computers, it is now within reach to simulate atmospheric motion on length scales ranging from meso- to micro-scale in one integrated simulation. The meso-scale model RAMS (Regional Atmospheric Modeling System) developed at Colorado State University (Pielke et. al. 1992) has been used in a large-eddy simulation of the neutral surface layer (Pielke, Nicholls, Walko, Nygaard and Zeng 1995). The turbulence model was extended with the Stochastic Backscatter Scheme (Mason and Thompson 1992), to account for the interaction between resolved and sub-grid waves. This improved the resolved Reynolds Stress profiles, and demonstrated the applicabillity of RAMS also on small scales (the resolution was 20m).

Institute for Energy Technology, the University of Bergen and the Norwegian Meteorological Office have recently joined forces to apply meso-scale models for wind energy applications and small-scale studies of air quality. The model MM5 developed at Pennsylvania State University is used in a graduate study on the wind energy resource.

3 Wind resource studies.

3.1 The national wind energy potential study 1980.

This study was based on data from the weather stations, and siting studies in the most interesting areas along the coast, assuming use of 3 MW wind turbines. It was concluded that a realistic potential is around 10 TWh, corresponding to approximately 10 % of the electricity consumption.

3.2 Update of the wind energy potential in 1990

The update was an attempt to give estimates of the wind energy potential in year 2000 as function of energy cost (Nygaard and Tallhaug 1990). The chosen technology was a 750 kW 'Danish concept' wind turbine. A limited area was studied in detail. The wind resource was estimated with WASP. Costs for upgrading grid were included. By comparing with the study for 1980, crude estimates for the potential were then extrapolated to the rest of the country. The resulting curves connecting potential and energy costs are shown in figure 3. The lower curve is the energy cost referred to the wind turbine. The higher curve is energy cost referred to the central grid, including grid reinforcement and losses. The main conclusion is that the total potential was similar to earlier studies.

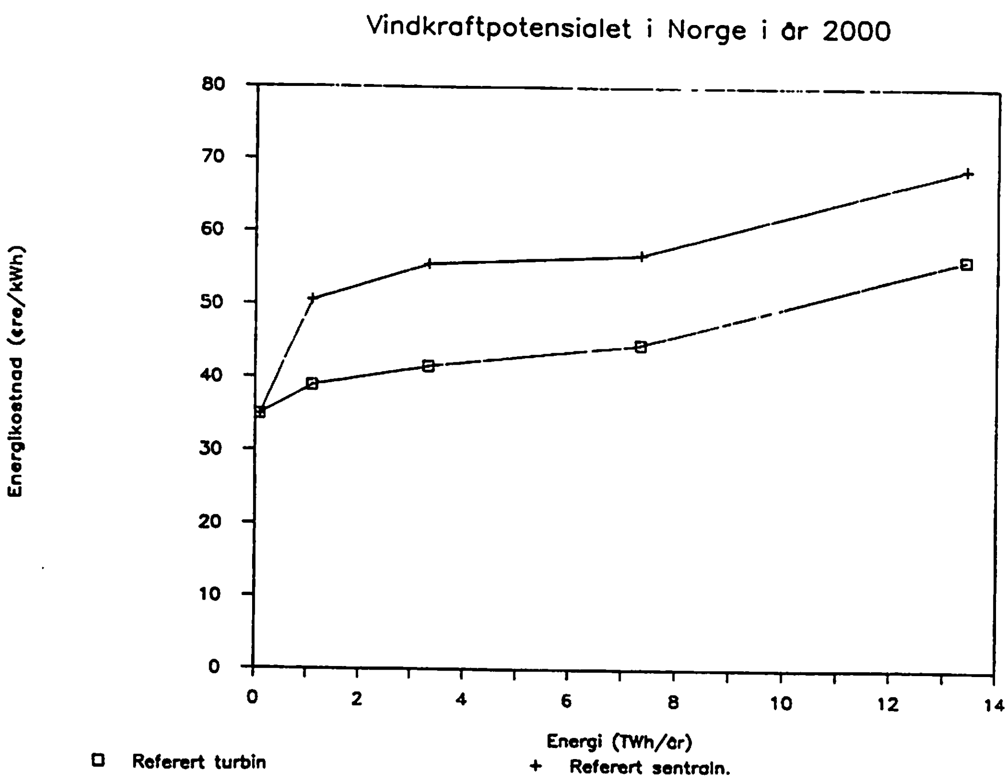


Figure 3: Marginal energy cost as function of potential in Norway

3.3 Windfarm database for Sør-Trøndelag.

The county of Sør-Trøndelag was studied in detail in 1993 to provide a list of windfarm projects sorted by increasing cost of energy. The study involved short-term measurements with 30 m masts at eight locations, MCP and use of the model WASP. Map studies and site visits resulted in relatively detailed plans for single wind-turbines and windfarms at around 70 sites. Grid and infrastructure costs were estimated. A commercial Danish 500 kW wind turbine from 1993 was used as reference. Figure 4 shows marginal energy cost as function of potential. In the upper curve, potentially controversial areas have been excluded.

3.4 Current activities

Most of the current activity on wind resource estimation is funded by windfarm developers. MCP and linearised models are still the rule, but it is expected that non-linear models increasingly will be used in complex terrain as computational expenses decrease. The resulting information is not open. The authorities lack a consistent overview of the wind resource for planning purposes, and The Norwegian Water and Energy Resources Administration has therefore initiated a project on wind resource estimation. One proposed approach to this is currently being evaluated, with a possible continuation in 1999 with generation of wind-maps.

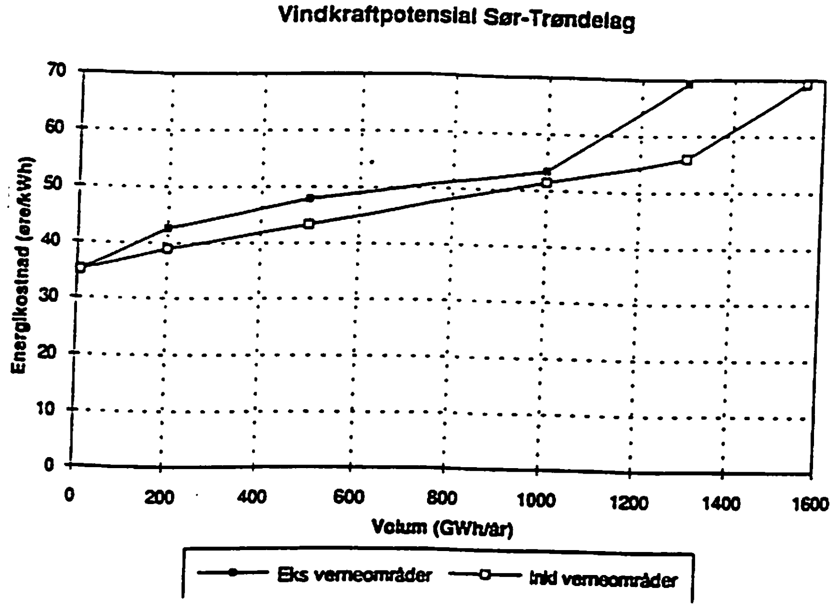


Figure 4: Marginal energy cost as function of potential in Sør-Trøndelag.

4 Conclusion

Norway has a significant wind resource that could cover more than 10 % of the electricity consumption. The interest for wind energy is increasing , and we could see commercial development in the near future. Because of the complicated terrain, MCP is used by most developers. A significant part of the knowledge about the wind energy resource is not open information, since it has been established by windfarm developers. A resource estimation project has however been initiated. The rapid decrease of computational costs is likely to increase the use of advanced numerical models for resource estimation in the near future.

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STATE OF THE ART OF WIND RESOURCE ESTIMATION IN THE NETHERLANDS

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Internet: http://www.ecofys.nl/

1 Introduction

Some 15 to 20 years ago the development of the modern wind turbines as we know them really started. As the objective was to produce electricity economically the need for methods to estimate the electricity production arose. Furthermore, knowledge of extreme wind speeds and gusts for design purposes was also required. So, in the eighties the decision was made to develop the Handbook for estimating wind resources.

Parallel to the development in wind energy the field of boundary-layer meteorology rapidly evolved. The Cabauw mast, a 200 m high mast erected solely for scientific purposes in The Netherlands by KNMI, especially stimulated this. The data from Cabauw provided the necessary input for the development of procedures to calculate wind speed profiles incorporating stability effects. This information was needed because of the required high accuracy in the estimated wind speeds. The simplification to assume a neutral atmosphere could mean the difference between profit and loss on a project.

As soon as projects have been realised, the next step a project developer wants to make is to monitor the performance of a wind farm. This depends on technical aspects like the availability and the actual Pv-curve on the one hand, and on the mean wind speeds on the other hand. The point is to be able to compare the actual performance against the expected performance. Technical aspects can be monitored or measured quite easily to check this, but this is not the case for the wind speeds. Therefore an instrument was developed called the WINDEX. Its purpose is to relate the electricity production of one particular month to the expected long-term average production. In this way the natural variations of the wind climate can be corrected for.

1.1 Dutch Handbook

The Dutch Handbook was specifically developed for The Netherlands. Although in the early stages The Netherlands was also involved in the European Wind Atlas it was decided to take another route. Although in many respects the underlying theoretical models are the same as in WAsP, the Handbook differs at some points.

First of all, the ambition level is in principle higher than that of WAsP, in that the required knowledge of the user is less. The user is led through the procedure in a step-by-step approach. A selection out of four wind speed data sets has to be made (one offshore, one coastal, one inland and one lowland). The only 'advanced' step in a standard calculation is the estimation of the roughness lengths. Additional models for calculating corrections due to obstacles and wake effects are provided. The Handbook works with geographically interpolations for the geostrophic wind field and for the average stability correction. Based on the Handbook detailed maps for the mean wind speed at 30 m of the windy (coastal) regions of The Netherlands have been produced.

However, after having used the Handbook method for a few years, two major flaws became apparent. The first was the fact that in many areas the wind speeds were overestimated considerably. For feasibility studies this is of course unacceptable. The second was an inconsistency in the methodology when used near the coast.

Some work has been carried out to modify the Handbook method in order to remove these flaws. However, there was no elegant physical solution for the second flaw, so a rather crude interpolation method had to be introduced. In order to reduce the overestimation the maximisation of the geostrophic wind speed was proposed.

At this moment no work is being done on revising the Handbook method, as there is no consensus about the solutions to the problems. Currently the Handbook method is still used in practice, but each (experienced) user will fine-tune and adapt the results. This will be done based on experience and 'feeling' in a non-reproducible way.

1.2 Dutch WINDEX's

In fact there are two WINDEX's used in The Netherlands. One (the 'official' WINDEX) was associated to the data-monitoring project as commissioned by NOVEM. In this project electricity productions of most wind turbines were monitored on a monthly basis for many years. The other WINDEX is the one as defined by Wind Service Holland (WSH), which can be found on the Internet.
As explained earlier, the need for the instrument WINDEX arose from the wish to compare the electricity production of a particular month against the estimated long-term average production. It is in fact a fraction, where the denominator represents the long-term average and the numerator the monthly value.
The 'official' WINDEX was mainly based on wind speeds. The denominator consisted of long-term wind speeds (>25 years) as provided by KNMI for four stations. The numerator was calculated on a monthly basis using about 15 meteorological stations. The wind speeds were converted to production figures using several standard Pv-curves and then averaged.
The problem with this WINDEX was that over a period of 10 years the annual average values were always <1. Although this is not impossible, it highly improbable and not consistent with other information. Furthermore, the definition is such that the long-term average value of the WINDEX does not have to be equal to 1, as it should be.
The WINDEX as presented by WSH is based on actual production figures. Several projects with more than 10 years data are taken as long-term reference. The reference is updated every year and should automatically converge to a stable mean value in due course.

2 Current work

Most of the work described in Chapter 1 had to be carried out in the time hardly any actual wind turbine data was available. Although the meteorological information and the boundary-layer models were available (and have in essence not changed since) it is now, after about 10 years, possible or even necessary to re-evaluate the used models and the results in the light of the many wind turbine production data that are presently available. In The Netherlands the need for correct wind speed maps has led to a project financed by NOVEM and several utilities and local governments. Adviesbureau E-Connection, CEA and Ecofys carry out this project. Furthermore, the need for a correct and better-defined WINDEX also became apparent within the context of the project mentioned earlier. This WINDEX is needed to be able to interpret actual monthly electricity production figures in the light of monthly variations compared to the climatological mean. This has led to a project financed by NOVEM carried out by Ecofys, CEA, MeteoConsult and Adviesbureau E-Connection.
The two projects are set up in such a way that (standard) calculations to estimate electricity productions at any given site and the calculation of a monthly WINDEX in order to monitor electricity productions compared to the long term average are based on the same methodology.

2.1 Validated wind speed map

The main objective of the project "Validated wind speed map" is to create wind speed maps with figures that are corroborated with actual production figures. This project focuses only on the windy provinces (where the wind turbines are mostly situated at present).
For the calculations WAsP has been selected. This to be in accordance with common practice abroad. The terrain conditions are processed by creating digitised computer files from topographical maps. Then calculations are made using the standard Pv-curves of the actual wind turbines at the actual hub heights. For a good coverage wind speed data of about 12 meteorological stations are used, in stead of the standard 6 provided in the European Wind Atlas.

The calculated values for each of the wind turbines are then validated by comparison to the actually reported electricity productions. Here corrections have been made with respect to non-availability on a monthly basis.
The end product that will be produced are wind speed maps for heights of 40, 60 and 80 m. The resolution of the isovents will (probably) 0,5 m/s, with an accuracy is 5%. This more or less depends on the quality of the validation points: in some regions many wind turbines are present to provide reference, while in others wind turbines are scarce.

2.2 New WINDEX

The need for a new and more accurate WINDEX arose from the previous project. In order to be able to interpret actual production figures in relation to the estimated long-term average, the WINDEX is the key instrument by definition. If applied to a data set of actual monthly production figures, correction with a perfect WINDEX would lead to a set of exactly the same values: the long-term average production.
In the project the main objective is the creation of a new WINDEX which is scientifically consistent and validated by actual production figures. Therefore a novel approach has been developed, namely to use WAsP on a monthly basis, in exactly the same fashion as for a standard calculation of the electricity production. In spite of the fact that WAsP is not specifically designed for use on a monthly basis the preliminary results are quite encouraging. It is possible to generate production figures with monthly wind speed tables, although the wind speed distribution can of course be very irregular. Furthermore, comparison of the means of 12 monthly calculations to annual calculations for over 100 projects shows very small deviations (usually 0-2%).

2.3 Planning

The work described here is still in progress. It is expected that the results will be available early next year. As a follow-up several new activities are considered:

- ◊ WINDEX on location;
- ◊ definition and dissemination of new generalised WINDEX;
- ◊ wind speed maps for less windy (inland) areas in The Netherlands

3 POWER – Predicting Offshore Wind Energy Resources

POWER is a JOULE-project, which runs from August 1998 until July 2001. The co-ordinators are the Rutherford Appleton Laboratory (UK). Contractors are Ecofys (NL) and Risø (DK); associated contractors are the University of East Anglia-Climatic Research Unit (UK) and KEMA (NL).
The main objectives of POWER are the production of wind speed maps for all European seas in GIS-format. Therefore the Coastal Discontinuity Model (CDM) will be developed and validated. Furthermore, the offshore wind resources will be estimated. The main focus is on the North Sea, where it is intended in the last stage of the project to make use of actual cases of planned offshore wind farms.
A brief outline of the methodology is as follows. Using large but coarse data sets of pressure data offshore geostrophic wind fields are produced. From these WAsP is used to calculate the near-surface wind field. The results are validated using the available near-surface wind speed data e.g. from oil and gas platforms and Vindeby. There is special attention for the coastal zone by the development of the CDM. Furthermore, the results of 'standard' WAsP calculations and CDM calculations will be integrated. Additionally, measurements with a mini-SODAR system will be made on the coast at two locations. The results will also be used to validate the CDM. Furthermore, study will be made of wind and wave loading using available near-surface data.
The characteristics of mini-SODAR (SOund Detecting And Ranging) systems are as follows. It is possible to make instantaneous measurements of the wind profile from 10 up to 250 m with a vertical resolution of 5 m. Both horizontal and vertical wind speeds plus wind direction are measured. The user can choose the averaging time, down to 10 s. Therefore measurement of turbulence intensities is possible. Also stability conditions (in a qualitative fashion) can be monitored.
The advantages of a mini-SODAR are that it is easy to install due to its low weight (portable by 3-4 people) and small dimensions (approx. 1 × 1 × 2½ m^3). Furthermore, there is no visual intrusion (but

acoustic intrusion instead); you can hear 'pings' of 4.500-9.000 Hz every second). However, calibration is not really possible like with an ordinary cup anemometer, although the accuracy has been tested against masts on several occasions and the results appeared to be satisfactory. It may prove that this type of system (costs typically $100.000) will replace the use of high masts, especially for relatively short periods.

4 Conclusion and Discussion

In conclusion, it can be stated that in The Netherlands the situation with respect to wind resource estimation is like this. In principle, wind speed data are abundantly available due to the high density of meteorological stations. However, many stations have recently become operational and can therefore not offer long-term data. Furthermore, the topography of a country like The Netherlands is rather simple, so no more than a model like WAsP is necessary. However, the economic role of wind energy in the competitive electricity market has reached a point where the margins are small. Therefore, a high degree of accuracy is required in the financial figures. This pushes the reliability and quality of predicting the electricity productions to the limit. Also, the need for monitoring the actual productions after realising the projects becomes more important. Whereas in the past environmental concerns and/or good publicity prevailed as reasons for installing wind turbines, nowadays economic considerations have taken over.

Typically the work described in the projects currently carried out takes into account the many data gathered from actual wind turbine projects. In this way it is possible to validate the results generated by WAsP. Although there is no real reason to doubt the results of WAsP, it has never been evaluated in the way undertaken here. The novelty of using of WAsP on a monthly basis as tested in the WINDEX project is something extra that might be used elsewhere as well.

A difficulty that will always remain is the fact that investors want an estimate of the mean electricity production over the economic lifetime (typically 10 years). This means there has to be reliable wind speed information over at least this period (barring climatological trends!). In The Netherlands it is not always possible to have this information. The Dutch meteorological institute KNMI does not usually have all the historical information together with the gathered data to be able to provide the required accuracy that is demanded by the people involved in wind energy.

Offshore wind farms have become more and more realistic in several European countries and also in The Netherlands, leading to the 100 MW demonstration near-shore wind farm within the next few years. Therefore the attention for the offshore wind climate has also increased. This is one of the reasons NOVEM also contributes to the JOULE-project POWER explained earlier. A database for the North Sea is available as described in earlier work by Coelingh et al. The data are collected by KNMI and are mostly from oil and gas platforms. Furthermore, in the coastal waters in the southwesterly province Zeeland a network of measuring posts has been installed (ZEGE). These data have also been studied for feasibility studies (e.g. for the 100 MW near shore wind farm). Although the data are not collected for the purpose of wind energy calculations, they may well be used as such.

Another region of interest is the inland region with lower wind speeds. As the wind turbine technology progresses with higher masts and larger rotor surfaces it has become more and more feasible to erect wind turbines inland. Because there are hardly any wind turbines at present to use as a reference, and because wind measurement are usually at 10 m high, NOVEM has commissioned a project to measure wind speeds at several locations on masts with heights of at least 60 m.

The earlier mentioned Cabauw mast of 200 m (with measuring equipment at 7 levels, 30 m apart) is also still running. Some data have been made available on CD-ROM, including wind speeds and direction and turbulence intensities. On the same CD-ROM data are presented from earlier measurements at high masts (>60 m) carried out by the Dutch central electricity generating board (Sep).

ACKNOWLEDGEMENT

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CIEMAT

31st IEA Experts Meeting
STATE OF THE ART ON WIND RESOURCE ESTIMATION

CIEMAT-DER

Ignacio Martí Pérez
Jorge Navarro Montesinos
RE 9-98

1. INTRODUCTION

CIEMAT-DER has a wide experience on Wind Resources Studies in Spain, with more than 10 years of experience in this field.

Two different sort of studies have been carried out:

- Regional studies.
- Micrositing studies.

Due to the situation related to wind energy in Spain, local governments are becoming interested in wind resources. For this reason, CIEMAT is involved in wind resources projects at regional scale.

Micrositing studies have been carried out for different companies: utilities, private and public companies. The objective is to find sites with good conditions to install wind farms, and to determine the energy that they are going to produce.

A different methodology has been developed for each scale. Taking into account that Spain has practically no flat terrain, micrositing studies imply a specific methodology for each case.

2. METHODOLOGY

2.1 Regional Scale

Regional studies require an appropriate database in order to consider all the wind climatologies present in the area of study. The National Meteorological Service has a network of meteorological stations with wind measurements. However, the situation of these stations is not always good from the point of view of resources estimation, and the quality of the data has to be verified because in certain cases there are changes in the measurement conditions. In practise, these databases are not suitable to use as input for the models, but they can be applied as a reference, especially as long-term references. Therefore, *it is necessary to make a measurement campaign* in order to create a valid database, useful to run wind field models.

The number of meteorological stations to be installed vary depending on the size and complexity of the area. This step is crucial because the final results are highly dependent on it. *All the different wind climatologies have to be present in the database.* There are great wind variations and strong local effects in complex terrain, therefore, the accuracy and resolution of the wind maps depend on the measurement campaign (number of meteorological masts and their location).

Once your database is ready for use, models play their role. In complex terrain, the way in which you use the models is different from flat terrain cases. Therefore, the methodology is again crucial to obtain realistic results.

Basically, two models are used: WASP and MATHEW. Due to their characteristics, WASP is more suitable for wind resource estimation studies. Mass conservation models (like MATHEW) can produce good results under special conditions (like islands), but they deal with instantaneous situations and it is not capable of dealing with average data. Therefore, it is difficult to obtain results which are representative of the general climatology of the region.

In order to know how the model works in the area, it is recommended to *validate the model* with the different meteorological stations. Using the data of one station you can estimate the value of the wind field in the site of another station, and then you can compare the estimations with the measurements. Thanks to this validation, an estimation of the behaviour of the model is obtained. Of course, this is not an exhaustive validation but it helps to decide which area can be modelled with each station.

In complex terrain vertical profiles are not well represented by logarithmic law (which is included in WASP). For this reason, and in order to avoid uncertainties and errors, we *take measurements at hub height* in the area of study and we measure the *vertical profile* as well. With measurements at hub height the roughness has a side effect on the results.

The period of time needed to complete a database in order to detect seasonal variations is usually *one year*. Moreover, it should be compared with long term references of more than 10 years of data coming from the National Meteorological Services.

Finally, the results depend on the input values that you have used (mainly wind and topography data). The final map is built depending on the resolution of the digitised maps and on the density of measurements in the area. Therefore, it has no sense to estimate a wind field with decimal resolution in regional scale studies.

2.2 Local Scale

Another approach to the problem of wind resources estimation is micrositing studies. Here the objective is to determine the best layout of the wind turbines in the site, and to estimate the energy production of the wind farm. The spatial scale of the problem is usually of a few kilometres.

Again, it is necessary to *make a measurement campaign* in order to build a wind database suitable to use as input data for the model. In this case, the density of measurements is higher than the density in a regional scale, and it *depends on* the *size of the wind farm* and on the *complexity of the terrain.*

Meteorological stations must be situated on representative places, well exposed to all wind directions, and covering all the different sub-areas (different heights and local effects).

The model must be validated for the area of study using the different stations in the way described above. The validation allows to determine which sub-areas can be modelled with each station. The best results are obtained when the wind estimations are at the same height level (above sea level) of the input data.

The vertical profile has to be measured in order to avoid the uncertainties related to logarithmic law.

One year of data is required in order to include seasonal variations, and long-term reference stations have to be used in order to avoid inter-annual variations of the wind.

Results are again conditioned by the input data. Conservative hypothesis must be considered when energy production estimations have to be made, so that minimum productions can be ensured.

3. DATABASES

3.1 Regional Scale

- Long-term wind data (10 years or more) having a good statistical correlation with the meteorological stations located in the area of study.
- Measurement campaign:
  Meteorological stations covering all the different wind regimes.
  Measurements at hub height.
  One year of data.
- Digitised maps of the region:
  Scale 1:200.000 to cover the entire region (for areas of 200x200 Km typically).
  Scale 1:50.000 to cover mountainous areas (complex terrain).
  Scale 1:25.000 in the surroundings of the stations (within a radius of 2 Km).

3.2 Local Scale

- Long term wind data (10 years or more) having a good statistical correlation with the meteorological stations located in the area of study.

- Measurement campaign:
  Meteorological stations covering all the different wind regimes.
  Measurements at hub height.
  One year of data.
- Digitised maps of the region:
  Scale 1:50.000 of all the area (in complex terrain, digitised maps must cover the surroundings of the area that could affect the wind field).
  Scale 1:5.000 in the surroundings of the meteorological stations.

4. STUDIED REGIONS

CIEMAT has made the following Wind Resources Maps:

- MURCIA.
- EBRO VALLEY.

In addition, these other regions are still in study:

- CASTILLA Y LEÓN.
- MADRID.

Micrositing studies have been carried out in the following regions:

- GALICIA.
- CASTILLA Y LEÓN.
- CANARY ISLANDS.
- EBRO VALLEY.
- GIBRALTAR STRAIGHT.
- MOROCCO.

5. RESEARCH ACTIVITIES

Wind Resources Division is working in the following fields:

- ***Atmospheric Turbulence***. CIEMAT is participating in JOULE projects whose objectives are the identification of the relevant parameters that can describe the turbulence of a site, and the effects on wind turbines. A 100-meter tower has been instrumented with cup and sonic anemometers in order to study the atmospheric boundary layer.

- ***Short Term Wind Prediction***. There is an important demand of predictions of wind farms energy production by wind farm developers and utilities in Spain,. We are developing a methodology based on HIRLAM models and Multivariate Analysis.

- ***Satellite Image Processing***. METEOSAT images are used to calculate the Solar Radiation Map of Spain, and we are going to cooperate with Spanish universities in order to use these images to estimate low resolution wind fields.

- ***MDD (Meteorological Distribution Data).*** It is a mission of the METEOSAT system provided by the Member States of EUMETSAT. CIEMAT is planning to obtain this meteorological data, which cover an extensive part of Europe. The objective is to consider the influence of the synoptic scale on other scales (mesoscale and local scale).

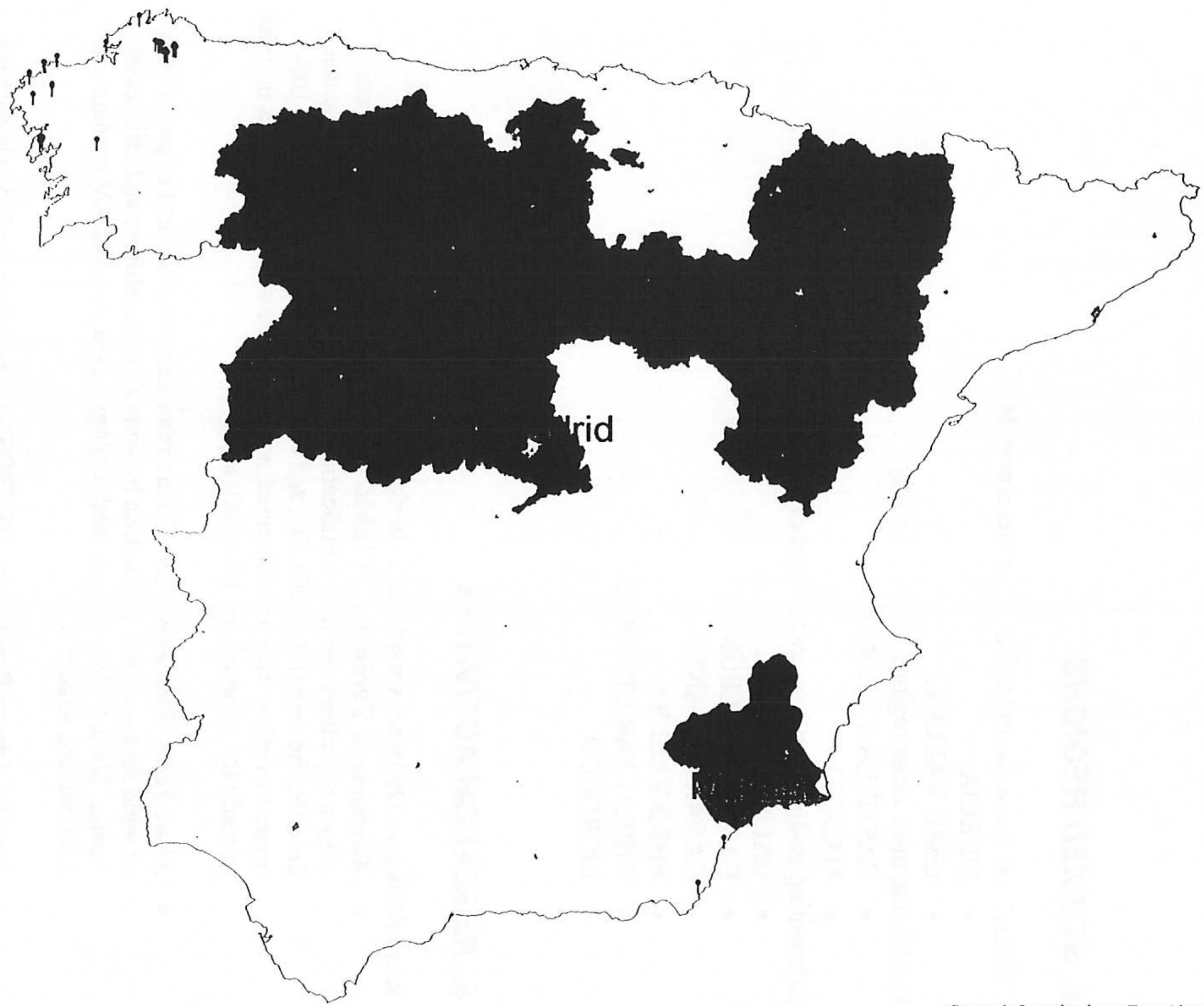
- ***Geographical Information Systems (GIS)***. GIS systems allow to study wind field information jointly with other geographical information (land use, environmental restrictions, ...). Geographical studies are carried out in order to detect areas that are not suitable to install wind farms.

Wind Regional Studies in Spain

Wind Measurement Stations

A. de S. Juan	La Carba43
A. Faladoira	La carba44
A. Valdelavía	La Guía
Arou	La Higuera
Bernardos	La Muela
Bustelo33	La Pedrera
Bustelo35	La Unión
Bustelo36	Lorca
Bustelo37	Malpica
C.Vaguada	Masteiro
Cabo Cope	Monte Ventoso
Caravaca	Moratalla
Carballeira	Oncala
Cedeira	P. de Francia
Cieza	P. de Sabuceda
Corme	Paúl
Corme2	Rueda de Jalón
Cresta Norte	Santa Mari¤a
Cresta Sur	Sierra Ascoy10
Dumbria	Sierra Ascoy19
Escoiras	Tirajana
F. Hispania	Tirajana2
F. Hispania2	Xistral1
Garabitos	Xistral2
Guardo	Xistral3
La Carba	Xistral4
La Carba41	Zas
La Carba42	Zas2

Main towns



Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Miner

Meso Scale Modeling with a Reynolds Averaged Navier–Stokes Solver

Assessment of wind resources along the Norwegian coast

by

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1 Introduction

Although the wind climate in Norway seems favourable, the exploitation of wind energy has so far been very modest. However, recently the general interest for wind energy has increased. Wind measurements are currently carried out at about 30-40 locations. The Norwegian Water Resources and Energy Administration (NVE) receives an increasing number of applications for erecting wind turbines. On this background NVE has decided to launch a project on meso scale wind modeling.

The meso scale modeling will cover the Norwegian coast line from the southern tip at Lindesnes up to the Russian border in the north. About 100-150 models with an extension of approximately $30 \times 30 \times 3$ km will cover the coast. A windrose will be associated to each model, with annual and seasonal mean wind speeds. The windroses will be established based on long term statistical weather data from 30 meteorological stations situated along the coast. Micro models will be established for some of the meteorological stations in order to correct for terrain induced speed–up effects.

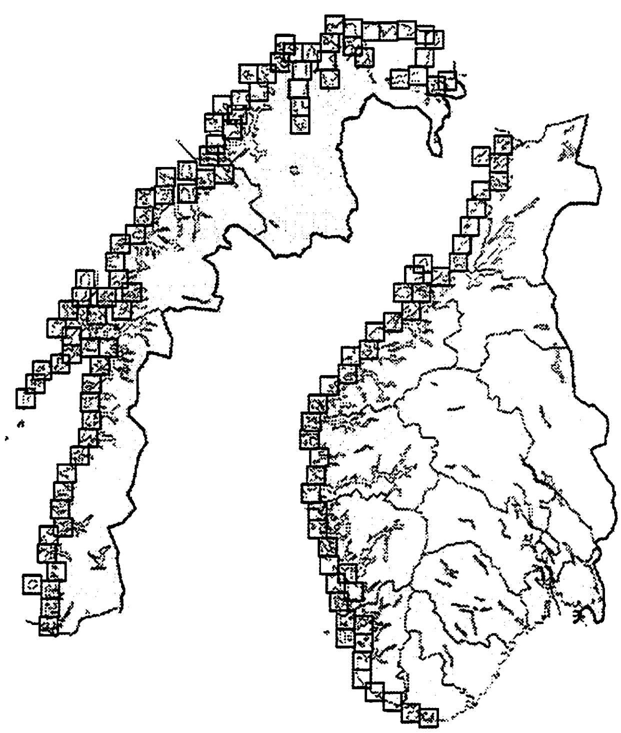


Figure 1: Meso scale models along the Norwegian coast, preliminary outline

The meso scale modeling will be undertaken in 1999. At present, verifications in several terrains with various geometrical complexity have been carried out. Description of the simulation tool and results from the verifications will be presented herein.

2 WIND–SIM a Reynolds averaged Navier–Stokes solver

WIND-SIM is a simulator for prediction of local wind fields and dispersion of air pollution. It is based on the general purpose CFD code PHOENICS. PHOENICS is an open code allowing users to add their own subroutines, a useful feature when simulating the atmospheric boundary layer (ABL), [Näslund et al. (1992)], [Grundberg (1994)], [Alm and Nygaard (1995)] and [Baklanov et al. (1997)]

2.1 Turbulence modelling

In connection with wind energy the wind field on meso and micro scale can be described by the steady state incompressible Reynolds averaged Navier–Stokes equations, given in standard notation.

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - (\overline{u_i u_j})\right) \tag{2}$$

In order to close the set, the turbulent Reynolds stresses are related to the mean velocity variables through the turbulent viscosity ν_T.

$$\overline{u_i u_j} = -\nu_T\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) + \frac{2}{3}\delta_{ij}k \tag{3}$$

Further the $k-\varepsilon$ model is used to relate the turbulent viscosity to k and ε, the turbulent kinetic energy and its dissipation rate.

$$\nu_T = c_\mu \frac{k^2}{\varepsilon} \tag{4}$$

$$\frac{\partial}{\partial x_i}(U_i k) = \frac{\partial}{\partial x_i}\left(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial x_i}\right) + P_k - \varepsilon \tag{5}$$

$$\frac{\partial}{\partial x_i}(U_i \varepsilon) = \frac{\partial}{\partial x_i}\left(\frac{\nu_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) + c_{\varepsilon 1}\frac{\varepsilon}{k}P_k - c_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{6}$$

Where the turbulent production term P_k is:

$$P_k = \nu_T\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} \tag{7}$$

The model constants in the so called standard $k-\varepsilon$ model have been found to take the values given in Table 1.

c_μ	σ_k	σ_ε	$c_{\varepsilon 1}$	$c_{\varepsilon 2}$
0.09	1.0	1.3	1.44	1.92

Table 1: Values of the model constants in the standard $k-\varepsilon$ model

The model constants in the standard $k-\varepsilon$ model have been tuned to fit some basic flow problems; shear layer in local equilibrium; decaying grid turbulence and a boundary layer where the logarithmic velocity profile prevails. The model is not very general, typically the model constants have been adjusted in order to mimic other flow regimes.

Considering a neutral ABL, the standard $k - \varepsilon$ model is unable to reproduce the right level of turbulence in the weak shear layer away from the ground. In this region the turbulent viscosity is overpredicted, [Detering and Etling (1985)].

The standard model constants have been modified in an attempt to improve the situation. The value of $c_{\varepsilon 2}$, determined from experiments with decaying grid turbulence, remains unchanged. The diffusion constant σ_k, close to unity following Reynolds analogy, also remains unchanged. Whereas the constant c_μ, determined from a shear layer in local equilibrium where c_μ is found to be equal to $(\overline{u_1 u_2}/k)^2$, has been reduced in accordance with measurements in the ABL [Panofsky et al. (1977)]. Finally, the constants $c_{\varepsilon 1}$ and σ_ε can been adjusted, guided by the relation from a boundary layer where the logarithmic law is valid:

$$c_{\varepsilon 1} = c_{\varepsilon 2} - \frac{\kappa^2}{\sqrt{c_\mu}\sigma_\varepsilon} \tag{8}$$

In this work the modified model constants given in table 2 have been tested.

c_μ	σ_k	σ_ε	$c_{\varepsilon 1}$	$c_{\varepsilon 2}$
0.0324	1.0	1.85	1.44	1.92

Table 2: Values of the model constants in the modified $k - \varepsilon$ model

2.2 Boundary conditions

Wall functions are applied along the ground. At the first node at distance d above the ground particular relations are imposed. The velocity profile is logarithmic with the inclusion of roughness. The turbulence is assumed to be in local equilibrium yielding:

$$k = \frac{U_\tau^2}{\sqrt{c_\mu}} \tag{9}$$

$$\varepsilon = \frac{U_\tau^3}{\kappa d} \tag{10}$$

Here the friction velocity is defined as $U_\tau = \sqrt{\tau_w/\rho}$, the von Karman constant κ is set equal to 0.4. Profiles for velocity, k and ε are imposed at the inlet. The profiles are developed in a numerical sub-model. Due to the anomaly of the standard $k - \varepsilon$ model in weak shear layers, as discussed above, analytical profiles for k and ε have also been tested. The analytical profiles are taken from [Huser et al. (1997)].

$$k = \frac{U_\tau^2}{\sqrt{c_\mu}}\left(1 - \frac{z}{h}\right)^2 \tag{11}$$

$$\varepsilon = \frac{U_\tau^3}{\kappa}\left(\frac{1}{z} + \frac{4}{L}\right) \tag{12}$$

Here h is the boundary layer depth, $h = 0.4\sqrt{U_\tau L/f}$, where f is the Coriolis parameter and L is the Obukov length taken as 10 000 meter for a neutral atmosphere.

3 Verification

This verification starts with a simple flat terrain and moves on towards more complex geometries. In general, numerical simulations can be contaminated with grid dependencies. Grid independent solutions is achieved by refinement of the grid, which in practical situations is very demanding with respect to computational costs. Therefore, it is important to gain insight into the errors made when modelling with grids too coarse to reflect the underlying topography.

3.1 Flat uniform terrain

Simulations over flat terrain have been carried out with varying roughness heights z_0. The boundary layer height has been set to 500 m, and the velocity profile is assumed to follow the logarithmic law.

$$\frac{U}{U_\tau} = \frac{1}{\kappa} ln \frac{z}{z_0} \tag{13}$$

The grid distributions are given in figure 2. The grid is refined towards the ground, the grading factor defines the ratio between the cell size at the lower and upper boundary. Resulting speeds at 50 above the ground are given in the same figure, as expected grid refinement improves the results. The standard $k-\varepsilon$ model was used, the modified model gave slightly larger discrepancies versus the logarithmic law.

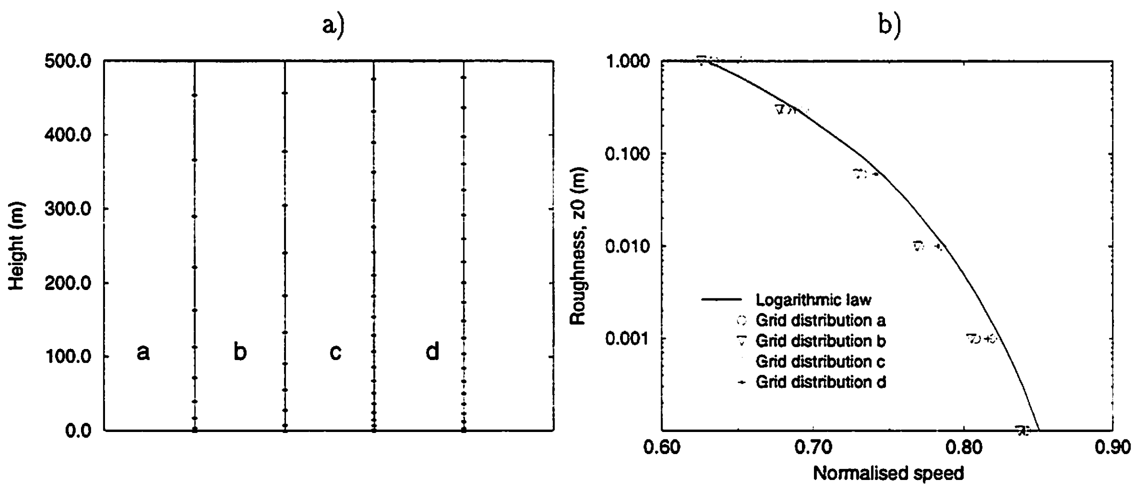


Figure 2: Flat uniform terrain
a) Grid distributions
b) Normalised speed at 50 meter, against roughness height

3.2 2D Hill

Speed-ups for simplified geometries are summarised in [Lemelin et al. (1988)]. The 2D hill given in figure 3 is reported to have a maximum speed-up of 0.65. The 2D hill has a characteristic slope of 0.28 (hill height/hill length) and a normalised roughness of 2.8 10^3

(hill length/roughness height). Speed–ups found in this work is depicted in figure 4. The grid dependency is not particularly significant, more remarkable is the variation due to the chosen turbulence model. The standard $k - \varepsilon$ model gives speed–ups in the order of 0.65, while with the modified turbulence model the speed–up is only 0.52. In figure 4 the streamwise velocity component along the ground is also depicted. Separation is observed with the standard $k - \varepsilon$ model, but not with the modified version.

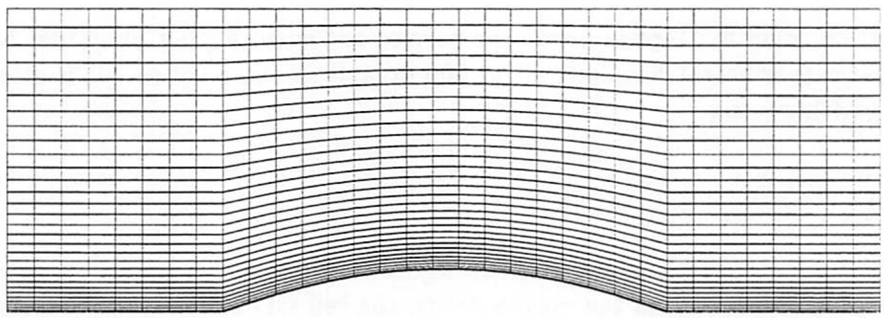


Figure 3: Grid distribution for 2D hill

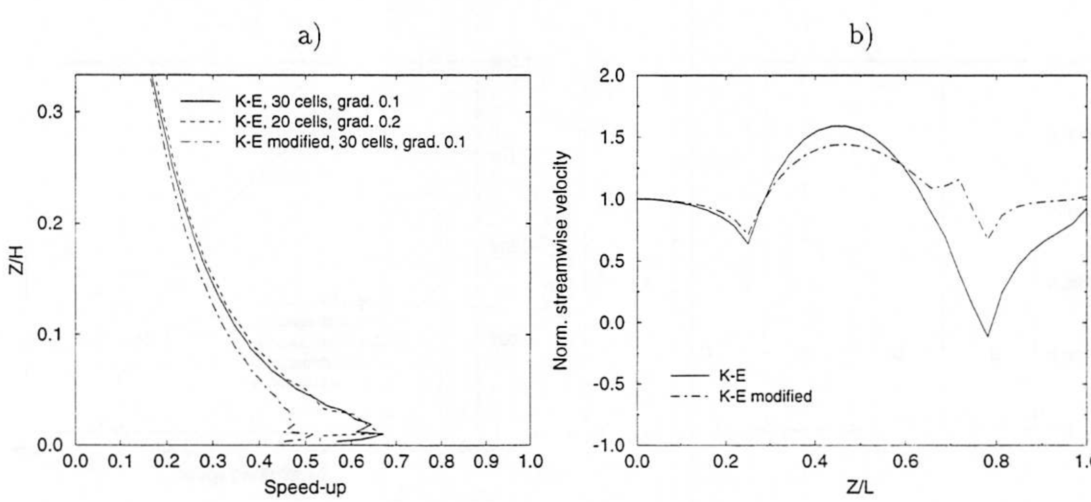


Figure 4: 2D hill
a) Speed-up at hill top
b) Normalised speed in streamwise direction, just above the ground

3.3 Askervein Hill

Field experiments were carried out at Askervein Hill in 1982 – 1983, as summarised in [Taylor and Teunissen (1987)]. The hill resembles an ellipsoid with major and minor axis of approximately 2 km and 1 km respectively. Maximum hill height is 116 m. An area with approximate extensions $3000 \times 3000 \times 1100$ meter is discretised with $40 \times 50 \times 30$ cells. Grid refinement is used in streamwise direction (flow direction from left to right) giving the finest grid near the hill top in the order of 40 meter, and in vertical direction giving the first cell height at approximately 3 meter. The topography is given in figure 5, which also presents the two lines A and AA where field experiments are available. Normalised speed–ups are given in figure 6. As seen for the simple 2D hill, the modified $k-\varepsilon$ model underpredicts the speed–up. As for the 2D hill the modified $k-\varepsilon$ model does not separate on the lee side. Details of the 3D separation zone is given in figure 7, giving the velocity field at a height of 10, which is just above the region with reversed flow.

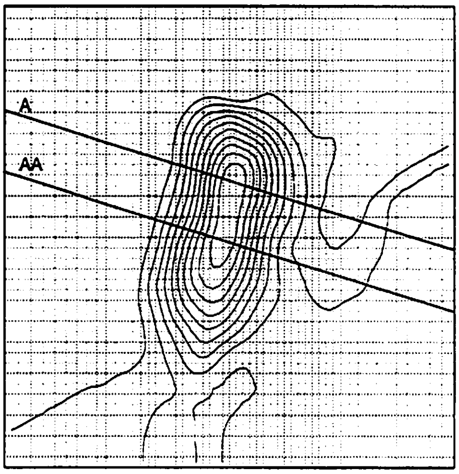


Figure 5: Grid distribution and topography for Askervein Hill, contour interval is 10 meter

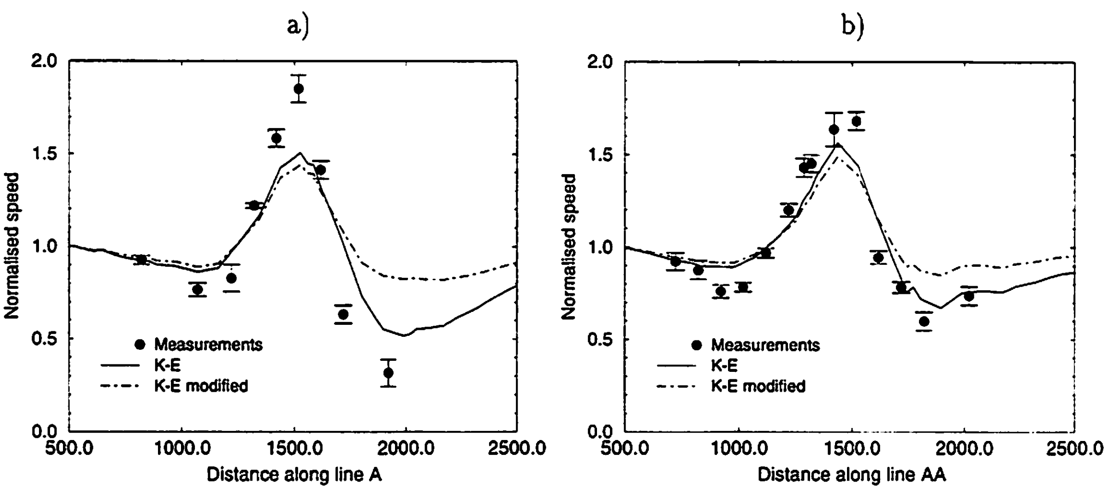


Figure 6: Normalised speed over Askervein Hill
a) Along line A, 10 meters above ground
b) Along line AA, 10 meters above ground

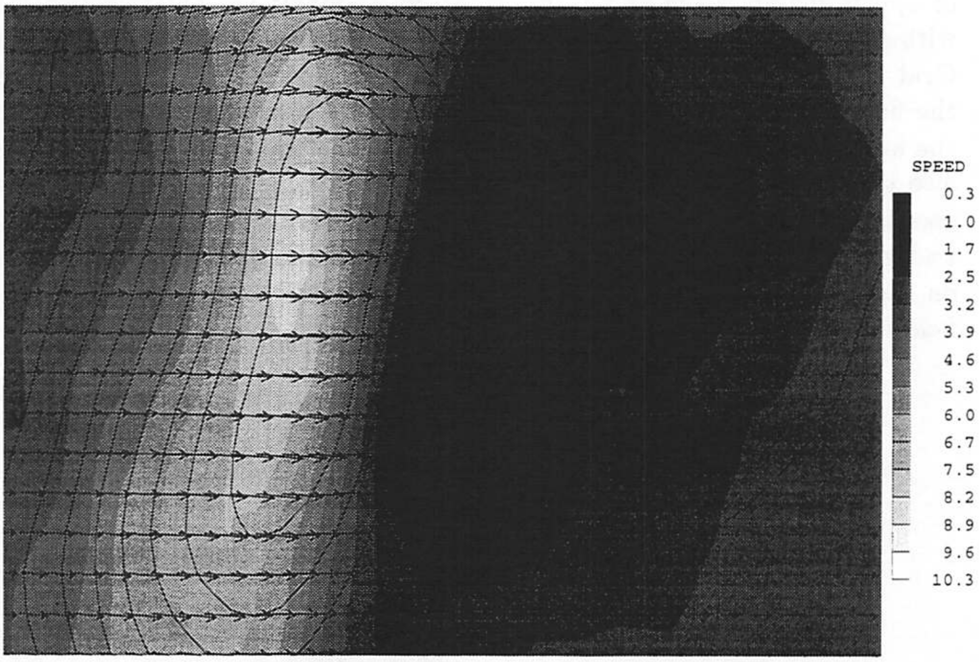


Figure 7: The velocity field with speed contours and velocity vectors at the lee side of Askervein Hill, 10 meters above the ground with standard $k - \varepsilon$ model

3.4 Torsnesaksla

Torsnesaksla is situated south of Tromsø in the northern part of Norway. The extension of the modelled area is 22 × 18 km, including the measuring masts at Hekkingen and Torsnesaksla, see figure 8.

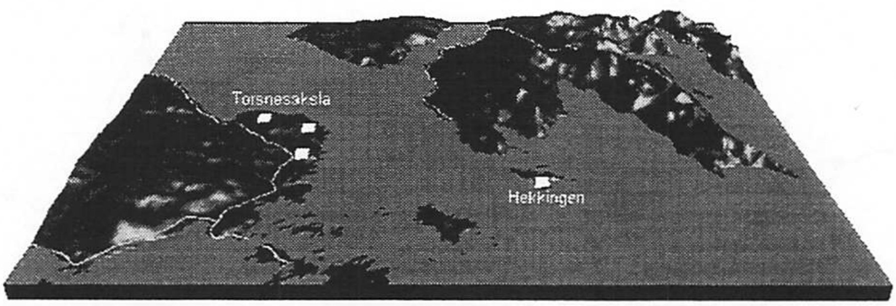


Figure 8: Torsnesaksla - meso scale model, view from north

3.4.1 Measurements

The meteorological station at Hekkingen lighthouse is used as a reference station with measurements at 10 meters height. At Torsnesaksla measurements have been undertaken since 01.05.98. The anemometers are situated at 20, 35 and 50 meters height. Two separate time intervals of approximately 4 and 3 months have been analysed and compared against the reference station at Hekkingen. The Distance between Hekkingen and Torsnesaksla is about 8 km.

Normalised mean speeds with Hekkingen as reference station is given in table 3 for 12 sectors, (1=N, 4=E, 7=S, 10=W). Note that measurements at different heights are used in the tables. The cross correlations are low for several of the sectors. Table 4 shows the spreading in directional distribution.

Results from the 3 months interval were taken during the autumn when the average wind speeds are higher than in the 4 months interval. These results also give the highest cross correlations, and is probably the best suited for comparison with meso scale simulations. In general the low cross correlations indicate that micro scale effects are important at the measuring sites.

Sector	4 months interval		3 months interval	
	Normalised speed	Cross correlation	Normalised speed	Cross correlation
1	1.53	0.83	1.15	0.59
2	0.85	0.57	0.99	0.46
3	0.89	0.46	1.00	0.66
4	1.18	0.39	0.96	0.92
5	1.24	0.58	1.01	0.80
6	1.15	0.65	1.12	0.83
7	1.77	0.41	1.32	0.73
8	2.06	0.52	1.07	0.64
9	0.97	0.59	0.59	0.40
10	0.68	0.45	0.79	0.44
11	1.01	0.56	0.78	0.63
12	1.60	0.81	0.98	0.77

Table 3: Normalised speed, $\text{Torsnesaksla}_{50}/\text{Hekkingen}_{10}$, and cross correlations versus directions

3.4.2 Meso scale simulations

The meso scale model covers the area of 22×18 km given in figure 8. The model extension in vertical direction is 3000 meters above the heighest mountain.

The topography and roughness have been extracted from a digital terrain model (DTM) covering the total area of Norway. The resolution of the DTM is 100×100 m. However, due to limited computer resources, a rather coarse grid has been used in the simulations with cells of 400×400 m in the horizontal direction. With this grid resolution it will not be possible to capture micro scale effects.

In the vertical direction 20 cells have been used with a refinement towards the ground, situating the first grid point at approximately 25 meters height. Therefore, an attempt to compare the simulations with measurements at 10 meters height must be based on extrapolation. In the results presented in figure 9, the measurements from the two time intervals presented in the above section are compared against results from the simulations at 50 meters height. The simulation results have also been adjusted with a factor equal to 1.2, which is the ratio between the speed at 50 meter and 10 meter using a logarithmic

Torsnesaksla → Hekkingen		1	2	3	4	5	6	7	8	9	10	11	12
	1	58	3	0	0	8	4	4	4	1	1	10	53
	2	124	14	3	5	5	9	5	7	1	9	8	51
	3	35	8	15	3	16	16	6	0	1	3	3	20
	4	12	6	13	7	13	21	2	2	0	1	3	10
	5	7	4	14	8	54	51	20	4	2	2	4	14
4 months	6	6	0	5	29	634	274	93	2	0	3	7	3
	7	4	4	1	14	34	17	31	5	0	1	2	3
	8	4	0	1	1	13	11	27	10	4	1	0	1
	9	7	2	0	4	18	17	38	15	11	10	3	5
	10	26	5	2	1	16	22	31	18	26	61	35	18
	11	105	3	3	4	23	23	15	11	2	18	53	97
	12	85	2	3	2	9	13	15	6	1	6	30	115
	1	115	1	1	1	5	9	9	2	3	1	9	110
	2	41	10	9	2	5	7	6	0	2	1	1	15
	3	1	0	17	2	0	4	2	0	0	1	0	1
	4	2	1	5	4	2	2	0	0	0	0	0	0
	5	3	1	11	2	5	0	2	0	0	0	0	0
3 months	6	6	4	8	15	685	143	15	1	2	1	1	5
	7	1	1	4	20	253	73	38	2	1	0	1	6
	8	6	3	1	1	3	19	26	14	9	4	4	5
	9	3	1	0	0	2	5	12	2	11	3	2	1
	10	2	0	0	0	1	3	4	4	2	3	0	6
	11	6	0	0	1	1	2	2	1	0	0	9	13
	12	29	1	0	1	6	10	4	1	4	0	53	77

Table 4: Directional distribution of measurements samples, 4 and 3 months measuring intervals

profile with roughness height set to 0.01. The logarithmic profile is only valid over flat terrain, which clearly is violated at the measuring sites. Most likely the adjustment factor will be less than 1.0 for sectors with speed–ups effects. This serves as an illustration of the difficulties encountered when comparing results affected by micro scale effects with a meso scale model. Although a comparison should be treated with care, it is still possible to detect similar trends in the simulations and the measurements. Southern wind, which is the dominating wind direction, shows the highest speed–up in agreement with the measurements.

The actual measuring site at Torsnesaksla is situated in the corner of a 400×400 m cell, as the averaged wind speed is calculated in the cell center, the adjacent cells could equally well be compared against the measurements. As a measure of this sensitivity, results from adjacent cells have also been presented in figure 9. Finally, a vector plot of the dominating wind direction is given, in figure 10.

Both the standard and modified $k - \varepsilon$ model have been tested. The discrepancies in the calculated normalised speeds are marginal, the displayed results are those with the standard $k - \varepsilon$ model. Profiles for k and ε developed in sub–models and the analytical profiles described in section 2.2 have also been tested. Again there was no noticeable effect on the normalised speeds.

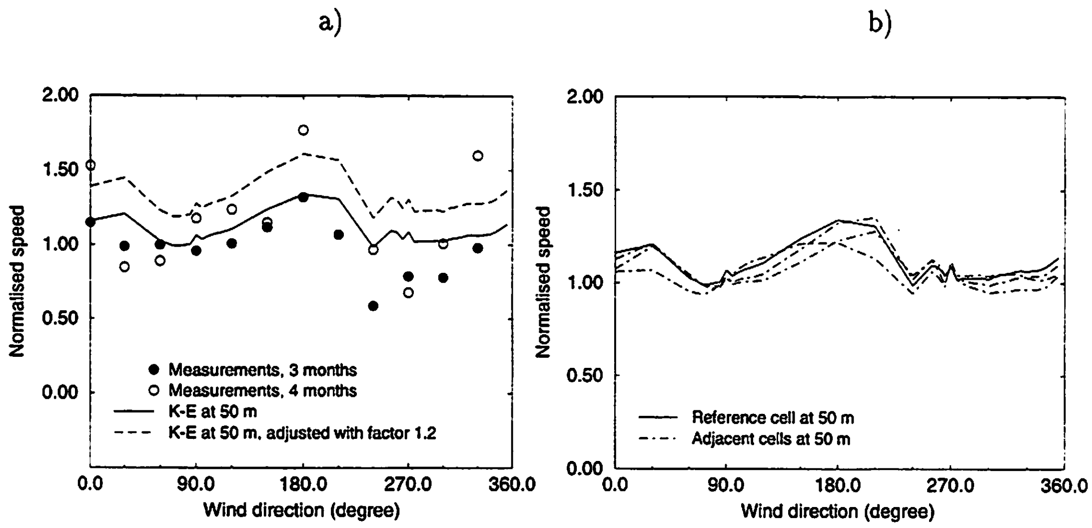


Figure 9: Normalised speed
a) Torsnesaksla/Hekkingen reference cell versus measurements
b) Torsnesaksla/Hekkingen adjacent cells

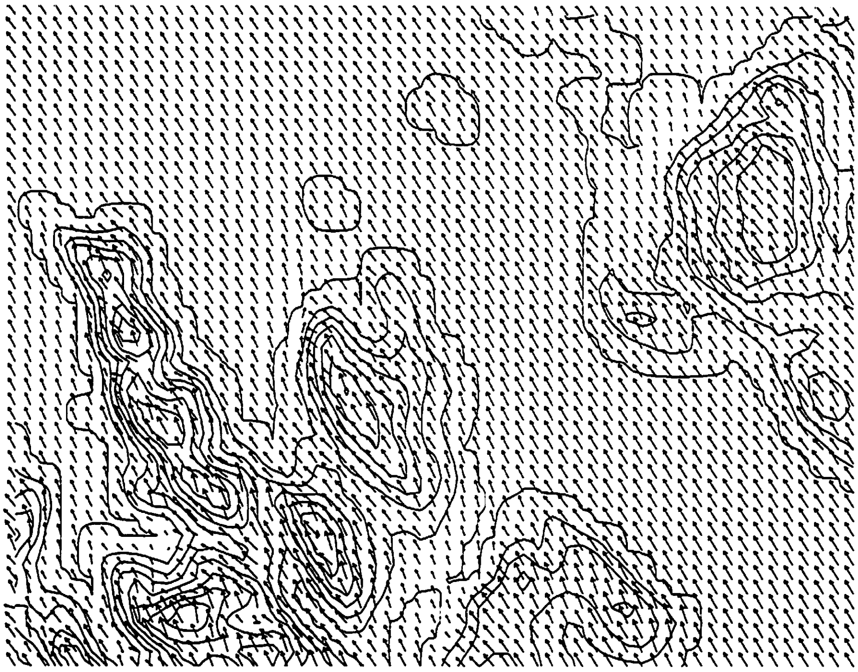
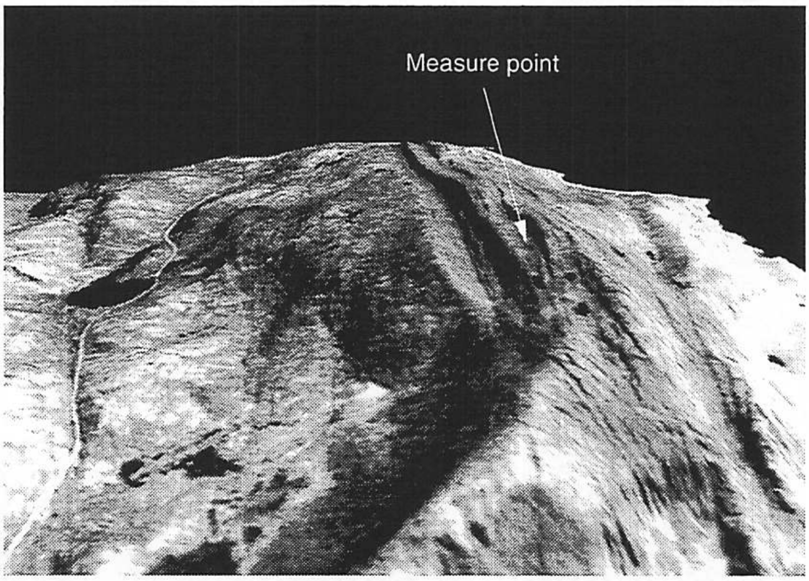


Figure 10: Velocity fields for wind direction 150°, height contour interval is 100 meter

3.4.3 Micro scale simulations

At both measuring sites, scale effects below the meso scale grid resolution is important. In figure 11 the topography at Torsnesaksla is presented with a resolution of 5×5 meter, the height elevation along a line in east-west direction is also given in the figure. In the meso scale model this line section was resolved with 10 cells. In a refined model the grid size is reduced to 100×100 meter. Obviously, the velocity field at the grid points adjacent to the ground displays a more detailed pattern in this refined model. Figure 12 gives an example with wind direction from 210°. A 100×100 meter cell marks the position of the measuring site, included is also the adjacent 400×400 meter cells in the meso scale model. Note that there has been no interpolation of boundary conditions between the two models, comparison of results in the vicinity of the borders will not be possible.



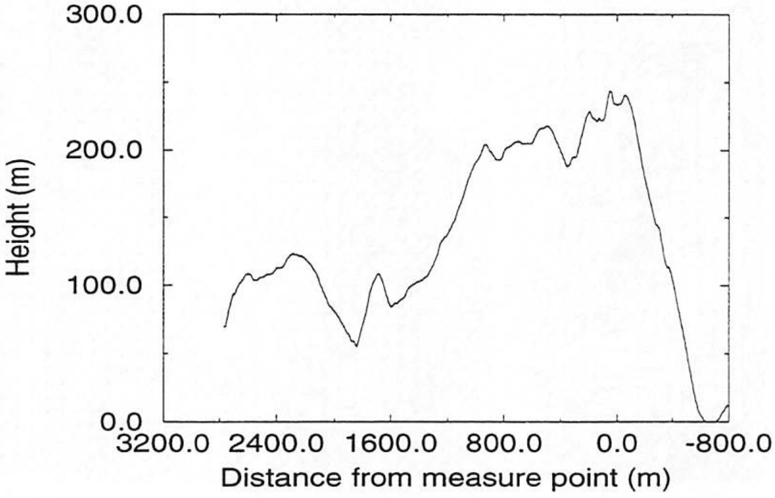


Figure 11: Topography at Torsnesaksla with grid resolution 5×5 meter, view from north (upper), height in east-west direction through measure point (lower)

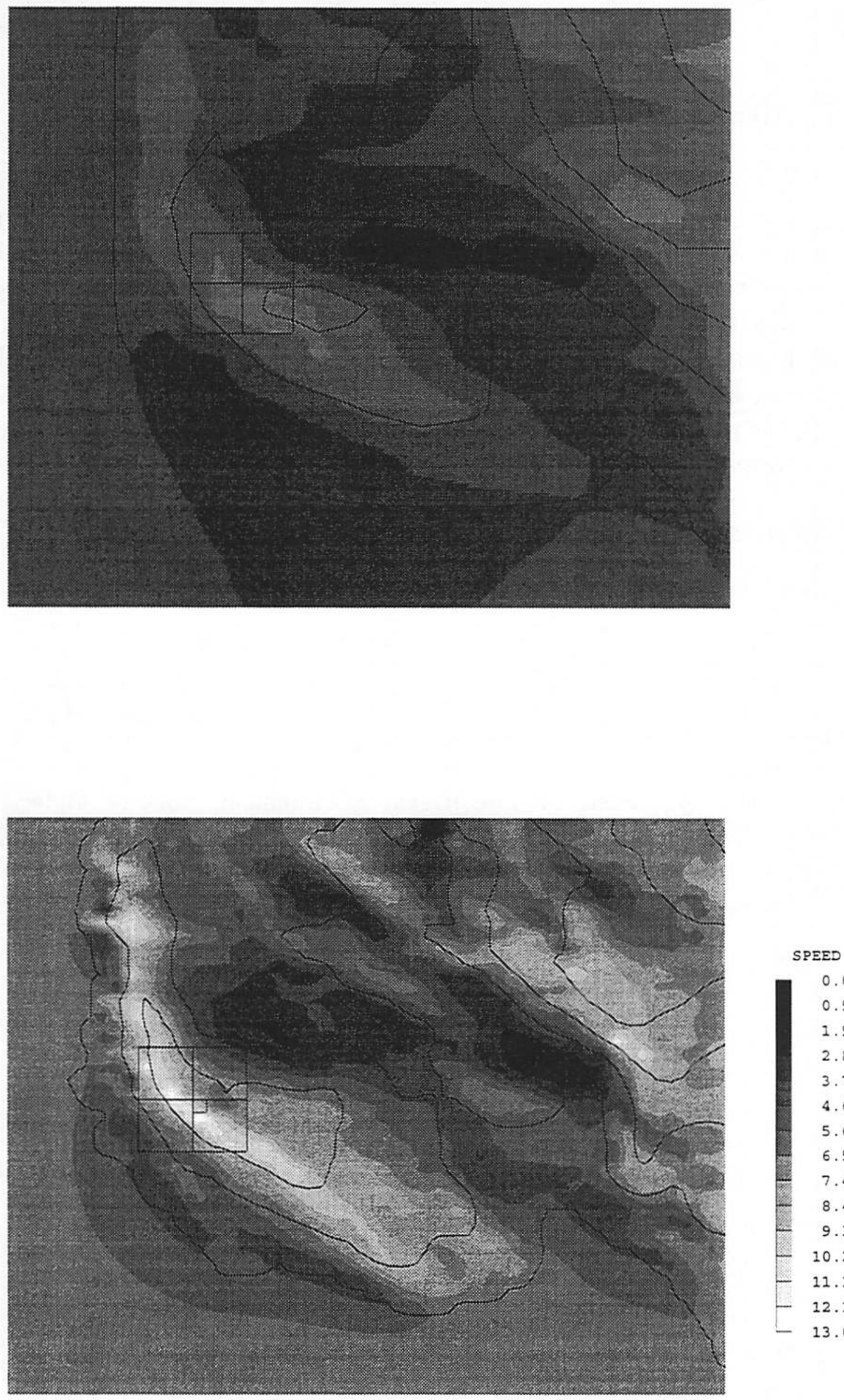


Figure 12: Speed contours for coarse (upper) and fine (lower) model, wind direction 210°, height contour interval is 100 meter.

4 Further work

The measurement data will be more representative as longer time series become available at Torsnesaksla. The meso scale simulations will be recalculated on a finer grid. Finally the development of an interface between meso and micro models will facilitate model nesting.

5 Summary and conclusions

A verification of the Reynolds averaged Navier–Stokes solver WIND–SIM has been performed. The verification started on simplified terrain and moved on towards complex terrain. It was of particular interest to gain insight into the errors made in meso scale modelling of complex terrain with grids to coarse to reflect the underlying topography.

A site in the northern part of Norway, with complex geometry and two measuring masts 8 km apart, was chosen. Although both measuring sites are affected by micro scale effects, similar trends are observed in the the simulations and the measurements. However, the case also illustrates the difficulties encountered when comparing simulations and measurements obtained on different length scales. The discrepancies is due to:

- Measurement series to short to represent mean velocities
- Meso scale model which does not resolve micro scale effects
- Incomplete physical model

Acknowledgements

This study was supported by The Research Council of Norway, under NYTEK project 126645/212. The author would also like to thank Norsk Miljøkraft for making the measurement data at Torsnesaksla available to the project, likewise the Institutt for Energiteknikk for their preparation of the measurements.

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Report to the IEA (R&D Wind) - meeting on State of the Art on Wind Resource Assessment , RISØ, October 1998

On behalf of the Australian Consortium

Introduction

As described in the National Activities Report to the IEA Wind Energy Annual report in 1997, Australia has seen limited implementation of wind power technologies. Several small scale developments (max 2.0MW) have involved "remote area" or non-grid connected installations. More recently, under the impetus of greenhouse emission concerns, there have been a number of grid-connected developments and proposals. A single 600kW turbine has been installed at Koorogang Island, Newcastle, NSW and a wind farm of 5MW (8*600kW) is operational at Crookwell, NSW. Further proposals have been announced for 10MW at Blayney, NSW and 20MW at Portland, Victoria, and a feasibility study is currently underway in Western Australia for 20MW at Albany. Federal Government initiatives include a 2% target for renewables by 2010 and a voluntary Greenhouse Challenge.

Wind data sets

The 1980's saw monitoring programs aimed at assessing wind resources in several states of Australia. Most of these programs were sponsored by government owned electricity utilities and research organisations. The programs involved networks of low-height (typically 10 to 30m) measurements at selected locations, numbering typically 15 to 20 or more. Often there were remote area, inland sites included in these networks to look at the feasibility of replacing expensive diesel based generation, though a few were aimed at large on-grid locations. Much of this data, in summary form, is publicly available. A good review of these data sets is found in [1].

In three instances these data sets have been used as the basis of Wind Atlas Analyses, along the lines of the European Wind Atlas Methodology (two included the use of the WA^{S}P model). Limited Wind Atlases are available for Victoria [2], Western Australia [3] and Tasmania [7]. The data sources tend to be quite sparse compared to the European data and the published results do not contain the full Wind Atlas and hence have insufficient information to produce energy predictions at the surface using WA^{S}P.

In recent times, wind resource monitoring has tended to be more focussed, usually associated with specific proposed wind farm developments, including those mentioned above. Most of this data has been collected by either government or private organisations that are operating in a increasingly

deregualted and competitive electricity industry. The wind data is either available to the public at a cost or is not available as it is proprietary information..
Wind data is currently being collected for a number of prospective sites in New South Wales, Victoria, South Australia, Western Australia and Tasmania. The monitoring is typically at 10m, 30m, 40m and as high as 65m.

Wind Resource Modelling

Broad area resource estimation

As mentioned above, wind atlases for three states have been produced. Two states using the WA^{S}P model and the European Wind Atlas methodology.

Applications to wind power developments

The limited number of developments in Australia to date have taken a variety of approaches to resource definition and micrositing. Some single turbine installations have used in-situ measurement without modelling. Some have relied on turbine suppliers to provide detailed information, providing on-site wind data and topographic information to the tenderers. (e.g. the Portland 10 MW proposal). Several developments have used WA^{S}P either in-house or through consultants to perform the initial feasibility and/or micrositing calculationsincluding (King Island (3*250kW), Esperance (9*225kW), Thursday Is (2*225kW),Crookwell (8*600kW), Blayney (10MW) and Toora (now defunct proposal for 20*500kW))

Model Verification

Information as to the success of the modelling deployed is not generally available in absolute terms from those who are using WA^{S}P. However, the results for King Island, where WA^{S}P was run using data from a single site and later compared to wind measurements at each turbine location were described as “good”. Western Power used WAsP to site their 9 225kW turbines at Esperance, and found yield predictions within 5% of the actual wind farm output averaged over several years of operation.

New developments in Australia

Wind Atlas Development

The wind atlas for Tasmania is currently being revised along the lines of the European Wind Atlas methodology. The atlas is being prepared using data from eight specific wind monitoring stations and sixteen Bureau of Meteorology stations.

Monash University compiling an Australasian wind atlas using the data available from existing and past state wind monitoring programs. The compiled wind atlas is planned for release in 1999 as part of an ANZSES sponsored Australasian wind energy handbook. The success of this Australian wide atlas is going to be limited by the proprietary nature of most of the new data sets.

Local scale modelling

The CSIRO has developed a local scale model [4], derived from MSFD, which is linearised, non-hydrostatic and features a full second-order turbulence closure. An extension to this, using adjoint data assimilation, allows for the incorporation of field data, measured in arbitrary terrain [5]. These linear models may have advantages over model such as WA^{S}P and MS/MICRO under a limited set of circumstances and are not likely good candidates for replacing either model. However, they do represent tools that demonstrably improve wind energy
estimates when operated by skilled operators. These models are currently being tested against the CSIRO network of tower data.

A non-linear, finite difference model is also under development by CSIRO. This model will accommodate steep terrain, which often leads to poor results when modelled with linear models.

Regional scale modelling

CSIRO Land and Water, in conjunction with CSIRO Atmospheric Research has embarked on a project to use a limited area model to provide background wind information to small-scale flow models. The model, TAPM (The Air Pollution Model), is a fast, PC-based prognostic three-dimensional meteorological and air pollution model [6]. The model, which is non-hydrostatic, can be run down to 3 km resolution. It is initialised with Bureau of Meteorology gridded synoptic fields from their LAPS (Limited Area Prediction System)at 75 km resolution for the whole continent or 25 km resolution for the southeast corner. It is planned to use TAPM model to produce wind fields which can be extrapolated to near surface values by the CSIRO small scale models or WA^{S}P for any desired location in Australia. Verification will be performed against the hub-height monitoring network in southeastern Australia.

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The Status of Wind Energy Resource Assessment as Viewed from a Meteorologist in the U.S.A.

29 October 1998

prepared by

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The conference sponsors (Risø Laboratory and U.S. National Renewable Energy Laboratory) have asked me to prepare an informal paper discussing my personal experience in the wind industry and my perception of the state of the art of wind resource assessment today—specifically with respect to items needing more attention.

My initial wind energy assignment was to co-author the first formal wind resource potential report for California, for the state's Energy Commission, which was completed in 1978. This study reviewed existing wind records, topography, and mesoscale wind patterns to identify promising areas across the state for wind power development.

This seminal work led to other assignments in California from 1978-1980, performed for the Energy Commission and major California utilities. The primary emphasis of these efforts was field data to collection to verify the predicted wind resource at key areas (including Altamont, Tehachapi and San Gorgonio Passes, where nearly all California wind development ultimately has taken place).

From 1980-1982 I worked as a meteorologist for Pacific Gas and Electric Company, helping to develop and implement their wind energy program. And in 1983 I worked for one of the original private companies doing wind energy development in California.

At the end of 1983 I started a meteorological consulting company, focusing on wind energy, which still exists today. Through the end of that decade, most of this activity was focused on California (with limited travel across the United States). During the 1990's, the increased interest in wind energy across the world has turned my work into a global job.

In the above capacities I worked with all major wind developers in the United States, helping to site wind turbines, project their wind resource, and similar items. I also served as principal investigator on various utility- and government-funded research projects to improve wind resource assessment techniques. I have personally sited 6000 wind turbines, which has given me many opportunities to evaluate which techniques work and under what circumstances.

California is well known to most wind energy resource analysts for its unusual meteorological conditions. The high winds of the three major passes mentioned above are not caused by strong upper-air winds, but rather from mesoscale circulation patterns associated with the semi-permanent high pressure cell in the eastern Pacific Ocean. Phenomena such as gravitational downslope accelerations, negative wind shears, and the enormous spatial variations in wind resource over relatively small distances, were uncovered in the early 1980's as detailed wind measurements commenced at actual wind farms. Combined with my academic training in boundary layer meteorology, the early years of wind energy development in California taught me that the atmosphere is prone to behave strangely—especially in high-wind areas which often create their own unusual microclimates.

This respect for the vagaries of microclimates has dominated my perspective to wind resource studies. Like nearly all my American colleagues, I have favored the field data-based approach to many aspects of wind resource assessment: micrositing, vertical shear, turbulence, etc. This perspective has made me cautious of numerical flow models for predicting wind resource, since they typically incorporate over-simplified atmospheric physics.

Of course, some people have shown skill and success with the models. Most wind resource analysts across Europe rely exclusively on model-based wind resource assessment techniques, with varying levels of accuracy.

In cases where the terrain, surface roughness and wind forcing factors are relatively simple and straightforward, then models can be expected to produce reasonably accurate results. In more complicated situations, their reliability is less.

A recurrent problem in our industry is the use of wind resource assessment modeling products by persons not properly trained in their use and/or without appropriate meteorological background to understand the concepts of the models. Without such an understanding, mistakes can easily occur.

Regardless of the technique used to perform a wind resource assessment, it is extremely important to document the associated uncertainties. Typically the final product of a wind resource assessment is the long-term mean annual net energy projection for a specified wind turbine array (number, type and hub height of turbines, as well as their locations). But this alone is insufficient for financial risk assessment. It is important to place such a projection in its proper context of statistical uncertainty.

A convenient expression of this uncertainty is the 95% confidence limits, which represent the levels at which there is a 2½% probability of not reaching (lower limit) and a 2½% probability of exceeding (upper limit). This corresponds to roughly 2 standard deviations. Specific probabilities of given target levels can also be determined.

There are numerous individual inputs into a wind resource uncertainty analysis. Some can be directly quantified; others need to be estimated based on the experience of the analyst. It is not the role of my paper to spell out guidelines for how to conduct an uncertainty analysis, but I think it important that the wind energy community state explicitly its importance (particularly to those with financial interests in the outcomes). Whether this means a formal review of the matter and/or adoption of general guidelines, I don't know. However, I see many reports written without a suitable discussion of confidence limits, in many cases with no discussion at all.

Another important issue facing the wind industry today is that of anemometer calibrations. There are two sub-issues here:

- absolute calibration of anemometers
- reconciliation of anemometers used for wind resource monitoring and performance curves

A recent study funded by NREL provides the most in-depth assessment of the Maximum #40 anemometer used widely throughout the world for basic wind resource assessment. Perhaps the NREL consensus calibration constants (slope 0.765 mps/Hz and offset 0.35 mps) should be officially adopted as a standard, with the caveat that a true calm wind is not assigned the offset. (And provisions should be made to determine equivalent calibrations for other types of sensors.) It certainly seems desirable to adopt a uniform standard across the world for something as basic as wind speed.

The calibration issue is of further importance when considering that turbine manufacturers often use different (i.e., more sophisticated) anemometers for performance curve testing than researchers use for wind resource field measurements. This creates the potential for mismatches between the two when the two types of sensors are calibrated in different wind tunnels (round-robin studies have confirmed the tendency for wind tunnels to differ). Any mismatch introduces the likelihood of errors in energy projections. Plus power curves furnished by different vendors are not standardized to the same absolute reference wind speeds.

There is a second issue with respect to performance curve documentation. The guidelines in flat, homogeneous terrain are simple, requiring a single upwind meteorological tower whose winds are assumed to be identical to that of the subject turbine. But in complex terrain, the so-called "site correlation" method is required. This involves placement of a reference turbine several rotor diameters upwind. The practical problem with this has been that many turbines are placed on ridges, and several rotor diameters upwind for the current generation of turbines (with rotor diameters greater than 40 m) is equivalent to more than 100 meters. This can easily place the reference anemometer in a somewhat different wind regime, and which increases the uncertainty in the performance curve tabulation.

Why not expand the guidelines to allow for reference anemometers *atop* the ridges and spaced laterally by whatever minimum separation distance is needed (probably one rotor diameter from the edge of the rotor disk would be adequate). The site correlation procedure (with its two masts) would still be required; however, the correlation between the reference and turbine anemometers would be much closer to unity and the linear regression equation would involve a lower standard error of estimate. Not to mention that it's often easier to erect tall towers atop a ridge than on a slope.

A final issue I recommend be considered by the wind community is the analytical vs. legal role of guidelines (e.g., IEC) in wind resource assessment. Over the past two decades, such guidelines have been developed both in Europe and the United States, perhaps elsewhere.

From the industry perspective of this meteorologist, such guidelines play an extremely valuable role in codifying an approach to complex problems. They especially help provide an objective basis for addressing many issues.

But as these guidelines have been adopted by the wind energy community, there has been a tendency for them to become virtually a legally binding set of procedures. In my opinion this situation has arisen because of the domineering role played by bankers, insurers, etc., who have started insisting upon them as the "correct" and "sole" approved methods of addressing wind resource issues.

This has led to numerous situations in my work, as well as those of colleagues, where blind insistence on a certain guideline is not the most effective (or even most proper) approach to a problem.

I think the wind community should step back and remind itself of the inherent uncertainty in trying to predict the atmosphere. We should encourage novel thinking and approaches to problems and include a role for practical knowledge. If a person follows a scientifically sound and justifiable analysis methodology, his results cannot be stated *a priori* to be less accurate or reliable than one who follows the preset "cookbook" approach. To this end, I would urge the wind resource community to stress that guidelines are simply one allowable methodology, but not the sole one.

There are many detailed topics that could also be discussed in this paper, but I find the above items are of a generic interest to the wind community. In conclusion, I believe that wind energy resource assessment has evolved considerably over the past 20 years. There are a variety of tools for performing such assessments. I look forward to continued work in this field, and hope to continue learning from each assignment.

The Status of Wind Energy Resource Assessment as Viewed from a Meteorologist in the U.S.A.

prepared by Richard L. Simon

- ***Field-Based Wind Resource Assessments vs. Numerical Modeling***
  - Complexity of terrain, microclimate, etc.
  - Experience of user

- ***Statistical Confidence Analysis***
  - Not always done, but important for financial risk assessment
  - Traditionally quasi-subjective, no specific guideline
  - No uniform approach for reporting

- ***Anemometer Calibrations***
  - Need for standardization, especially with Maximum #40 sensor
  - NREL study provides in-depth investigation

- ***Turbine Performance Curves***
  - Mismatch when anemometers used for performance curves are of different type and non-reconciled calibration as anemometers used for micrositing/wind resource assessment
  - Need improved strategy for performance curve measurement in the field, especially on ridges

- ***Role of IEC and Other Guidelines in Wind Resource Assessment***

  Concern over tendency for them to become legally binding at the expense of other valid techniques

WIND RESOURCE ESTIMATION AND MAPPING AT THE U.S. NATIONAL RENEWABLE ENERGY LABORATORY

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1. Background

The National Renewable Energy Laboratory (NREL) has developed an automated technique for wind resource mapping to aid the acceleration of wind energy deployment. The new automated mapping system was developed with the following two primary goals in mind: 1) to produce a more consistent and detailed analysis of the wind resource for a variety of physiographic settings, particularly in areas of complex terrain; and 2) to generate high quality map products on a timely basis. Using computer mapping techniques reduces the time it takes to produce a wind map that reflects a consistent analysis of the distribution of the wind resource throughout the region of interest. NREL's mapping system uses commercially available Geographic Information System (GIS) software packages produced by ESRI, of Redlands, California. The main GIS software is ARC/INFO™, a powerful and complex package featuring a large number of routines for scientific analysis.

The mapping system is designed to display regional (greater than 50,000 km^2) distributions of the wind resource. The maps are intended to denote areas where wind energy projects could be feasible. The wind power density, rather than wind speed, is presented on the wind resource maps since it provides a truer indication of the wind resource potential. The primary output of the mapping system is a gridded color-coded wind power map in units of W/m^2 and equivalent mean wind speed for each individual cell. Most of the final wind resource maps have a 1 km^2 grid cell resolution. Despite this high resolution, the maps are not intended to be used for micrositing purposes because of terrain induced variability of the wind resource that can occur within a grid cell. Regional wind resource maps using this new system have been produced for Mexico, Chile, Indonesia (Elliott and Schwartz, 1997), and China. Countrywide wind resource assessments are underway for the Philippines, the Dominican Republic, and Mongolia. Regional assessments in Argentina and Russia are scheduled to begin soon (Figure 1).

2. Approach

The computer mapping system uses an empirical and analytical approach to determine the level of the wind resource for a particular location. The wind mapping system does not use, at this time, any explicit boundary layer equations or geostrophic adjustment equations as some other wind flow models do.

The major meteorological assumption that underlies the NREL mapping technique is that there are empirical relationships in many parts of the world between the free-air (higher than 100-200 meters above the ground level) speed, the wind speed over the ocean (where applicable), and the distribution of the wind resource over the land areas. Empirical relationships have been noticed in previous NREL wind resource assessment work for well exposed locations with low surface roughness in diverse areas of the world. Accordingly, the wind resource values presented on the maps are the estimates for a non-sheltered location with low surface roughness (short grasslands, for example). NREL's mapping system takes a "top down" method in the adjustment of much of the available wind data. That is to say, the NREL approach takes the free-air wind profile in the lowest few hundred meters above the surface and adjusts it down to the surface. NREL decided to use the "top down" method because of many problems with the available land-based surface wind data in most of the world. A lack of information about observation procedures, and anemometer hardware, height, exposure, and maintenance history are just a few of the problems. In addition, many areas of the world with the potential to have good to excellent wind resource sites have very few or no meteorological stations present. The result is that overall the available surface wind data from meteorological stations is not reliable enough to use directly as input in the wind mapping system. However, these data are critically analyzed to assess the wind characteristics (seasonal, diurnal, directional, etc.) in a study region.

3. Data Sets and Analysis Methods

The following section is a brief summary of the major data sets used in NREL's wind resource assessment methodology (Figure 2).

3.1 Surface Data

DATSAV2 - This global climatic data base, which was obtained from the U.S. National Climatic Data Center (NCDC), contains digital hourly surface weather observations from first-order meteorological stations throughout the world. This data set is the primary source of surface wind information used in our assessments. NREL currently has over 25 years of DATSAV2 data in its archive, spanning the period 1973 to mid-1998. Meteorological parameters such as wind speed, wind direction, temperature, pressure and altimeter setting are extracted from the hourly observations and used to create statistical summaries of wind characteristics.

Marine Climatic Atlas of the World - This data set, compiled from historical ship observations, presents summarized wind statistics for a 1° latitude by 1° longitude grid. Measurements are concentrated along the major shipping routes. Included are summaries of the monthly means and standard deviations of wind speed, pressure, temperature, and wind direction frequency and speed.

Special Sensor Microwave Imager (SSMI) - The SSMI, which is part of the Defense Meteorological Satellite Program, provides 10-m ocean wind speed measurements. This dataset provides much more uniform and detailed coverage of oceanic wind speeds than the "Marine Climatic Atlas of the World." NREL currently has ten years of SSMI data covering the period 1988 to 1997.

3.2 Upper-Air Data

Upper-air data can provide an estimate of the wind resource at low levels in the atmosphere and contribute to the understanding of the vertical distribution of the wind resource. This is useful in estimating the winds on elevated terrain features and for estimating the wind resource at other exposed locations in a particular region.

Automated Data Processing Reports (ADP) - This dataset contains upper-air observations from rawinsonde instruments and pilot balloons for approximately 1800 stations worldwide. Observation times include 00, 06, 12, and 18 Greenwich Mean Time (GMT). Wind information is available from the surface, the mandatory pressure levels (1000 mb, 850 mb, 700 mb, and 500 mb), the significant pressure levels and, for some stations, specified geopotential heights above the surface. NREL currently has over 25 years of observations from 1973 through mid-1998.

Global Gridded Upper Air Statistics - This data set contains monthly means and standard deviations of climatic elements for the mandatory pressure levels on a 2.5 degree global grid. The data were obtained from the NCDC and cover the period 1980 to 1991. This dataset is used to supplement the ADP information in areas where upper-air data are scarce.

Reanalysis Data - This data set created by the U.S. National Centers for Environmental Prediction and the National Center for Atmospheric Research contains worldwide information of wind, temperature, and other variables on a terrain- following 208 km resolution grid with over 18,000 points. The output is available four times a day at 00, 06, 12, and 18 GMT. This data set has better vertical resolution in the boundary layer than the ADP data. NREL has obtained 40 years (1958-1997) of the raw data and is currently investigating the optimum way of integrating Reanalysis into the wind resource assessment methodology.

3.3 Data Analysis

An accurate wind resource assessment is highly dependent on the quantity and quality of the meteorological input data into the automated system. NREL reviews the data sets mentioned above and previous wind energy assessments as part of its overall evaluation. The use of multiple data sets is necessary since the quality of data in any particular dataset can vary and because high quality data can be quite sparse in many regions of the world.

A critical analysis of the climatic data is performed to ensure the meteorological input is as precise as possible. Wind characteristic summaries are generated for surface and upper-air observations. The generated summaries are cross-referenced against each other to understand the prevalent wind characteristics in the study area. For example, the interannual surface wind speeds are evaluated to identify obvious trends in the data or periods of questionable data. Data periods determined to be most representative are selected from the entire record for use in assessments. The goal of the data analysis and screening process is to develop a conceptual model of the physical mechanisms, both regional and local in scale, that influence the wind flow. The ultimate goal of the analysis is to enable the meteorological analyst(s) to gain a conceptual model of the physical mechanism(s), whether produced by large and/or local scale factors that cause the wind to blow in a particular region. The conceptual model guides the development of the empirical relationships that serve as the basis of the algorithms that calculate wind power. The analyst(s) is ultimately responsible for preparing the input meteorological data for the mapping system.

4. Mapping System

The mapping system is divided into three main components: the input data, the wind power calculations, and the output section that produces the final wind resource map. These components are described below.

4.1 Input Data

The two primary model inputs are digital terrain data and formatted meteorological data. The elevation information consists of Digital Elevation Model (DEM) terrain data that are used to divide the analysis region into individual grid cells, each having its own unique elevation value. The United States Geological Survey Earth Resource Observing Satellite Data Center recently produced new DEMs for most of the world. The new data sets have a resolution of 1 km^2.

The meteorological inputs to the mapping system are vertical profiles of free-air wind power density, wind power roses (which specify the percentage of total power from the wind by direction sector), and the open ocean wind power density, where appropriate. The vertical profiles are broken down into 100 m intervals centered every 100 m above sea level (asl), except for the lowest layer which is at 50 m asl. The wind power rose is used to determine the degree of exposure of a particular grid cell to the power producing winds. The open ocean wind power density is derived from the SSMI and ship wind speed observations, converted to wind power density, and extrapolated to 30 m for use by the mapping system.

4.2 Wind Power Calculations

The mapping system is designed to calculate the wind power for those grid cells that meet certain exposure and slope requirements. Therefore, the mapping system identifies the most favorable wind resource areas. The vertical profiles of free-air wind power density serve as the input for a base wind power density value for a particular grid cell. The wind power calculations in the wind mapping system are adjustments to the base free-air wind power density values of each grid cell. The factors that either decrease or increase the base wind power value for a particular grid cell are terrain considerations, relative and absolute elevation, the aspect of the terrain, distance from ocean or lake shoreline, and the influence of thermal or other types of small-scale wind flow patterns. When a coastal area or an area with large water bodies (lakes, estuaries, and fjords) is being mapped, then the distance between a grid cell and the body of water also becomes an important component of the wind power calculation. For areas not near a large water body, the wind power is derived from the vertical profile of wind power density. However, for areas within a few kilometers of an ocean, lake, or other large water body, the mapping system calculates the power in one additional way. The additional method calculates the power based on the ambient wind flow near the surface and the amount of fetch the prevailing winds have across the water body. The final wind power estimates for these coastal or lakeshore cells are based on the maximum value calculated from either of these methods.

4.3 Mapping Products

The primary product of the mapping system is a wind power density map of favorable wind resource areas. The wind resource values presented are estimates for non-sheltered locations with low surface roughness (short grasslands, for example). The DEM data can be used to create a color-coded elevation map, a hill-shaded relief map, and a map of the elevation contours. When combined with the wind power maps, these products enable the user to obtain a feel for the three-dimensional distribution of the wind power for the analysis region.

4.4 Limitations of Mapping Technique

There are several limitations to the mapping technique, the first of which is the resolution of the DEM data. Significant terrain variations can occur within the DEM's 1 km^2 area, thus the wind resource estimate for a particular grid cell may not apply to all areas within the cell. A second potential problem is the development of the conceptual model of the wind flow and its extrapolation to the analysis region. Many complexities in the wind flow exist which make this an inexact process. Some of the complex factors include the structure of low-level jets and their interaction with the boundary layer, and localized circulations, such as land-sea breezes, mountain-valley flows, and channeling effects in mountainous areas. These factors effect the amount of momentum that is transported to the surface from free-air levels. These processes are only simply approximated in the mapping system. Finally, the power estimates are valid for areas with low surface roughness. Estimates for areas with a higher surface roughness need to be adjusted down by as much as 25% to 60% depending on the amount of obstructions to the wind flow.

5. Conclusion

We have encountered a wide variety of wind climates and boundary layer interactions in the course of NREL's analysis and wind mapping projects. Due to this factor, the general structure and the individual algorithms used in the mapping system are continually evolving in order to continue to produce the most useful wind maps. We have started to validate some the system results (Elliott and Schwartz, 1998), recognizing that this is not currently feasible in some regions because of the lack of quality wind measurements. Validation results will be used to help improve the mapping system.

6. Acknowledgments

I would like to thank the rest of NREL's wind resource assessment group-Dennis Elliott, George Scott, Steve Haymes, Ray George, and Donna Heimiller-for their contributions to software development, data processing, and GIS mapping applications. This paper was written at the National Renewable Energy Laboratory in support of the U.S. Department of Energy under contract number DE-AC36-CH10093.

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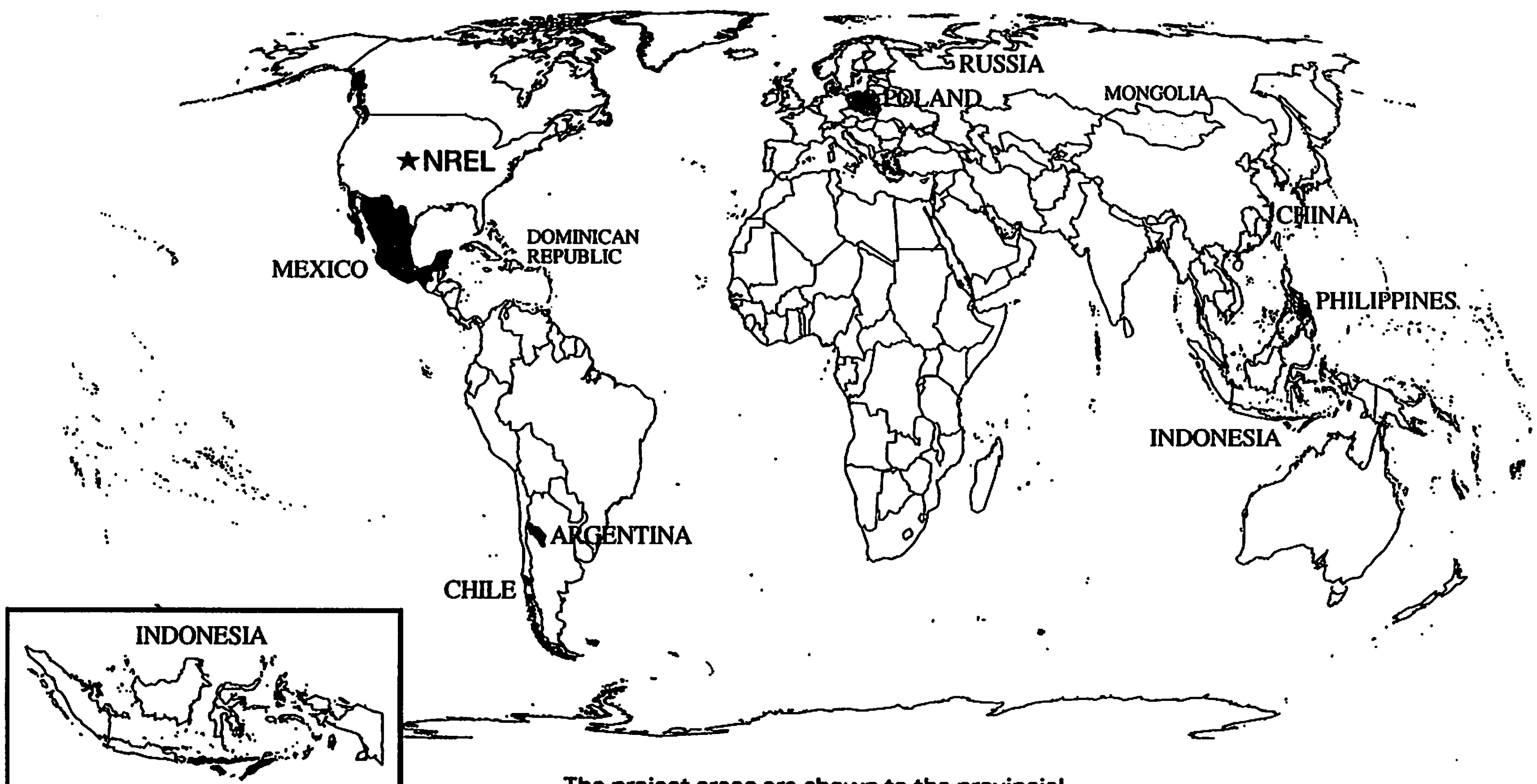
Figure 1. **NREL International Wind Resource Mapping Projects**



Projects

- Automated GIS maps since 1996
- Subjective maps from 1993 to 1995
- Automated GIS maps since 1996 and subjective maps from 1993 to 1995

The project areas are shown to the provincial or regional level and may not represent the true extent of the actual wind maps. The automated maps are developed with NREL's GIS mapping system. All of the wind maps are based primarily on data from NREL's global meteorological and topographic data sets.

Political boundaries are from ArcWorld.

US Dept. of Energy - National Renewable Energy Laboratory

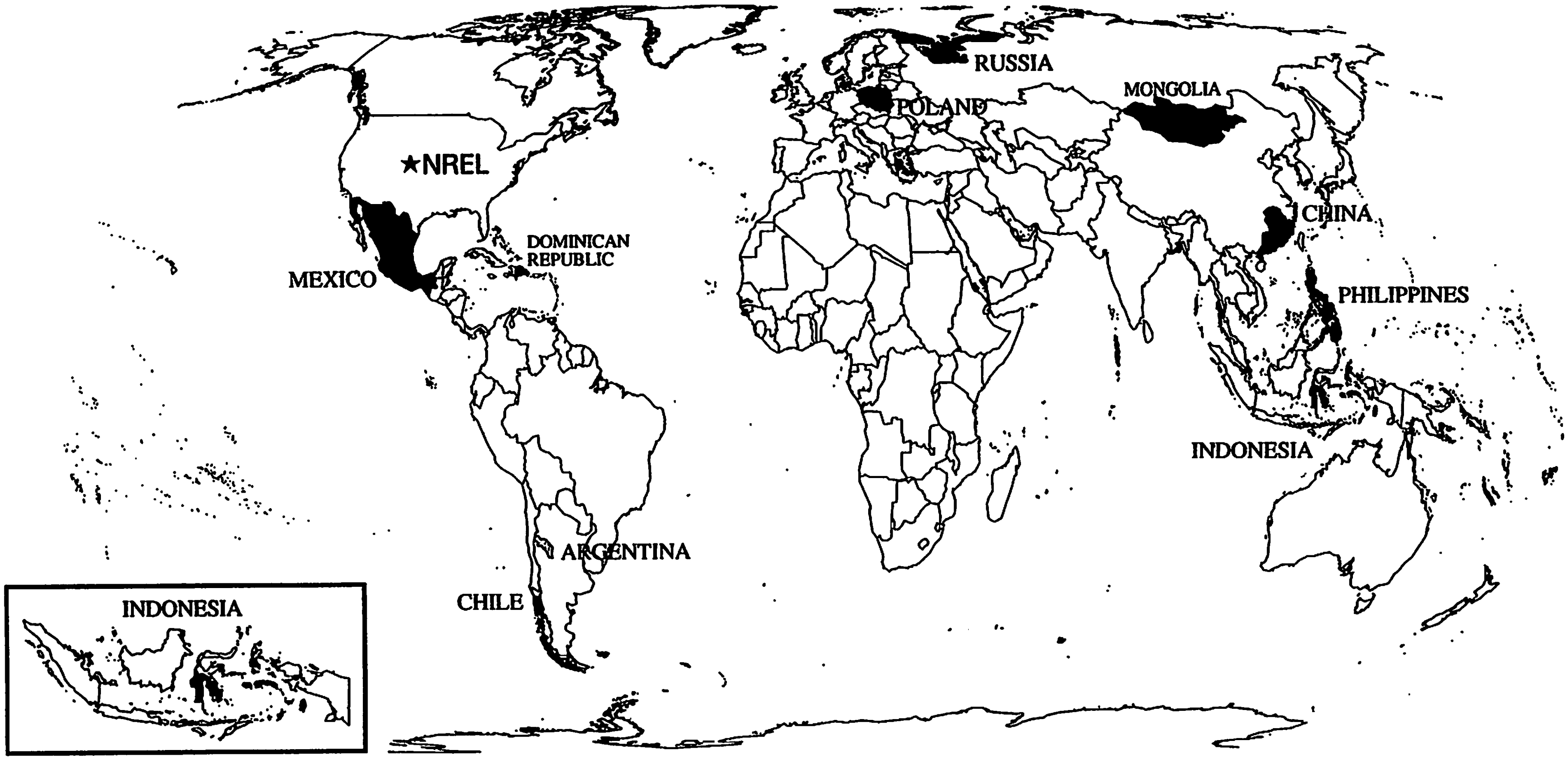
NREL

Figure 2.

Major Climatic Data Sets used by NREL for Wind Resource Assessment

Data Set	Type of Information	Source	Period of Record
DATSAV2	Global surface observations	NCDC	1973-1998
Marine Climatic Atlas of the World	Gridded statistics of historical ship wind observations	NCDC	1854-1969
Global Gridded Upper Air Statistics	Gridded upper air statistics	NCDC	1980-1991
NCEP Upper Air ADP Data	Global rawinsonde and pibal observations	NCAR	1973-1998
DMSP Satellite SSMI Data	Global 10-m ocean wind speeds	JPL and Remote Sensing Systems	1988-1997
Reanalysis grbsanl files	Gridded surface and upper air statistics	NCAR	1958-1997

NREL International Wind Resource Mapping Projects



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US Dept. of Energy - National Renewable Energy Laboratory

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Simulations of the Climatological Wind Field with the MIUU model

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Introduction

Mapping the climatological wind field for wind energy purposes, it is important to study both land and sea areas. Over a land area, the geostrophic wind field, but also topography, roughness etc. are well-known factors affecting the wind climate at a certain site. But, in coastal areas, factors related to the land-sea transition also contribute to a rather complex wind field, which may affect the wind at quite large distances from the coast.

The purpose of the simulations presented here is to estimate the climatological wind field over an area of the order of 100 000 - 1 000 000 km^2, with a horizontal resolution of about 2 - 10 km and at levels of interest for wind energy. A three-dimensional meso-scale model, the MIUU model, has in earlier studies proved to simulate this kind of situations very well when compared with data from several field experiments (e.g. Enger 1983, Enger 1990, Tjernström 1987; Smedman et al. 1996a; Andrén 1989). The approach has been to identify the main flow driving parameters for the wind field. Climatological data of these parameters are then compiled. Climatological statistics of geostrophic wind and temperature are used. Based on this, a weighting of all simulations are performed.

The MIUU Model

The MIUU model, which is used for the simulations has been developed at the Department of Meteorology (since 1998: Department of Earth Sciences - Meteorology), Uppsala University, Sweden (Enger, 1990). The model is three-dimensional and hydrostatic. The topography is introduced in the model by application of a terrain following coordinate system (Pielke 1984). The turbulence is parameterized with a level 2.5 scheme, according to Mellor and Yamada (1974). A detailed description of the closure can be found in Andrén (1990). The model is described in detail in Tjernström (1987). The model gives prognostic equations for wind, temperature, humidity and turbulent kinetic energy.

To reduce the influence from the boundaries upon the area of interest, the model area is much larger than the area of interest. One other reason to use a large domain is when advective effects are important for the wind field in the area. Thus in the horizontal a telescopic grid is used, to achieve the highest resolution in the central areas and still have a large enough domain to reduce the influence of the boundaries. In the vertical, the lower levels are log spaced while the higher levels are linearly spaced. The lowest grid point is at height z_0, where z_0 is the roughness length.

At the lower boundary height above sea level, temperature and roughness length have to be specified at each grid point. The land surface temperature and its daily and monthly variation have been taken from synoptic measurements at stations around the area of interest. The climatological sea surface temperature has been evaluated from sea surface temperature maps. The terrain height has been taken from a digitized map with a resolution of 500 m. The roughness length over land has been estimated from maps by judging the relative fraction of forests, fields, urban areas and lakes within each grid area.

A Method to Model the Climatological Wind Field

In the ideal climatological study, all synoptic and boundary conditions should be covered, but this would require an unrealistic large number of simulations. Since the MIUU model is rather computer time consuming to run, some compromises have to be made. First, the most important flow forcing parameters have to be identified. These parameters must then be varied in order to cover a wide range of atmospheric conditions. Parameters important to the wind field are: geostrophic wind - strength and direction, thermal stratification - the daily temperature variation, surface roughness, topography, land-sea temperature differences and thermal wind.

The pressure gradient, i.e. the geostrophic wind, is the primary driving force of the wind. Using only the mean climatological geostrophic wind speed in the simulations would reduce the effect of thermal stratification, as the daily stability variations would be much larger with a lower geostrophic wind speed than with a higher. This effect is sometimes very important, why it is important to include simulations with different geostrophic wind speeds (Sandström, 1997). The optimum would be to perform simulations for a large number of geostrophic wind speeds, but this would be almost impossible in view of computer time demand. Therefore model runs with three values of the geostrophic wind speed, 5 ms^{-1}, 10 ms^{-1} and 15 ms^{-1}, have been performed. These simulations are then weighted together according to the observed geostrophic wind speed distribution.

The air temperature shows a clear annual as well as a daily variation, which also must be included in the simulations. To limit the number of model runs but still include the annual variations, 4 months (January, April, July and October) have been selected to represent the four seasons. The monthly climatological mean temperature and daily variation for each of the four months have been used. To include the spatial differences, synoptic stations have been selected to represent different parts of the model area. The temperature between the stations has been estimated by linear interpolation. The mean temperature for each of the stations also varies according to wind directions, which may give different thermal stratification. This means that the mean temperature for different directions must be evaluated. Also here a compromise has to be made to limit computer time. Therefore wind direction in eight sectors have been used to include the directional dependence of the temperature.

The daily variation of sea surface temperature is rather small compared with the variations of the air temperature. Therefore, model runs were made with the climatological mean sea surface temperature at each grid point, for each of the four months, with no daily variation but with a spatial variation.

The roughness length over land has been determined from vegetation maps over the area. The roughness over land has been divided into three roughness classes. Areas covered with forest (z_0 = 0.8 m), sparse forest (z_0 = 0.5 m), coastal and agriculture areas (z_0 = 0.1 m). Over the sea z_0 is assumed constant = 0.00025 m.

To include the most important parameters affecting the wind field, simulations have been performed for the four seasons represented by the climatological temperatures and daily variations for the months January, April, July and October; 3 geostrophic wind speeds 5, 10, 15 ms^{-1} and with eight wind direction sectors. Thus we end up with 96 model runs to cover the most important parameters determining the boundary layer wind field. All these simulations must then be weighted together using climatological data of the geostrophic wind. Each simulation is performed to represent a 24 hour period, which takes about 4 hours of computer time on a Pentium II PC, 450 MHz, including initialization. Thus, a study takes 3 weeks computer time.

All model runs were weighted together using climatological statistics of the geostrophic wind, using the distribution for each wind direction sector and the distribution of the geostrophic wind speed for each wind direction sector. Summation over all model runs and hours will give the climatological mean value for each month and grid point. Simulations were only made with three geostrophic wind speeds, while the wind speed distribution calculated from data (synoptic station) is divided into 20 classes, which means that each of the 3 geostrophic wind speeds has to represent a range in the distribution

In this study four months have been used, each representing a season. It has been shown by Bergström (1996) that this approach is accurate enough. This means that the annual mean wind speeds can be calculated by taking the mean of the four individual months. Thus, the result from a study of the climatological wind field may be presented as the (annual or seasonal) mean wind speed, or wind energy potential, at different heights. The wind speed distribution may be displayed.

Studied Areas

Figure 1 shows the areas that has been (and today are planned to be) studied with this method, giving the climatological wind field.

Bergström (1996) has studied the wind climatology in the Blekinge area, in the south-eastern part of Sweden, (area 1 in Figure 1). The model domain was in this case 160x160 km and the grid resolution in the central parts was 2 km. In addition to the simulations described above, Bergström also performed simulations representing warm and cold air advection.

The Baltic Sea (area 2 in Figure 1) is the largest area studied with this method (Sandström, 1997). Some result from that study will be presented below, as an example of this method.

At the request of the county administration of Västra Götalands län, the climatological wind field over this county has been studied recently (Leif Enger, personal communication). The model domain (area 3 in Figure 1) is about 250 x 250 km, and the grid resolution is in this case 1.5 km over the whole area. In this study, there are some difference in details regarding the method, in comparison to the other studies described (e.g. for the climatological weighting, comparison with 8 years of hourly data from 10 towers and two SODAR in the area of interest have been used instead of climatological data of the geostrophic wind.) Only preliminary results exists (October 1998, Leif Enger, personal communication).

For all these three studies, comparisons between modelled and measured mean winds have been performed, with very good agreement (Bergström, 1996, Sandström, 1997 and Leif Enger, personal communication).

As a part of the EU-project MOWIE, (Mountain Wind Energy), measurements are/will be performed in Sourva and Pyhätunturi (area 4 and 5 in Figure 1, respectively). For these areas, the wind field will also be simulated with the MIUU model (personal communication, Birgitta Källstrand and Hans Bergström). The two last mention persons will also perform a detailed study of the wind climatology of a part of the coastal area along the east coast of Sweden (area 6 in Figure 1) during 1999.

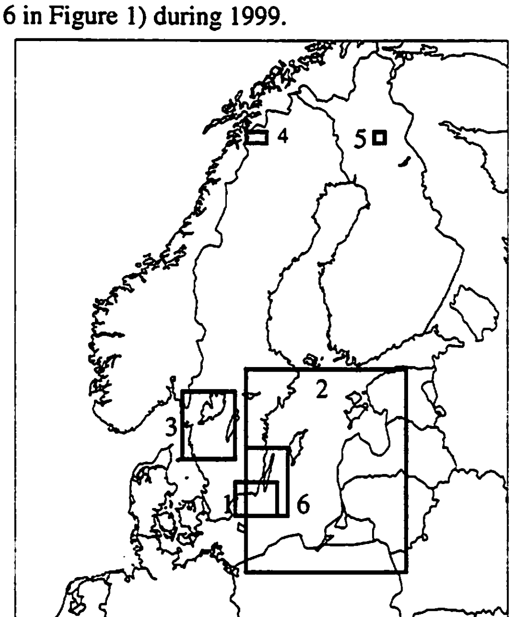

Figure 1: Areas where the climatological wind field are (or are planned to be) simulated with the MIUU model. (The numbers are refering to the text.)

Baltic Sea Study

As an example of simulating the climatological wind field with the MIUU model, the Baltic Sea study (Sandström, 1997) will be described in brief. The model domain (800 km x 900 km) and the area of interest, i.e. the Baltic Sea, is shown in Figure 2. In the horizontal, there is a grid distance of 5 km in central areas of the Baltic Sea, around 10 km in the coastal areas, and 25 km at the boundaries.

Four synoptic stations have been selected to represent different parts of the model area (Figure 2), Helsinki represents the Finnish area, Bredåkra represents Sweden, Riga represents the Baltic States and Lübeck represents Poland and Germany. The temperature between the stations has been estimated by linear interpolation.

Wind and temperature data to calculate the geostrophic wind (using a wind model by Bergström, 1986) were taken from Ölands Södra grund (Figure 2). The geostrophic mean wind speed was found to be 10.1 ms^{-1}, which could be compared with the values given in Petersen et al. (1981) for Denmark, 10.2 ms^{-1}. Used in the simulations are the geostrophic wind direction distributions for the four sectors and four months as well as the wind speed distribution for each sector and month. In Højstrup et al. (1996) an estimate of the geostrophic wind speed is presented, showing that the mean wind speed decreases from the south-west to the north-east over the Baltic Sea. This combination of data gives a geostrophic wind speed which is 10.2 ms^{-1} in the south-west corner, which decreases to 9.5 ms^{-1} in the north-east.

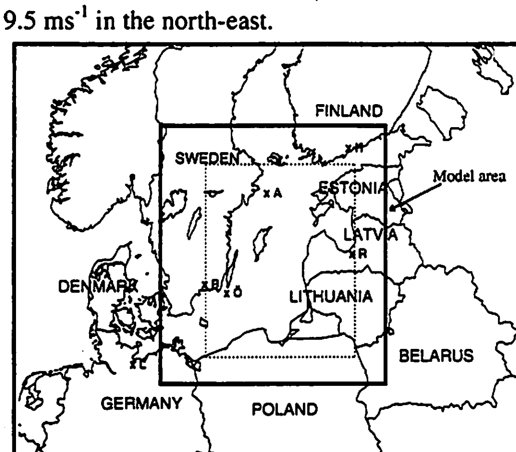

Figure 2: Map of the model area in the Baltic Sea study (the rectangle). The dotted line shows the area of special interest. Synoptic stations used for temperature statistics: B=Bredåkra, H=Helsinki, R= Riga, L= Lübeck. Lighthouses with climatological measurements: Ö=Ölands södra grund, A= Almagrundet.

In Figures 3-4, the modelled annual mean wind speed at 66 m and 153 m are presented. The model results cover the Baltic Sea area and the surrounding countries. The modelled wind speed over land is not shown in the Figures since the simulations have been focused on the wind field over the Baltic Sea area. The transition from lower wind speed over land to higher wind speed over sea is rather sharp at lower heights while at higher levels it becomes more of a smooth transition zone. As expected, the highest wind speed is found in the central parts of the Baltic sea, with values close to 8 ms^{-1} at 8 m, around

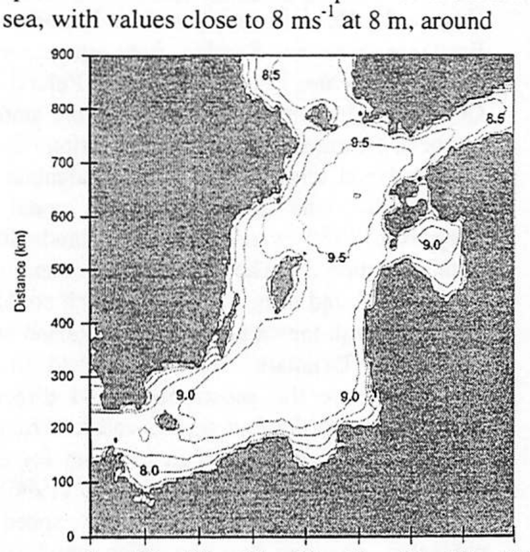

Figure 3: Simulated annual mean wind speed (ms^{-1}) at 66 m height.

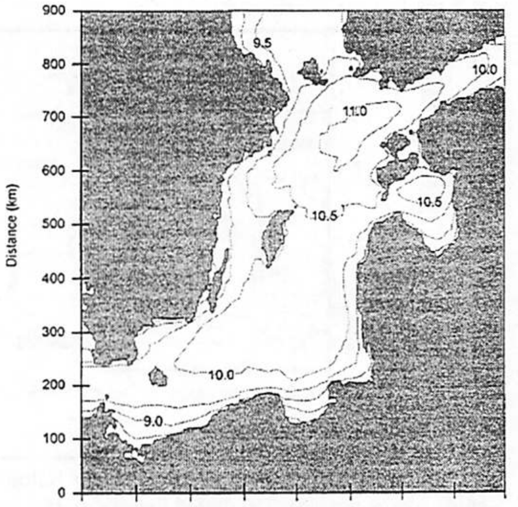

Figure 4: Simulated annual mean wind speed (ms^{-1}) at 153 m height.

9.5 ms^{-1} at 66 m and up to 11 ms^{-1} at 153 m. High wind speeds are also found in the Gulf of Riga. The annual mean geostrophic wind speed varies spatially between 9.5 and 10.2 ms^{-1} from the north-east to the south-west. The annual geostrophic wind speed is about the same as the wind speed found at 153 m in the southern part of the Baltic Sea. But in the northern part, the wind speed at 153 m is more than 1 ms^{-1} higher than the geostrophic wind speed. The high wind speed area in the northern part of the Baltic Sea is probably caused by low level jets, i.e. local wind maxima at relatively low levels (see next section and e.g. Gerber 1989, Stull 1988, Smedman et al., 1996b, and Källstrand 1998). The high wind speeds close to the Latvian and Lithuanian coast are due to the fact that westerly geostrophic winds are the most frequent, with an occurrence of 42 % in the sector 225° - 315°.

Thermal effects

The Baltic Sea is surrounded by land surfaces, which means that advective effects from land areas will influence the wind and turbulence structure over the sea regardless of wind direction. The location of the Baltic Sea at fairly high latitudes causes the land surface temperature to be higher than the sea surface temperature during a large part of the year, which will give a stable internal boundary layer over the sea. Measurements show that the lowest 100 m of the marine boundary layer over the Baltic Sea is probably stably stratified during between 1/2 and 2/3 of the time (Smedman et al. 1997, personal communication, Hans Bergström). The growth of the stable internal boundary layer may affect the wind speed for large distances from the coast, giving decreasing wind speeds at lower levels (Källstrand et al., 1998). Also, at the top of this internal boundary layer a low level jet may develop as a result of frictional decoupling at the coast (Smedman et al. 1996b), when warm air (from the surrounding land areas) is advected out over the cooler sea. This produces an analogy in space to the well-known nocturnal jet (Blackadar 1957). The fact that the annual simulated wind speed at higher levels in the Baltic Sea is supergeostrophic, implies that low level jets are frequent and with high speeds.

The growth of internal boundary layers and low level jets, together with sea-breeze circulations, are examples showing the importance of taking thermal factors into consideration when the wind field is studied, especially in coastal areas and over sea. They may contribute to a spatial variability of the wind field also on a climatological basis.

Summary and conclusions

A method to simulate the climatological wind field using a three-dimensional higher order closure mesoscale model (the MIUU model) is described. A number of simulations are performed, with different wind and temperature conditions, and a weighting based on climatological data is then made. This method is applicable for mapping the wind resources with a resolution of 2-10 km (for areas up to 1 000 000 km^2). To use this method the geostrophic wind field, the temperature from one (or more) site(s), the topography and the roughness are needed. Comparisons between model results and measurements show very good agreement, for all three studies that so far have been performed with this method.

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Applicability of mesoscale models for wind resource estimation

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Mesoscale models have been designed to simulate atmospheric currents over complex terrain including the effects of terrain height, land use, physical properties and state of the soil. The state of development is now that non-hydrostatic models, which are suitable for nearly all scales of atmospheric processes, are going to be used now for operational high resolution numerical weather forecasting. The progress of computer power enables larger model domains and higher spatial resolutions so that small topographic structures can now be considered without loosing information about larger scales. Nesting or domain decomposition techniques applied on parallel computers make simulations with locally high resolutions and accuracy possible without increasing wall clock times.

Nevertheless mesoscale models require large computational efforts so that they usually run on so called supercomputers or at least on work station clusters. Not only for computational reasons they can only been applied to simulations of short episodes. Therefore the main problem of using these models for wind resource estimation is to construct synthetic wind statistics from a limited number of simulated episodes. For this purpose a statistical dynamical approach has been developed since 20 years.

The statistical dynamical approach combines a statistical description of the large scale climate, usually provided by operational weather analysis systems, and mesoscale model simulations. The necessary assumption used in this approach is, that the local climate state is the result of a modification of the large scale climate state by the topography, and that the local climate state is a unique function of the climate state on larger scales. This unknown function has to be estimated by the mesoscale model.

In a first step a set of physical parameters has to be chosen which are suitable to describe the state of the large scale climate and which are also external parameters of the mesoscale model. The most obvious parameters are the components of the gradient of the large scale pressure field or equivalently the components of the geostrophic wind and a static stability parameter. But also other additional parameters may be important like a sea surface temperature if the domain of interest is located near the coast so that the regional climate is influenced by sea breeze effects. From these parameter sets a multi dimensional frequency distribution is required, which can be used to define categories of "typical" episodes. For this purpose different cluster analysis methods have often been applied. For each of these episodes a simulation with the mesoscale model is performed. Taking the frequency belonging to the chosen episodes or categories the model output is aggregated to statistics of all model variables at all grid points of the model. As a result frequency distributions are provided by this procedure of all model variables for the whole model domain with the spatial resolution of the model. And because of the strong physical basis of mesoscale models the procedure can by applied everywhere.

This procedure has been applied successfully in many cases as they can be found in the literature not only for wind resource estimation but also for down scaling the output of global circulation models applied for forecasts of climate change. But unfortunately the method implies several assumptions which can not be proved objectively. Beginning from the number and choice of the external parameters, the classification of the episodes to be simulated up to the design of the model simulations, most tasks have to be fixed subjectively up to now, although physical constraints can be formulated for the choice of the parameters and the errors caused by the clasification can be estimated. Nevertheless the results of the procedure should be evaluated for example by comparison to observations.

In principal this approach is limited by the validity of the basic assumption on the existence of the unique function between the large scale and local scale state of the atmosphere. For example in cases of steep terrain or of strong stable stratifications bifurcation phenomena may become important, so that dynamical constraints on applicability have to be considered, which are not well known up to now. At this point basic research on the dynamics of mesoscale processes is still required. These constraints become important in applications with high spatial resolution because the maximum slope resolved by the model depends on the chosen grid size.

As mentioned above operational high resolution numerical weather forecasts will be available soon on scales, which are of interest here. Up to now the quality of these forecasts are not known. For example sufficient initialisation schemes are not available up to now and only very few experiences exist on the influence of the large gap between the resolutions of the forecast model and of the observational networks necessary to define the initial state. And ignoring the possible errors of these forecasts stable wind statistics will be available only after many years. But nevertheless the results of these forecasts of only few years can be aggregated to wind statistics also by the statistical dynamical approach, which may be much cheaper than performing many additional mesoscale model simulations.

Statistical-Dynamical Downscaling of Wind Climatologies

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Sufficiently accurate information of the available wind power on regional and local scales is a prerequisite for optimum wind turbine siting under economic and social constraints. Often wind statistics are derived from long-term near-surface observations at synoptic stations. However, the spatial density of such data is usually inadequate to deduce high resolution windspeed maps on regional scales, and observations at the standard height of 10 meter may be disturbed by close obstacles and vegetation. In particular over complex heterogeneous terrain the data may also be influenced by dynamically or thermally induced local circulations which probably cannot be corrected for. We aim at estimating the wind climate on regional and local scales by use of long-term upper-air data and a numerical model. Near-surface observations are used for comparison reasons only.

The large-scale wind climatology is calculated by a cluster-analysis of a time series of radiosonde data at 850 hPa (wind) and between 100 m and 1.5 km (temperature gradient) over 12 years. A total number of 143 cluster was found to represent the time series appropriately under the constraints of 3 fixed stability classes, a maximum number of 150 cluster due to limited computer resources, and reasonable standard deviations for windspeed and -direction in each cluster. For each cluster a highly resolved steady-state simulation was performed with the non-hydrostatic mesoscale model GESIMA (= Geesthacht Simulation Model of the Atmosphere). The resulting wind fields are statistically evaluated by weighting them with the corresponding cluster frequency. The resulting 3-dimensional wind field and the frequency distributions of windspeed and -direction are compared with observations at synoptic stations. An estimate of the power output of wind turbines is calculated by combining windspeed frequency distributions and the respective power curve and is compared to the actual power output.

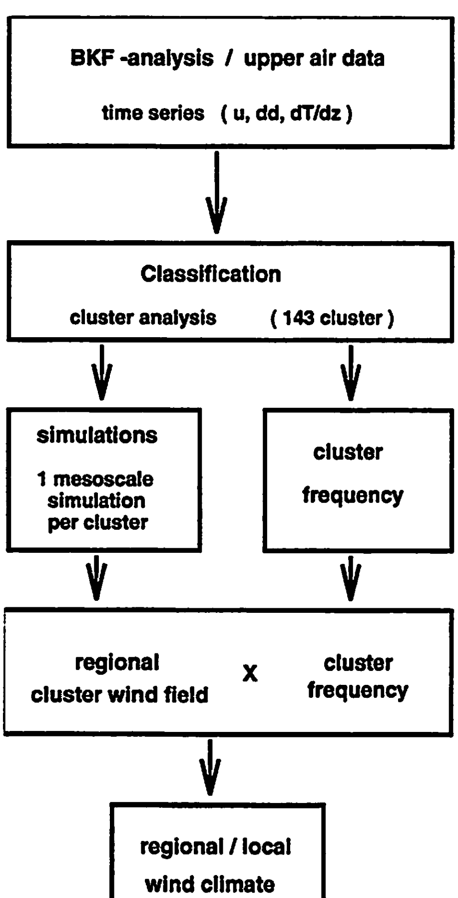


Fig. 1: Sketch of the statistical-dynamical downscaling approach

The solution domain (Fig. 2) covers a region of 80 x 87 km with flat terrain as well as the „Teutoburger Wald" area with hills up to 330 m a.m.s.l... The grid resolution in the horizontal is set to 1 x 1 km, and the vertical grid spacing increases from 20 m at the surface to 400 m at the upper boundary which is located at 3480 m. A total number of 80 x 87 x 19 grid points is used.

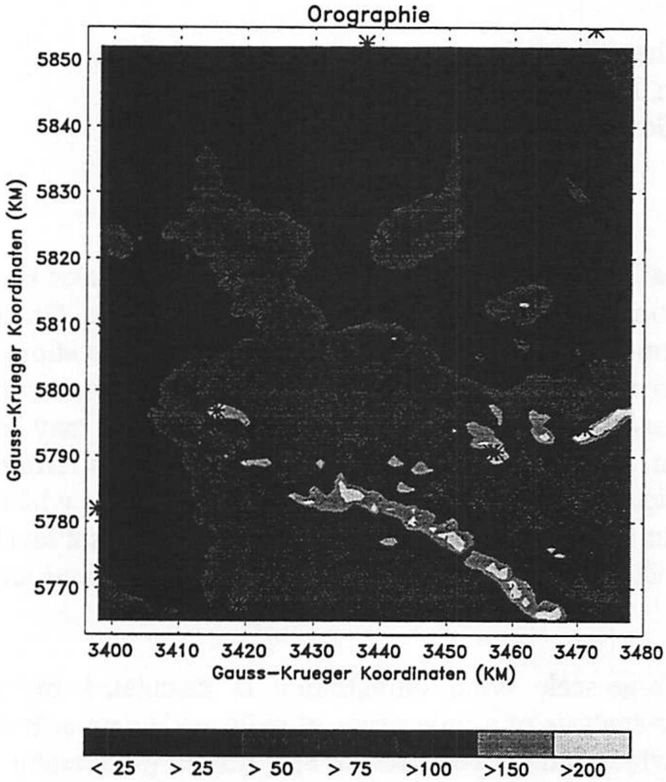


Fig. 2: Orography of the simulation area with locations of wind observations (squares) and wind turbines (stars).

The surface roughness distribution was described by 10 land-use classes with roughness lengths ranging from 2 mm for lakes to 2 m for the center of big cities according to Wieringa [4]. Forested areas were characterized by a roughness length of 1 m and a displacement height of 8 m. The hilly regions are almost completely forested whereas the flat terrain is characterized by farmland with bushes and smaller groups of trees. Large areas of moorland can be found in the north-eastern part.

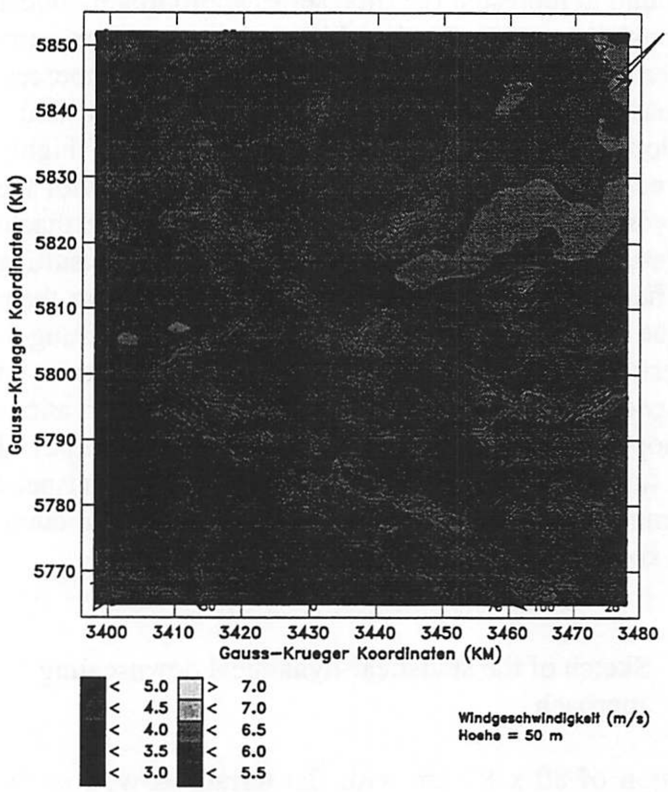


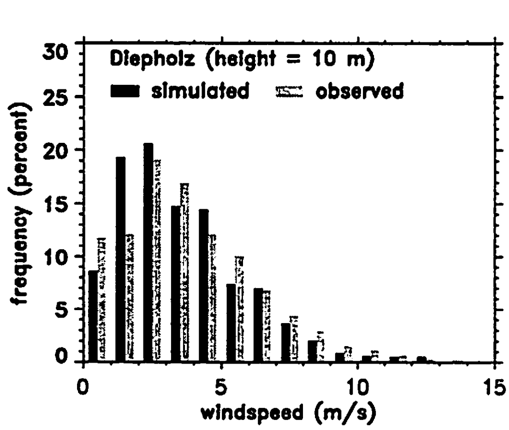
Fig. 3: Regional distribution of wind speed at 50 m height.

The mean wind field at 50 m height indicates that regions with values below 5 m/s coincide almost all with forested areas and bigger cities. The retardation effect implied by roughness length and displacement height dominates the orographically induced speed-up over the relatively low and gentle hills. Test simulations with equal roughness length overall and with/without a displacement height for forests indicate that this is the fact below about 100 m height on top of the hills.

The average windspeed and energy flux density observed at the synoptic stations and WMEP stations (a special german Wind Measuring and Evaluation Program for wind energy assessment) at 10 m height and calculated for the same height and the respective model grid are listed in Table 1. The agreement between observed and simulated windspeed values at the synoptic stations is good whereas the energy flux density shows differences up to about 20 percent. The WMEP stations reported from 1991 to 1993. This different time period and to some extend sheltering effects may have caused less agreement with the simulated data than is the case for the long-term synoptic data. The energy flux density was calculated for each cluster wind field because this parameter is more suitable for comparing the power of the wind at different locations than the mean windspeed as it takes into account the nonlinear relationship between windspeed and wind energy.

Table I: Mean wind speeds and energy flux densities at weather stations and WMEP observations (o) compared to simulated data (s). The coordinates refer to Fig. 2.

	coordinates x / y	u (m/s) o	E (W/qm) o	u (m/s) s	E (W/qm) s
Diepholz	3455 / 5828	3.8	89	3.6	70
Hopsten	3401 / 5801	4.1	99	4.1	100
Greven	3410 / 5778	3.7	74	3.6	76
Osnabr.	3435 / 5791	3.2	42	3.0	63
WMEP 1	3452 / 5831	3.5	70	4.0	100
WMEP 2	3436 / 5828	3.4	74	3.6	75
WMEP 3	3458 / 5809	2.9	45	3.5	75



A comparison of the simulated and observed frequency distributions of windspeed and -direction is shown in Fig. 4 for the weather station Diepholz (coordinates 3455/5828 in Fig. 2) which is representative for all stations. There are relatively large differences at low windspeeds and an overrepresentation of southwesterly winddirections.

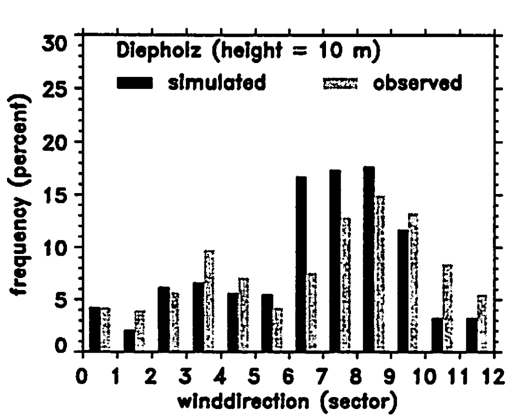


Fig. 4: Observed and simulated frequency distributions of windspeed and -direction at the weather station Diepholz

The power output of wind turbines is assumed to be more suitable for a comparison with model output because the area of immediate influence on the wind characteristic at hub height becomes greater with increasing tower height. Hub height of the wind turbines considered in this study vary between 30 and 41 m. Differences between actual and calculated power output reach up to 50 percent (Fig. 5). A detailed error analysis is not given here but it should be mentioned that there is obviously no bias in the calculated wind climatologies.

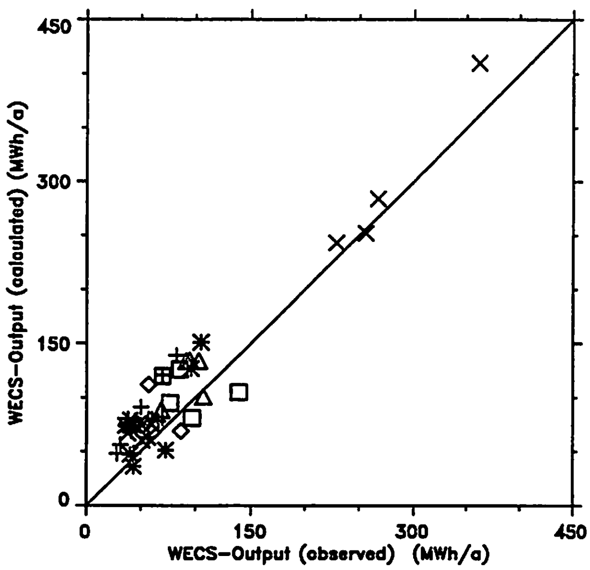


Fig. 5: Observed and simulated wind turbine power output. Different symbols refer to different types of wind turbines.

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Wind Resource Estimation in South Africa

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1. Introduction

Garrad Hassan is an independent wind consultancy which, since 1984, has undertaken assignments in more than 30 countries on 5 continents. Clients include all major manufacturers and most major developers world-wide, financial institutions, the European Commission and various multilateral and bilateral development agencies. The Company has a Memorandum of Understanding with Lloyds Register.

This paper outlines the method and results of recent computational wind flow modelling undertaken for the Eastern Cape Province (ECP) of South Africa within the context of "Renewable Energy Sources for Rural Electrification in South Africa", an EC projecfrom 1997-1999. The project is 50% funded by Directorate General XVII (Energy) of the European Commission in the frame of the JOULE-THERMIE programme of RTD and 50% co-funded by CSIR Aerotek of South Africa.

2. Method

The approach used may be broken down into the following stages:

- research physical geography
- research wind climatology
- determine wind data availability and quality
- check and pre-process wind data
- choose domains
- run meso-scale model
- check and combine domain results
- validate (long term)

2.1 Physical Geography

ECP extends over an area of some 170,000 km^2 and is thus about four times as large as Denmark. Elevation ranges from sea level to about 3,500 m and latitude from about 30-35° S. The principal physical features of the province, as shown in Figure 1, are:

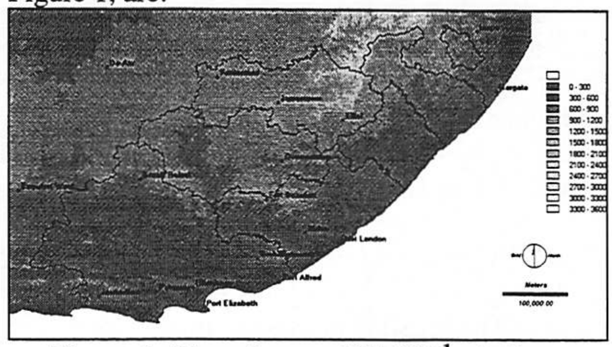

Figure 1: Elevation and SAWB[1] stations

- a long coastline with the Indian Ocean
- a relatively low-lying coastal plain
- the "great escarpment" 100-200 km inland
- the Drakensberg mountains in the north-east

2.2 Wind Climatology

2.2.1 Synoptic winds

A good knowledge of the synoptic-scale weather system variations over a region is essential before the wind resource mapping of that region can be attempted. Considerable effort was made to source reliable descriptions and analyses of the synoptic weather systems over ECP. The following text summarises information contained in references [1] to [9].

South Africa lies almost entirely within the subtropical high pressure belt, which is located at a latitude of approximately 30°S, and is skirted to the south by the circumpolar westerly air stream. Consequently, the country is largely under the influence of an upper air westerly air flow. Low level perturbations of this, which cause the weather seen in the atmospheric boundary layer, are due to successions of depressions, troughs and high pressure systems which move along the coast or across the interior from the west.

[1] South African Weather Bureau

The surface temperatures of the seas play an important rôle in conditioning most of the air masses around South Africa. Considerable temperature differences exist between the warm Mozambique and Agulhas currents of the east and south seaboards, and the cold Benguella current and upwelling of cold waters under the influence of south-easterly trade winds to the west.

The "coastal low" is the dominant synoptic system. It has counterparts in South America and Australia, but is better defined in South Africa due to the escarpment that borders much of the coast. It is essentially a lee-side low, with its existence due, at least in part, to the interaction of synoptic flow at escarpment level (1500 m and more) and the sharp drop to sea level.

Typically, coastal lows form off the south-west and south coasts and proceed rapidly up the east coast. The passing of coastal lows is persistent throughout the year, though the time interval between any two can vary from less than 24 hours to more than a week. Most coastal lows are centred offshore within 100 km of the coast. Commonly, their passing is marked by a sharp transition from a strong, steady easterly wind, due to an ocean high to the south-east of ECP, to a more turbulent westerly wind, due to the coastal low.

Another important type of weather system in the ECP context is the "bud-off high". This is initially an eastward ridge of the dominant anti-cyclone[2] that exists over the Atlantic Ocean to the west of Africa. During winter, when this high pressure cell is at its farthest north, these bud-off highs appear over the interior of South Africa, ensuring that the west and south coasts experience continuing westerly winds. In summer, the dominant high pressure cell is farther south, and bud-off highs typically form off the south coast of Africa then proceed rapidly up the east coast. These bud-off highs are directly linked with the majority of precipitation over the eastern part of South Africa and are often associated with severe weather conditions. Once a bud-off high has proceeded up the east coast, it is usually associated with the establishment of a high pressure area over the north-east interior, which in turn is often associated with the formation of coastal lows in the south-west.

In summary, the predominant synoptic weather systems in South Africa are somewhat different for coastal and for interior regions. Coastal regions experience weather that is considerably more variable than that of the interior, which is dominated by large high pressure systems stabilised by the continental land mass, and may, if all other factors are similar, be expected to have a generally greater wind speed. The movement of coastal lows and bud-off highs along the coast generate winds that are parallel to the coastline, rather than simply from the east and west.

Moving away from the coast and into the interior, the change in pressure gradients between the small coastal synoptic low pressure systems to the larger and more stable inland high pressure systems tends to bend the isobars of the latter towards the coast. As a result, with reinforcement at some inland locations from the "Berg winds" described below, inland prevailing wind directions are largely perpendicular to the coast.

2.2.2 Local winds

The general wind regime determined by the synoptic weather systems can often be considerably modified and/or supplemented on a local scale by various combinations of topographical and thermal effects. The following is a list of such possible effects.

1. **Berg winds** - these are hot, dry mountain winds specific to South Africa. They occur when a combination of high pressure over the north-east interior and a low pressure off the south-west coast results in the cold, dry air mass which exists over the interior being forced over the escarpment and towards the coast. The sharp descent over the escarpment causes adiabatic warming of the dry air, resulting in Berg winds at lower levels. Such winds can last from hours to several days and blow mainly perpendicular to the coast.
2. **Land and sea breezes** - these occur when there is a sufficient temperature contrast between a large water mass and a large land mass. The land heats up during the day at a higher rate than the sea, setting up a convective circulation that transfers heat from land to sea and results in an onshore breeze.

[2] Being in the southern hemisphere, South African seasons are 6 months out of phase with those in Europe and the "Coriolis force" (due to the Earth's rotation and curvature) acts in the opposite direction so that low pressure systems circulate clockwise and high pressure systems circulate anti-clockwise.

The flow is reversed as the land cools during the night. This local thermal effect can be expected to occur throughout the coastal regions of ECP. It typically extends up to a few tens of kilometres inland and results in the overall wind speeds in coastal regions being increased slightly.

3. **Katabatic winds** - these occur when cold air over hill tops descends down the valley slopes, being replaced with warmer air rising from the valley floor. The cold air falls down the inside of the valley wall, then subsequently down the valley itself, creating a localised wind resource. Also known as mountain winds.
4. **Anabatic winds** - again associated with valleys, these winds typically form in the morning, when the valley is filled with a pool of heavy cold air. Solar warming of the air closest to the valley walls causes this air to rise, creating upslope, or anabatic, winds. Also known as valley winds.
5. **Orographic channelling** - this occurs when the local topography results in channelling of the wind in a valley, thus increasing the local wind resource. This is often combined with the formation of katabatic winds within the valley system.
6. **Topographic enhancement** - this occurs when the wind flow is forced over a hill, thus increasing the wind speed at the top of the hill compared to that lower down the hillside. The extent to which flow is forced over, rather than around, such features is determined by atmospheric stability.

Items 1 to 4 above are terrain-generated winds, while items 5 and 6 are terrain-modified.

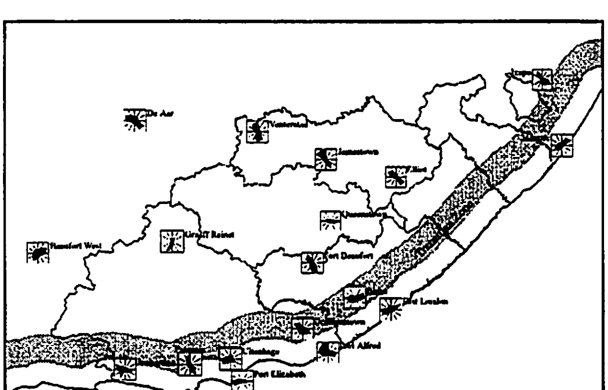

Figure 2: Wind distributions and transition zone

2.3 Meso-scale Models

Two general types of wind flow model have been used to date by Garrad Hassan in wind speed assessment. The first type are based on the Jackson-Hunt theory, which aims to satisfy the Navier-Stokes equations conserving both mass and momentum, and are usually called dynamic models. The second type aim to satisfy only the conservation of mass, and are usually called mass-consistent models.
Both types of model have been used in this study. WindMap[3], a modified version of the NOABL mass-consistent model, provides a potential flow solution that is considered to be reasonably representative of the wind flow above the inner layer. WAsP [10], a dynamic model, also produces a potential flow solution above the inner layer, which is typically about 20 m. Therefore, both models are expected to provide similar results well above ground level. However, the wind data used to calculate the regional speeds at 60 m height were recorded at only 10 m. Therefore, WAsP was used to "clean" each set of meteorological station data of local terrain and obstacle effects and to estimate the average wind speed over the 1 km square cell within which each meteorological station was located. This pre-processing, using WAsP, provided more representative wind data to be used as inputs to WindMap which was, in turn, used for the task of estimating the wind speeds on a regional scale.

2.4 Wind Data

Ideally, wind data from surface stations used to initialise a meso-scale model should have the following characteristics:

- as many datasets as manageable
- uniformly distributed throughout region
- longest possible recording period
- instrumentation, location, environs all constant
- all datasets concurrent
- all sites well exposed and sensors >10 m agl
- locations representative of domains
- instrumentation well maintained, calibrated and documented

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[3] WindMap™ is available from Michael Brower <mbrower@mediaone.net> Brower & Company, 154 Main Street, Andover, MA 01810 USA Phone: +1-978-749-9591 Fax: +1-978-749-9713 Web: http:\\www.browerco.com

2.4.1 Wind data availability and quality

Although a South Africa Wind Atlas had been published in 1995 [1], the ECP content thereof had been derived using WAsP in 1987 [2]. Although the author of both documents (Professor Roseanne Diab of the University of Natal) had used the best initialising wind data available at that time, this was not considered adequate in the present context.

Prof. Diab was contracted to review the present status of wind data and, on this basis, 18 datasets were eventually obtained from SAWB meteorological stations. All stations used the same model RM Young anemometers, which were located at 10 m agl. All data covered a similar period of time, which was of about four years duration. Consideration was given to length of recording period, data reliability and concurrence of data for each of the sites.

SAWB started a programme of upgrading their meteorological stations from early 1993. The data selected for the study were recorded after the stations had been upgraded and are considered to be more reliable than the earlier readings. The homogeneity of the datasets was also considered. The 18 datasets finally selected on the basis of the above criteria were from locations distributed throughout ECP and its bounding rectangle. The meteorological station locations are shown in Figures 1 and 2.

Data were first checked for errors by Prof. Diab and again by Garrad Hassan. However, the resulting quality controlled data still included local effects, particularly sheltering by nearby obstacles, that could cause them to be unrepresentative of the general winds for that locality.

2.4.2 Wind data pre-processing

Analysis of each of the datasets to remove, as far as possible, the effects of local obstacles and terrain, and then to estimate the generalised wind speed over the 1 km square WindMap "cell" in which the meteorological station is located, was undertaken through the use of the dynamic wind flow model WAsP.

The local obstacle details and other information were obtained through site visits. Ideally, experienced Garrad Hassan staff would have visited all the meteorological stations to obtain these data. However, the project budget did not allow for this approach due to the remoteness of many of the stations and poor transport facilities, so Garrad Hassan sub-contracted the work to two competent local parties identified during the first study visit. Both parties were provided with survey forms prepared by Garrad Hassan for each meteorological station to ensure that the necessary details were obtained.

The obstacle information gathered during these site visits was checked by careful calibration and inspection of 360° photographic panoramas taken at each site, and full obstacle description maps created. This process served to highlight several discrepancies between the actual locations of the meteorological stations and their locations given in SAWB literature. Queries to SAWB failed to resolve such discrepancies. This obviously reduces confidence in the historical homogeneity of the recorded data from these sites, and raises the possibility that wrong meteorological station locations had been used unknowingly with some of the datasets. However, it is considered that the error that this uncertainty is likely to introduce in the final results will be small, if not negligible. Any major discontinuity in the history of the data would have been highlighted during the checking process, and the few positional discrepancies that were highlighted were of several hundred metres distance, in which case averaging over a 1 km square area should considerably reduce the effect of any errors introduced in this way.

Nonetheless, as a result of all the aforementioned checks and screening procedures, only 11 of the 18 datasets originally selected were used to initialise WindMap.

2.5 Topography

The calculation of the regional winds requires a digital elevation model (DEM) of the terrain and, optionally, a map detailing surface roughness.

The data were input to WindMap across the region at a resolution of 1 km, with each cell representing the mean elevation and roughness length for the area covered by that cell. A cell size of 1 km square was used as a reasonable compromise between resolution and computing requirements. The full bounding rectangle covering ECP, plus the extra area needed to prevent edge effects in the wind speed mapping, measured 840 x 538 km.

The DEM, converted to horizontal 1 km square resolution from 400 m square resolution data, was obtained from CSIR and is shown in Figure 1. The surface roughness data were based on a reclassification of vegetation indices for the bounding rectangle, and was also supplied by CSIR. Originally, a dataset showing actual landcover had promised a more precise and up to date surface roughness classification. However, this dataset covered only the ECP area and did not extend beyond its borders. While the vegetation index could be used to fill in the roughness values outside ECP, this tended to introduce artificial discontinuities when one dataset gave way to the other. It was decided that the most acceptable route in establishing the roughness map was to reclass the vegetation index for the region. While perhaps not as detailed as the landcover information, it was of sufficient resolution and accuracy for the study.

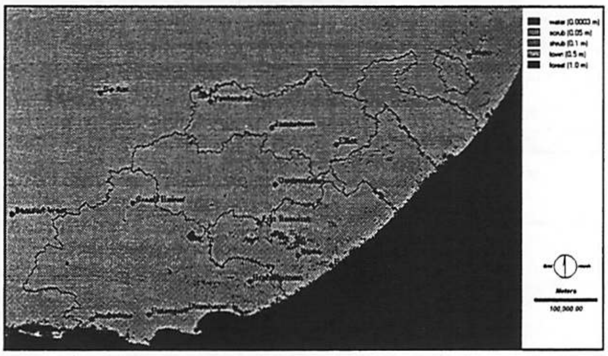

Figure 3: Surface roughness

In addition to these data, urban areas and water bodies, such as lakes and dams, were included. The final roughness map is presented in Figure 3.

2.6 Stability

The WindMap model uses three main parameters in determining a region's meteorological stability:

- surface layer height;
- stability ratio;
- Monin-Obukhov stability length, *L*.

It was initially intended to complete the WindMap modelling with all three parameters set for a neutral atmosphere. However, while such an approach may be suitable for a windy, temperate climate, it was decided that it was not necessarily appropriate for ECP, where wind speeds were expected to be lower and where the stabilising effect of the sea was going to be lost far inland. The following brief discussion of the three parameters is taken from [11] to [14] and based on Garrad Hassan's own experience.

2.6.1 Surface layer

The surface layer height is the height over which the wind speed is assumed to follow a logarithmic profile and is dependent on both surface roughness and stability length *L*. The logarithmic equation is generally not considered to be valid above a height of 100 to 200 m above the ground, even though surface properties and heat flux may well affect winds up to 2000 m height.

2.6.2 Stability ratio and stability length

The difference between the stability ratio and stability length is that the former functions throughout the model domain and strongly affects how much acceleration occurs over, rather than around, obstacles, whereas the latter affects only the logarithmic profile within the near-surface layer. There is a theoretical link between the two, though experience indicates that the link is not strong enough nor sufficiently well defined quantitatively to be "hard-wired" into the modelling process. Consequently, in WindMap, how these two parameters are set is left to the judgement of the user informed by available data.

For a flat, barren plain, typical of many areas being modelled in ECP, it is quite likely that during the day the atmosphere is thermally unstable and a stability ratio of 1 or more is appropriate. At night, the stability ratio would need to be reduced to well below 1 to reflect the fact that the land surface cools very rapidly, resulting in a strong reversal of the daytime heat flux and a stable atmosphere. In very hilly or mountainous terrain, values of stability ratio less than 0.5 are not justified, since the stable layer is quite shallow and does not extend to the height of the mountain tops. In relatively flat terrain, however, the hill tops may be entirely within the stable layer, in which case a value of stability ratio of 0.05 - 0.1 might be justified. This will result in much higher predicted acceleration over hills and ridges than the neutral value of 1.

Where wind shear data are available, the choice of stability length, *L*, may be established from the right combination of surface roughness and stability length that is both physically reasonable and gives the right shear exponent. If there is both daytime and night time shear data, then a large difference in the shear exponent reflecting the different stability conditions should be evident.

The choice of values for these parameters is also helped considerably through having upper air data for the region being modelled, particularly in mountainous regions with relief greater than 1000 m. However, good quality local wind shear data were not available and Garrad Hassan did not at that time hold upper air wind data for the region. It was therefore concluded that the following principles should be applied:

- For stability considerations, ECP could be divided into mountainous, coastal and plains regions.
- The surface layer height was set to 100 m for all regions.
- In regions where most of the terrain is mountainous, the relief is so much greater than the surface layer height so the stability ratio was set to 1 for neutral conditions. The stability length, *L*, was set to "slightly stable", as there will often be stable layers in the valleys and surrounding plateaux.
- Where most of the terrain is flat open plain, the stability ratio was set to 0.5, for slightly stable conditions, to account for the long periods of night-time stability compared to short periods of daytime instability. The stability length, *L*, was set to "slightly stable", as high surface shear values have been found in similar large plain areas in the USA [14].
- Where most of the terrain is coastal, both the stability ratio and the stability length were set to reflect neutral conditions, due mainly to the stabilising effect of the sea but also to the higher wind speeds that were expected to be encountered.

2.7 Regional Wind Modelling

The rectangle bounding the region being studied was divided into 17 overlapping smaller domains of 200 by 200 km. The geographical extent of each domain was established so as to achieve at least a 30 km overlap with neighbouring domains to avoid edge effects, and by the requirement that the initialising meteorological station was as close to the centre of the domain as possible.

These 17 domains consisted of 12 covering the inland areas, and 5 covering the coastal areas. As discussed previously, ECP experiences very distinct synoptic and localised winds over inland and coastal regions. An overlap zone starting 30 km from the coast and finishing 70 km from the coast was used to blend the coastal with the inland results. This is shown in Figure 2.

The individual domains, together with the initialising meteorological stations, are presented in Figures 4 and 5. Each domain included one meteorological station that was used to initialise the WindMap simulation. Where there were additional meteorological stations within a domain, the data were used to validate results from WindMap.

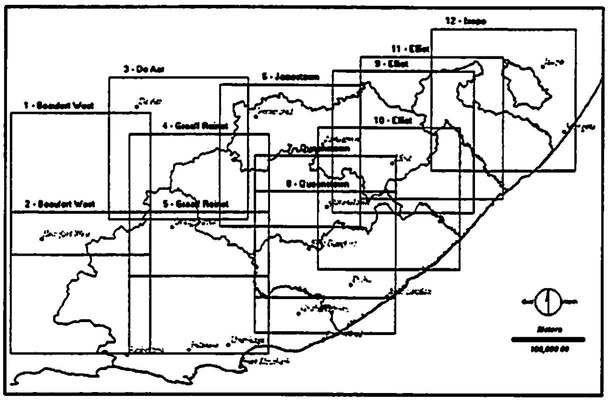

Figure 4: Inland domains

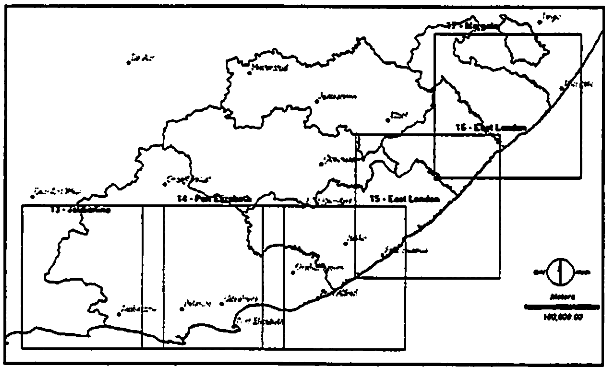

Figure 5: Coastal domains

Once the simulation for each domain was complete, the wind speed estimate for the cell in which the initialising meteorological station was located was compared with the mean wind speed of the initialising data. The result for the whole domain was then factored up or down according to the ratio of these two values. For example, the results for domain 1 gave an annual mean wind speed (amws) of 6.015 m/s at 60 m for the cell in which Beaufort West meteorological station was located. The initialising data for Beaufort West indicated an amws of 6.21 m/s. Therefore, the results were factored by 6.21/6.015 = 1.0324. This is an essential exercise as it removes the error that is brought about through tolerance values by WindMap when adjusting the initial wind field. The scaling factors required for the 17 domains ranged from 0.944 to 1.073

2.8 Combining Results

The initial ECP-wide result of the modelling was a patchwork of 17 overlapping 200 x 200 km wind speed estimates that did not match up perfectly with each other. Such a scenario was consistent with previous results of this approach to modelling and it had been intended from the outset to minimise these "overlap errors" at the end of the analysis.

2.8.1 Iterative scaling

The approach that was used to adjust the wind speeds in the overlapping areas to avoid discontinuities between adjacent domains is described in [15] and is as follows.

Each domain has overlaps with all of its neighbouring domains. For example, domain 1 overlaps with domains 2, 3, 4 and 5. Domain 1 therefore has 4 overlap areas. Each overlap area has two mean wind speeds - that associated with domain 1, and that associated with the overlapping domain. The approach used minimises the difference between these two mean wind speeds for each overlap area by calculating a scaling factor for each domain.

The algorithm that calculates these scaling factors is given as:

$$^{x}F(i) = 1 - 0.5\left[1 - \frac{^{(x-1)}V_n(i)}{^{(x-1)}V(i)}\right]$$

where :

x is the current iteration

$^{x}F(i)$ is the new factor to be applied to domain i

$V_n(i)$ is the average of the neighbouring mean wind speeds for overlaps with domain i

$V(i)$ is the average of domain i mean wind speeds in the areas of overlap

If the algorithm is to be applied to two overlapping areas with no other neighbours, the two factors to be applied to the two domains would be obtained after just one iteration. However, for more complex situations, such as the example given and those encountered in this study, several iterations are required for the factors to converge to a given tolerance level.

This technique does not eliminate any errors inherent in the analysis, but merely minimises their effect. Domains that were predicted to have low wind speeds in relation to their immediate neighbours will be increased slightly, while domains that were likewise high will be reduced slightly. Any domains that appear to be extreme will be affected the most. The method is effective if it is suspected that the wind data used to initialise the WindMap model are not truly representative of the wind climate for their locality. Had confidence in the data that were used to initialise the WindMap model been high enough, this stage could have been omitted altogether and differences between speed estimates for domains across the study area would have been undiminished. Such an approach would have been more acceptable with, among other factors, an increased number of initialising stations.

For the iteration process, a tolerance of 0.3 % was used, in line with previous work [15], to determine when convergence of the factors had been achieved. The factors for the 5 coastal domains converged in 10 iterations, and those for the 12 inland domains converged in 12 iterations. The final scaling factors for each domain are given below in Table 1.

Domain	Initialising station	Factor
1	Beaufort West	0.9935
2	Beaufort West	1.0062
3	De Aar	0.8130
4	Graaff Reinet	1.0146
5	Graaff Reinet	1.0664
6	Jamestown	0.9936
7	Queenstown	1.0063
8	Queenstown	0.9896
9	Elliot	1.0632
10	Elliot	1.0557
11	Elliot	1.0468
12	Ixopo	1.0558
13	Joubertina	1.2178
14	Port Elizabeth	0.8291
15	East London	1.0494
16	East London	1.0365
17	Margate	1.0810

Table 1: Final iterative scaling factors

The coastal runs showed the greater variation in scaling factors. This is not surprising as for such a large area more than 5 domains would have been necessary. The number of domains that could be used was limited by the 4 meteorological stations available to initialise the simulations. In particular, Joubertina lies deep in a valley and is sheltered from the coastal wind regime by a high mountain massif that stretches from 5 to 15 km from the coast. Also, the location of the anemometer immediately adjacent to a house and within about 50 m of tall trees is far from ideal. These factors most likely mean that Joubertina data do not satisfactorily represent the local coastal wind climate. Joubertina would not have been used in the modelling process for this reason had the lack of alternative meteorological stations for that area not necessitated it.

The inland domains have much less variation in the scaling factors. Ignoring domain 3, which was initialised from De Aar and which produces very high wind speed estimates when compared to its neighbours, the scaling factors had a range of 0.99 to 1.07. This would indicate that the inland runs showed very good agreement with each other, with the majority being increased slightly due to the influence of De Aar.

It is apparent that both Port Elizabeth and De Aar wind speeds are considerably higher than those of their neighbouring stations. There would appear to be only three possible reasons why these sites would not be representative of the local wind resource:

- calibration error;
- airflow enhancement over obstacles;
- very localised terrain enhancement.

Calibration error is extremely unlikely at either site as they are both main SAWB meteorological stations.

Airflow enhancement over obstacles is not an issue at Port Elizabeth as the anemometer site is well exposed. It may be possible at De Aar, where there is a small building in close proximity to the mast. However, such an effect should have been removed by the initial WAsP modelling.

Very localised topographical enhancement could conceivably occur at Port Elizabeth as it is situated at the end of Cape Recife, which is a large peninsula where wind flow off the sea may be rapidly accelerated over the land. In this case, the wind speed recorded at Port Elizabeth would be representative of only a limited area around Algoa Bay, Cape Recife, St. Francis Bay and Cape St. Francis and would extend only a few kilometres inland. This is probably the most likely explanation and would mean that the final wind speed map as presented above underpredicts the wind speeds of these areas by 15 to 20 %.

Very localised terrain enhancement is much harder to argue for De Aar. It is a very well exposed site, set in a large semi-arid plain. To the north-east there is a small elevated building, otherwise it is well exposed in all directions. It is situated at the south-west end of a long slender ridge and is elevated approximately 10 m to 15 m above the surrounding plain. It is possible that De Aar experiences very stable atmospheric conditions that would result in acceleration of flow from the plains over this small ridge to an extent that could not be removed by the WAsP modelling, which assumes neutrally stable conditions. However, it is extremely unlikely that any flow enhancement at De Aar would exceed a few tenths of a metre per second when compared to the wind speed over the plains.

It may be concluded, therefore, that the wind speeds shown in the regional wind speed map for the De Aar area are most likely underestimated by 10 to 15%, even though this is anomalous when compared to neighbouring results. The extent of this situation is very difficult to judge as there are no supporting datasets for well over 100 km in any direction.

The alternative possibility which is, perhaps, supported by the above discussion is that the data for Port Elizabeth and De Aar are representative, and data from the other stations are not due to siting or technical shortcomings. Only three of the 18 meteorological stations selected are known to be permanently staffed by SAWB staff - Port Elizabeth, De Aar and East London. The East London data are not so strikingly high compared with those of neighbouring stations as the data from Port Elizabeth and De Aar. Several possible reasons for under-recording of wind speeds can be envisaged, and most of these would be more likely to occur at unmanned stations.

2.8.2 Merging of domain overlaps

The process described above still does not provide perfect matching of adjacent domains on a cell by cell basis in the overlap areas. Cell by cell discrepancies are due not to errors in the initialising data, but to limitations of the modelling process itself. Thus, where one domain gives way to another, discontinuities can still be found. These were eliminated by a follow-on process of merging domains over the areas of overlap. This process, which is illustrated in Figure 6, is a linear interpolation between the overlap area boundaries as follows:

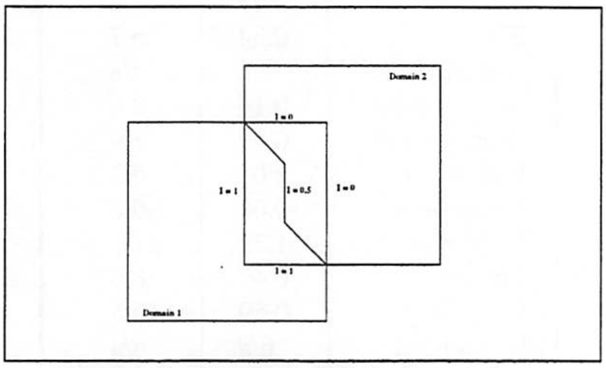

Figure 6: Merging of domain overlaps

A transition zone the size of the overlap area is created, with one equal to 1, fading across the overlap area to the far side where it is equal to 0. The wind speeds in the overlap area are then calculated by:

$$V = V_1 * i + V_2 * (1 - i)$$

where :

V is the calculated wind speed in the overlap area

V_1 is the wind speed from domain 1

V_2 is the wind speed from domain 2

i fades from 1 at domain 1, to 0 at domain 2, across the overlap area

2.8.3 Merging of coastal and inland zones

During the modelling process and subsequent merging of domains, coastal and inland zones were treated separately. With the wind maps for the two regions completed, they then had to be merged to form the final map for the whole of ECP. This was achieved in a manner very similar to the merging of adjacent domains above.

The boundary between the two zones and their respective wind climates was determined by examining the wind roses for all available meteorological stations as shown in Figure 2. Any meteorological station whose wind rose showed prevailing winds predominantly parallel to the coast was deemed to be in the coastal region, while those meteorological stations with wind roses that showed prevailing winds predominantly perpendicular to the coastline were deemed to be in the inland region. Uitenhage was the station farthest inland which displayed predominantly "coastal" winds, while Ixopo was the closest station to the coast to display "inland" winds. Patensie was classed as coastal as its northwest and southeast wind rose was considered to be due to its location in a valley of the same orientation rather than a function of its synoptic weather patterns. Both Grahamstown and Bisho Airport displayed wind roses that were neither clearly coastal nor inland. Thus, the coastal zone was judged to stretch up to 30 km inland, with the inland zone starting 70 km inland. A transition zone was created, with 70 km inland and more being assigned a value of 1, and 30 km inland and less being assigned a value of 0. The equation given in 2.8.3 was then used to merge the wind speed estimates in the overlap area, with V_1 being the inland wind speeds and V_2 being the coastal wind speeds. Although this was a rather simple way of defining the transition zone, it was considered the most practical approach for the limited number of suitably placed meteorological stations available.

3. Results

3.1 Regional Wind Map

The final map showing the estimated annual mean wind speeds at 60 m height for ECP is shown in Figure 7 below.

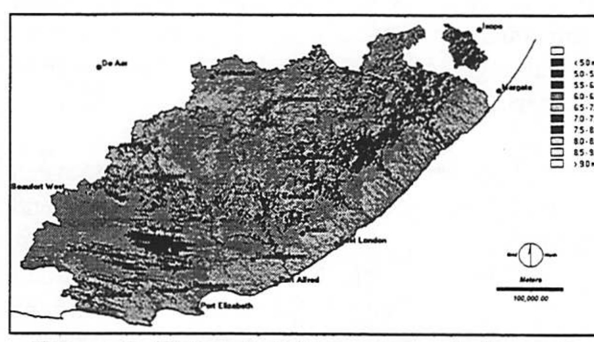

Figure 7: Estimated 60m mean wind speeds

The coastal areas show wind speeds of 6 to 7 m/s, with the area around Cape Recife (Port Elizabeth) west to Cape St. Francis being particularly windy. The coastal mountain range around Patensie and Uitenhage shows wind speeds in the range of 7 to 9 m/s. The "rippled" nature of the wind speeds between East London and Margate reflects the series of deep river valleys, perpendicular to the coast, that are found in this region. The model predicts low wind speeds in the sheltered river valleys and higher wind speeds for the intervening hills. The high wind speeds of the coast are reduced farther inland, with the coastal plain experiencing relatively low wind speeds of 5 to 6 m/s. The low wind speeds of the coastal plain exist as far as the great escarpment, which stretches from the northeast of Elliot, to the east of Queenstown, south of Fort Beaufort and then west northwest to Graaff Reinet and Beaufort West and marks a considerable change in elevation from the coastal plain to the high plateau of the northern interior. This change in elevation is reflected in the higher predicted wind speeds. The mountainous areas around Fort Beaufort, Graaff Reinet and Jamestown are reflected in the relatively high mean wind speeds of 7 to 9 m/s that are predicted in these areas.

In the following section, an attempt is made a evaluating the consistency of the final wind speed map. It must be stressed that consistency, and not accuracy, is being assessed as it is not possible to evaluate the accuracy of the map without extensive long-term field measurements. However, if the map is consistent, it will be accurate in representing the relative "windiness" of areas, thus enabling high wind speeds areas to be accurately identified.

3.2 Consistency of Regional Wind Map

The consistency of the map can be gauged, at least in part, by comparing the 60 m wind speeds, estimated by WAsP and averaged over the same 1 km square, for each meteorological station with the value given by the map. This comparison is summarised in Table 2..

It can be seen that there is good matching between the wind speed estimates for the regional map and the majority of the inland meteorological stations. It must be stressed, however, that the small number of available meteorological stations allows only limited comparison which is restricted further as only 5 stations were reserved for use as independent checks on the final predictions.

The largest differences between expected mean wind speeds and the mean wind speeds predicted by the wind speed map exist at the meteorological stations which have already been identified as being rather high or low in comparison with their neighbours - namely Port Elizabeth and De Aar, which both have high amws, and Joubertina, which has a low amws.

Station	Error [m/s]	Error [%]
Beaufort West	0.02	0.3
Bisho Airport	-0.77	-10.5
De Aar	-1.48	-18.7
East London	0.27	4.2
Elliot	0.34	5.7
Fort Beaufort	n/a	n/a
Graaff Reinet	0.16	2.6
Grahamstown	0.49	7.9
Ixopo	0.01	0.2
Jamestown	-0.04	-0.6
Joubertina	1.22	21.8
Margate	0.47	8.0
Patensie	0.59	10.6
Port Alfred	n/a	n/a
Port Elizabeth	-1.32	-17.1
Queenstown	-0.01	0.0
Uitenhage	0.80	13.7
Venterstad	0.66	11.9
mean of absolute values	**0.54**	**8.4**
standard deviation	**0.71**	**10.5**

Table 2: Comparison of regional wind map estimates with localised WAsP predictions

The method implemented in this study produces a conservative regional wind speed map, and is relatively transparent when it comes to identifying and quantifying likely sources of error. For example, it can be seen that the wind speeds in the Port Elizabeth area have been reduced by a factor of 0.83 in order to converge with neighbouring results. Although this is a rather small dataset for such a large area, thus making it hard to draw any firm conclusions, Table 2 nonetheless appears to indicate relatively good agreement with expected results.

It is also worthwhile comparing the consistency of the final wind map with the individual domain results as this provides an indication of how effective the post-processing methods have been. Table 3 shows the estimates of individual domain simulations where meteorological stations, other than the one used for initialisation, were available for checking purposes. As can be seen from the table, only domains 6,7,8,10,14 and 15 contained more than one meteorological station.

Station	Domain	Error [m/s]	Error [%]
Bisho	7	-1.11	-15.1
	8	-1.01	-13.7
	15	-0.86	-11.7
Elliot	7	0.19	3.2
Grahamstown	8	0.31	5.0
	15	0.36	5.8
Jamestown	10	-0.97	-14.6
Patensie	14	1.87	33.5
Queenstown	6	-0.37	-6.1
	10	-0.33	-5.4
Uitenhage	14	2.16	37.0
Venterstad	6	0.70	12.6
mean of absolute values		**0.85**	**13.6**
standard deviation		**1.04**	**17.0**

Table 3: Comparison of regional wind map estimates with individual domain estimates

Comparing results in Tables 2 and 3, it can be seen that the mean error of the final map is two-thirds that of the individual domains, suggesting that the post-processing of results has been very effective. It is also apparent from Table 3 that the largest errors originate from domain 14 which, together with domains 3 and 13, was affected the most by the iterative matching technique.

4. Concluding Remarks

The method and results for estimation of the ECP wind resource have been presented. This exercise has been just one task within a much broader commercial contract with a strictly limited budget and timescale and the approach used may therefore have been less sophisticated than comparable work undertaken in an academic or research context. It is nonetheless considered more than adequate for identification of the most promising areas for wind energy deployment in ECP which is the principal requirement in the broader context of the EC JOULE-THERMIE project.

The problems associated with the use of less than perfect surface station wind data to initialise the model have been discussed in detail. It should be borne in mind that these problems are countered by a significant advantage of this approach over the exclusive use of upper air data. As noted in the analysis of the wind climatology of ECP, localised winds due to thermal and other effects, in particular Berg winds, significantly affect the wind resource in ECP. Such effects are reflected in real surface station data to at least some degree.

It is also concluded that a thorough understanding of the wind climatology of any region to be modelled in advance of determining the fine detail of the method is of paramount importance.

5. Acknowledgements

The financial support of both the European Commission and CSIR Aerotek which has enabled this work to be undertaken is gratefully acknowledged.

Professor Roseanne Diab provided invaluable local meteorological knowledge and an effective interface with SAWB. Most of the climatological references were obtained from her personal library.

The meteorological station surveys were undertaken by Joanne Boule from the University of Natal (Durban) and Andries and Craig van der Linde of P E Technikon (Port Elizabeth).

CSIR Environmentek prepared and provided all of the topographical datasets used.

Finally, Michael Brower was consistently prompt and informative in his responses to queries about WindMap.

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GARRAD HASSAN

COMPARISON OF ALTERNATIVE GREENHOUSE GAS MITIGATION OPTIONS - WIND ENERGY

The IEA Greenhouse Gas R&D Programme (IEA GHG) was established in 1991 to evaluate technologies that can be used to reduce greenhouse gas emissions from the use of fossil fuels and identify targets for useful R&D. Studies to date have primarily focused on CO_2 abatement at power stations, forestry sequestration and methane abatement.

The IEA GHG Programme wishes to put these options in perspective with other ways of reducing/avoiding emissions. To this end, it is commissioning a series of studies on alternative mitigation options, with common technical and economic assumptions.

Garrad Hassan (GH), with project partners ECON, have been contracted by IEA GHG to conduct the first in this series of studies on options in the electricity generation sector. The option under consideration is wind power.

AIMS AND OBJECTIVES

Of all the emerging renewable energies, wind energy is currently commercially viable in many places, and is being deployed across the globe. Unit prices from some wind farms are approaching US$ 0.03/kWh.

Ultimately, the study will deliver cost/supply curves showing the cost of using wind energy to offset CO_2 for different quantities of CO_2 avoided. Pursuant to this end-goal, the world-wide costs and potential capacities of wind energy and the costs of and potential for avoiding GHG emissions require detailed assessment.

REGIONAL ASSESSMENTS

Europe, China, India and the United States have been selected for detailed assessment on the basis of their adequate wind resource, relatively developed wind energy markets and the combined scope provided for meaningful extrapolation to the rest of the world.

For each region, there are six main tasks:

- Identify suitable land areas
- Estimate wind energy potentials
- Assess electricity network effects
- Estimate wind energy costs and outputs
- Predict avoided emissions
- Generate cost-supply curves

Accompanying qualitative analyses include assessment of the influences of markets and regulation, future trends in the design and costs of wind turbines, and future advances in other technologies such as electricity storage.

GH is leading the project and is undertaking the wind energy-specific technical and economic aspects of the study. A significant aspect of the study is the use of a Geographical Information System (GIS). Wind regimes are modelled from meteorological, topographical and other data. These are then combined with other GIS data such as land cover, nature conservation areas and population, to provide estimates of areas suitable for wind power. Both onshore and offshore locations are included in the appraisal.

Costs are estimated as a function of wind speed, distance from the grid and location.

ECON is responsible for estimating levels of CO_2 mitigation and assessing market and regulatory effects. Econometric models will be used to simulate emission reductions at various costs and in different market environments.

GLOBAL ASSESSMENT

Results from these detailed assessments will then be extrapolated to give a cost/supply curve for all countries world-wide which are considered to be suitable for wind energy.

DURATION

September 1998 - June 1999

DELIVERABLES

- Final Report for members of the IEA GHG Programme.
- GIS model and datasets.

Subsequent to this, the IEA GHG Programme may issue a summary report of this work, which would be available world-wide.

PROJECT PARTICIPANT DETAILS

Client: IEA Greenhouse Gas R&D Programme.

The IEA GHG is a non-profit making international organisation, supported by fifteen countries worldwide, the European Commission and several industrial organisations. It operates under the terms of an 'Implementing Agreement' provided by the International Energy Agency.

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Project leader: Garrad Hassan and Partners Limited.

Garrad Hassan is a leading international consultancy providing independent expert advice on all technical, commercial, environmental and strategic aspects of wind energy and related technologies to a world-wide public and private sector client base. GH has its main office in Bristol (England), and other offices in Glasgow (Scotland), Wellington and Auckland (New Zealand), and Geesthacht (Germany)

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Project partner: ECON, Centre for Economic Analysis.

ECON is an independent research institute offering consulting services in macroeconomics, electricity, energy, environment, labour markets, industrial economics, development economics, transport, and construction. In recent years the energy, electricity, and environment groups have experienced the greatest growth. ECON has offices in Oslo and Stavanger (Norway), Stockholm (Sweden) and Paris (France).

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CRES

31st IEA Experts Meeting

STATE OF THE ART ON WIND RESOURCE ESTIMATION

October 29 - 30 1998, RISOE, Denmark

Mean-flow-field Simulations over Complex Terrain

by

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and
Dr. D.I. Douvikas, Wind Energy Sector

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CRES

INTRODUCTION

CRES is developing micro-siting tools for mean flow field estimation over complex terrain during the last four years. The work is carried out along two lines of different complexity. Along the first (MODEL1), an "engineering approach" is followed, resulting to a fast computational tool based on the viscous-inviscid interaction technique. A second approach (MODEL2), which is based on the numerical integration of the Navier-Stokes equations, is developed in parallel. Both models assume mechanical, only, turbulence and may take into account varying terrain roughness. The computational cost of the second approach is almost two orders of magnitude higher than the first. In addition, MODEL2 is very demanding in computer memory restricting, thus, its applicability to rather small surface grids (of the typical order of 100 X 100). On the other hand, MODEL1 includes less "physics" and cannot provide any reliable information regarding the evolution of atmospheric turbulence along the topography. Its prediction in strongly separated flow regions, when present, is also poor but somehow more accurate than that of a simple potential flow solver. At the present time MODEL1 consists the "working horse" of CRES on numerical wind potential estimation. Systematic application of the models has revealed much difficulty in estimating the inherent accuracy of the models, since overall accuracy is strongly dependent on external factors like the terrain description or even the reliability of the experimental data against which one compares. A short description of the two models is attempted below, while more details and application examples are provided in the two annexes that follow. A list of relevant publications is also included for further details.

MODEL1. 3-D Boundary Layer Solver

The method is based on the weak viscous - inviscid interaction technique. The inviscid "background flow" is provided by a three-dimensional full potential solver (a field method) which may account for density variation effects. The heart of the method is a 3-D integral viscous boundary layer solver developed specifically for atmospheric flows. The boundary layer is partitioned into an inner and an outer layer and the velocity profiles in the longitudinal direction are considered in a separate way. In the transverse flow direction the Mager's velocity distribution is adopted.

To derive the boundary layer equations the analysis of the mass and momentum equations is performed in their deficit form (inviscid-viscous) on a curvilinear coordinate system (u_1, u_2, u_3) which describes the topography. Considering the classical two layer partitioning of the flow (inner and outer layer), the resulting non-linear system of equations is consisted from the following equations:

- Integral momentum equation in u_1 (longitudinal) direction for the inner layer.
- Integral momentum equation in u_1 (longitudinal) direction for the outer layer.
- Integral momentum equation in u_2 (transversal) direction.
- Entrainment equation.
- Continuity equation.

The characteristic integral thicknesses which appear in the above equations are calculated analytically ftom the adopted velocity profile distibutions. The corresponding Jacobian matrix of the system is also calculated analytically. The non-linear system of PDEs is solved using the Runge-Kutta method. The integral formulation of the problem is suitable for the development of an effective computational tool which considerably reduces the computational cost.

MODEL2. 3-D Reynolds Averaged Navier-Stokes Solver

A fully 3-D Reynolds averaged Navier-Stokes code has been developed for atmospheric surface layer simulations. The governing equations are solved in their unsteady incompressible form using a conjugate gradient formulation for the pressure, along with fully implicit time discretization schemes. In its present

version the method is limited to the kinematic field (purely mechanical turbulence which is, anyway, a fair assumption for the higher wind speed regime), only, since no energy / temperature equation is involved. In certain aspects the method resembles the so called pressure correction schemes. Cell-centered volumes are used for the continuity equation while vertex centered volumes are used for the momentum equations. To allow for memory consuming fine resolution of the topography a multi-block implicit solver has been developed. Apart from the primitive variables which are stored on the complete grid, all the additional variables needed in the implicit part are stored on sub-blocks of desired, reduced, space. Turbulence is modeled by means of the k-ω two equations model with modified constants for atmospheric flows. Wall functions taking into account surface roughness provide the needed boundary conditions.
If detailed information on the turbulence structure is sought the standard Boussinesq approximation must be replaced by a non-linear constitutive law. Such a law is currently applied at a post-processing level for estimating the individual Reynolds stress entries from the computed strain tensor. Evidently the applied procedure is not 'exact' and presents a tendency for overestimating deviations from isotropy.

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2. Douvikas D., '3D Flow Computation Over Complex Terrain - An Integral Based Formulation', *CRES Report, 1997.*
3. Douvikas D., Chaviaropoulos P. '3D Viscous Computation Over Complex Terrain Using Integral Boundary Layer Method', *EWEC 1997, Dublin, Ireland October 1997.*
4. Douvikas D., Chaviaropoulos P. CRES' contribution to *12-Monthly Progress Report of 'Power Performance Assessment - JOR3-CT96-0114' project (Annex 3), 1997.*
5. Chaviaropoulos P., Douvikas D. 'Mean flow field Simulations over Complex Terrain using a 3-D Reynolds Averaged Navier-Stokes Solver', *ECCOMAS 98 Conference, September 7-11, 1998.*
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7. Douvikas D., Chaviaropoulos P. CRES' contribution to the *Final Report of 'Power Performance Assessment - JOR3-CT96-0114' project, 1998.*
8. Chaviaropoulos P., Douvikas D. 'Mean Wind Field Prediction over Complex Terrain in the presence of Wind Turbine(s)', *Abstract submitted to EWEC 1999, Nice, France.*
9. Douvikas D., Chaviaropoulos P. 'CRES' 3-D Boundary Layer Method for Complex Terrain Micrositing. Application Examples', *Abstract submitted to EWEC 1999, Nice, France.*

APPENDIX I

3-D Boundary Layer Solver

3-D ATMOSPHERIC BOUNDARY LAYER COMPUTATION USING INTEGRAL METHODS

- **INTERACTION TECHNIQUE BETWEEN POTENTIAL AND VISCOUS FLOW.**
- **THE GOVERNING FLOW FIELD EQUATIONS ARE DENELOPED IN THE CURVILINEAR COORDINATE SYTEM (u_1, u_2, u_3) WHICH DESCRIBES THE TERRAIN.**

VELOCITY PROFILES

- **LONGITUDINAL DIRECTION**

THE BOUNDARY LAYER IS PARTITIONED INTO AN INNER REGION (Inner Layer) AND AN OUTER REGION (Outer Layer).

$$u_s = \left(u_{e,s} - u_{e,s0}\right) + \frac{u_{tl}}{k} \ln\left(\frac{z}{z_0}\right) \qquad \text{(Inner Layer)}$$

$$u_s = \left(u_{e,s} - u_{e,s0}\right) + \frac{u_{tl}}{k} \ln\left(1 + \frac{\delta_l}{z_0}\right) + \frac{u_{tm}}{k} \ln\left(\frac{z}{\left(z_0 + \delta_l\right)}\right) \qquad \text{(Outer Layer)}$$

- **TRANSVERSE DIRECTION - Mager's VELOCITY PROFILE FAMILY**

$$u_N = \tan\varepsilon_w \, u_s \left(1 - \frac{z - z_0}{\delta}\right)^2$$

- **INTEGRATION OF THE DEFICIT FORM OF THE FLOW EQUATIONS IN THE DIRECTION u_3.**

NON LINEAR SYSTEM OF EQUATIONS

- **INTEGRAL MOMENTUM EQUATION IN u_1 DIRECTION FOR THE INNER LAYER.**
- **INTEGRAL MOMENTUM EQUATION IN u_1 DIRECTION FOR THE OUTER LAYER.**
- **INTEGRAL MOMENTUM EQUATION IN u_2 DIRECTION.**
- **ENTRAINMENT EQUATION.**

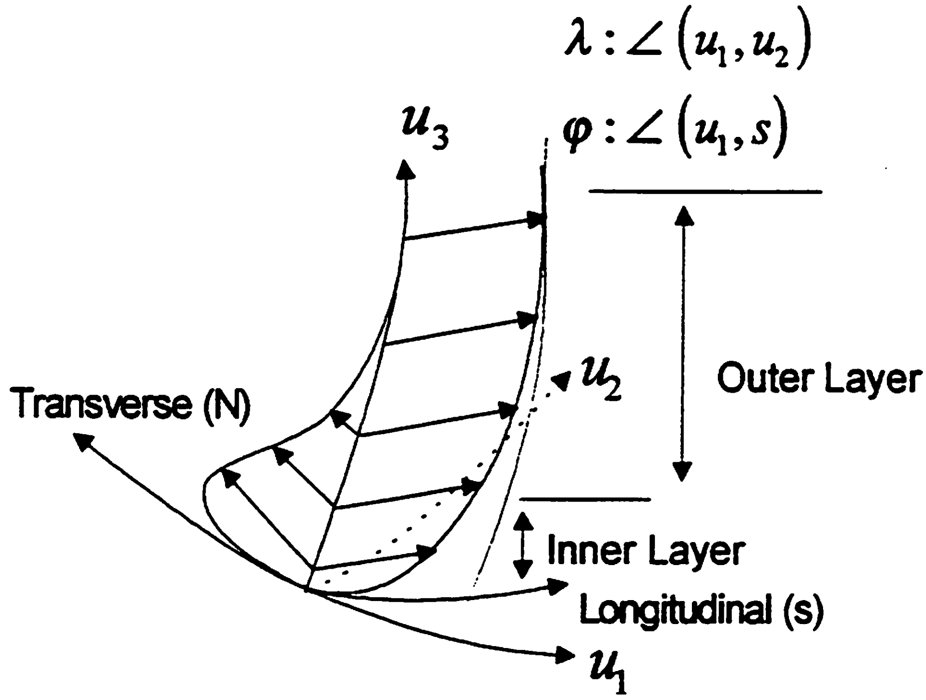
- **GENERALIZED FORM OF THE EQUATIONS**

$$\frac{1}{\sqrt{g_{11}}}\frac{\partial \underline{F}(\underline{x})}{\partial u_1}+\frac{1}{\sqrt{g_{22}}}\frac{\partial \underline{Q}(\underline{x})}{\partial u_2}+\underline{R}(\underline{x})=0$$

VECTOR OF UNKNOWNS $\underline{x}=\begin{pmatrix}\delta_I\\ u_{tI}\\ u_{tm}\\ \tan\varepsilon_w\end{pmatrix}$

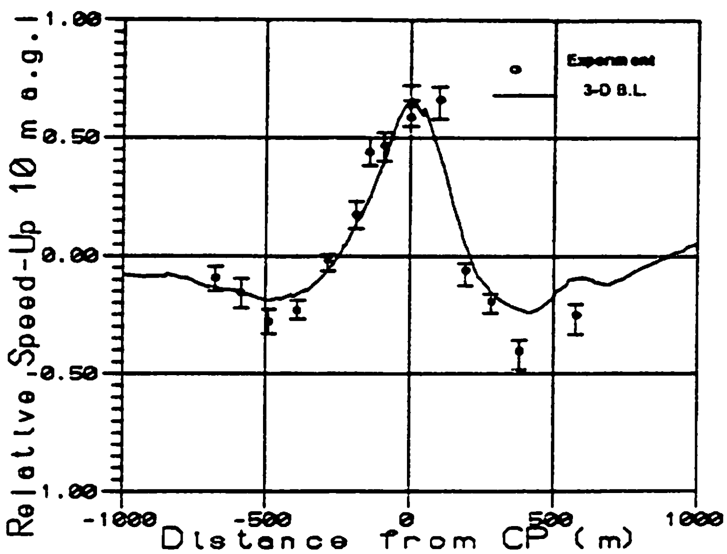
- **THE NON LINEAR SYTEM OF EQUATIONS IS SOLVED USING 2^{nd} ORDER Runge-Kutta METHOD.**

- **THE RESULTING CHARACTERISTIC INTEGRAL QUANTITIES AS WELL AS THE JACOBIAN OF THE NON LINEAR SYSTEM OF EQUATIONS ARE CALCULATED ANALYTICALLY FROM THE ADOPTED VELOCITY DISTRIBUTIONS.**

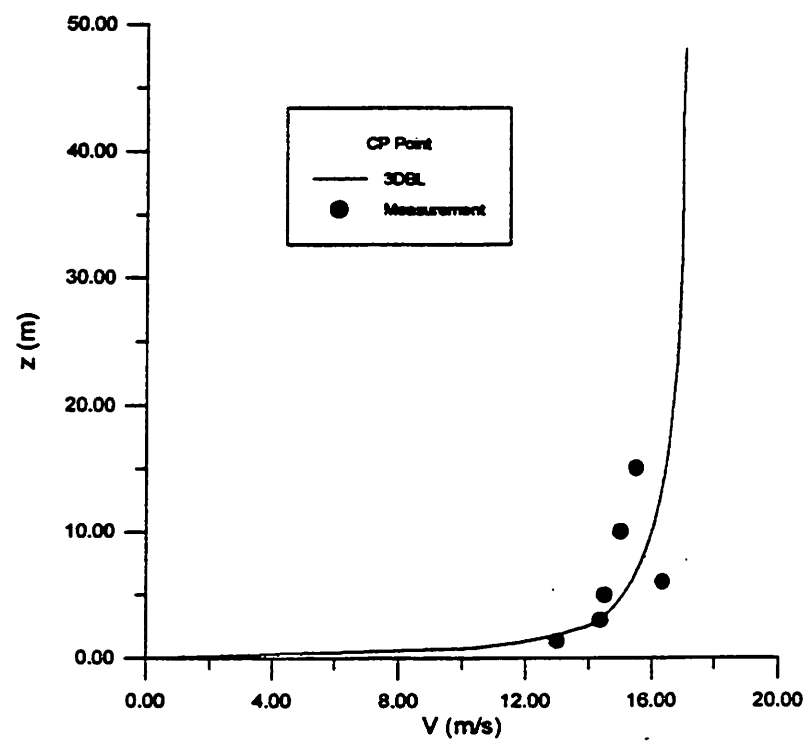


$\lambda : \angle(u_1, u_2)$
$\varphi : \angle(u_1, s)$
u_3
u_2
Outer Layer
Transverse (N)
Inner Layer
Longitudinal (s)
u_1

ASKERVEIN HILL

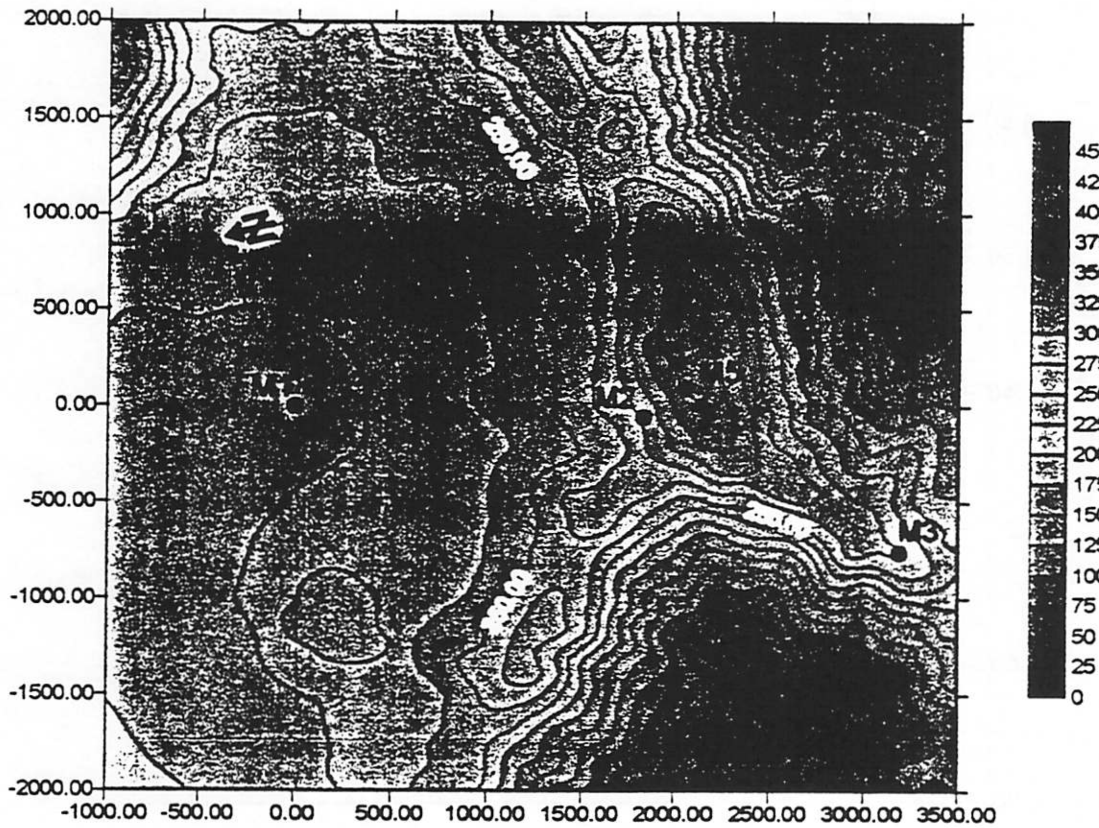


RELATIVE SPEED-UP AT 10 m a.g.l.

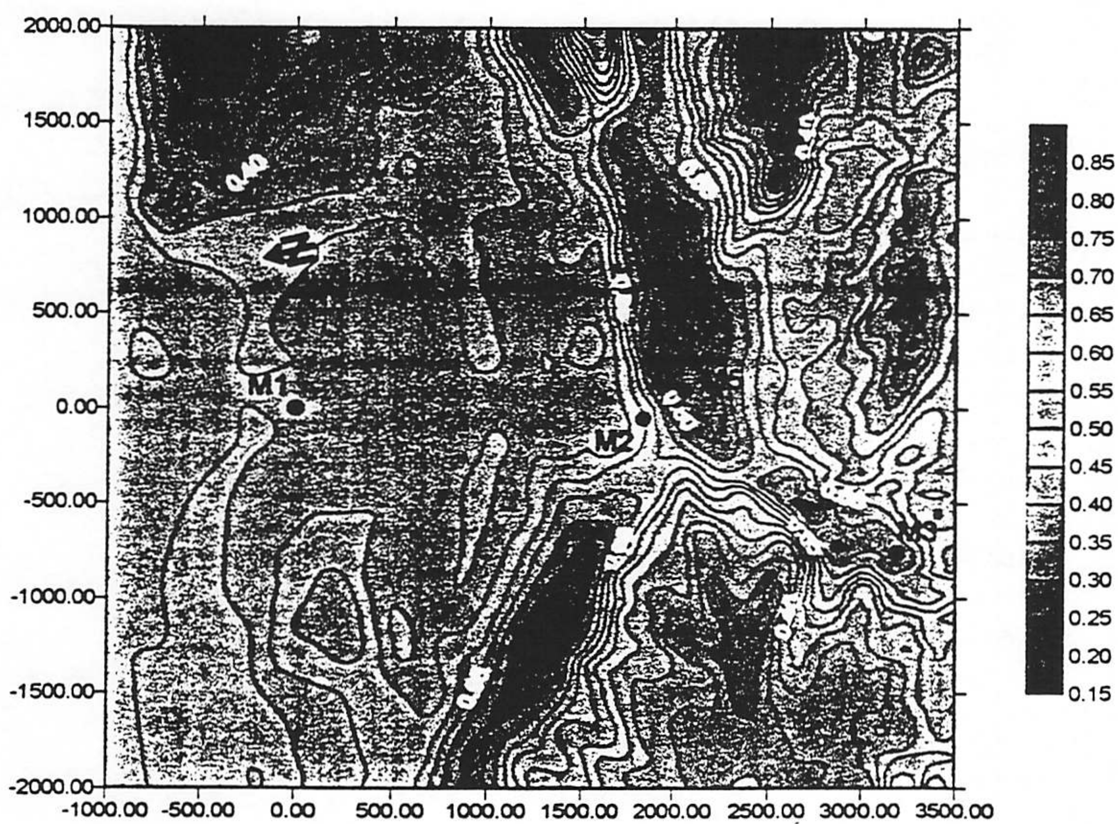


VELOCITY PROFILE AT CP POINT

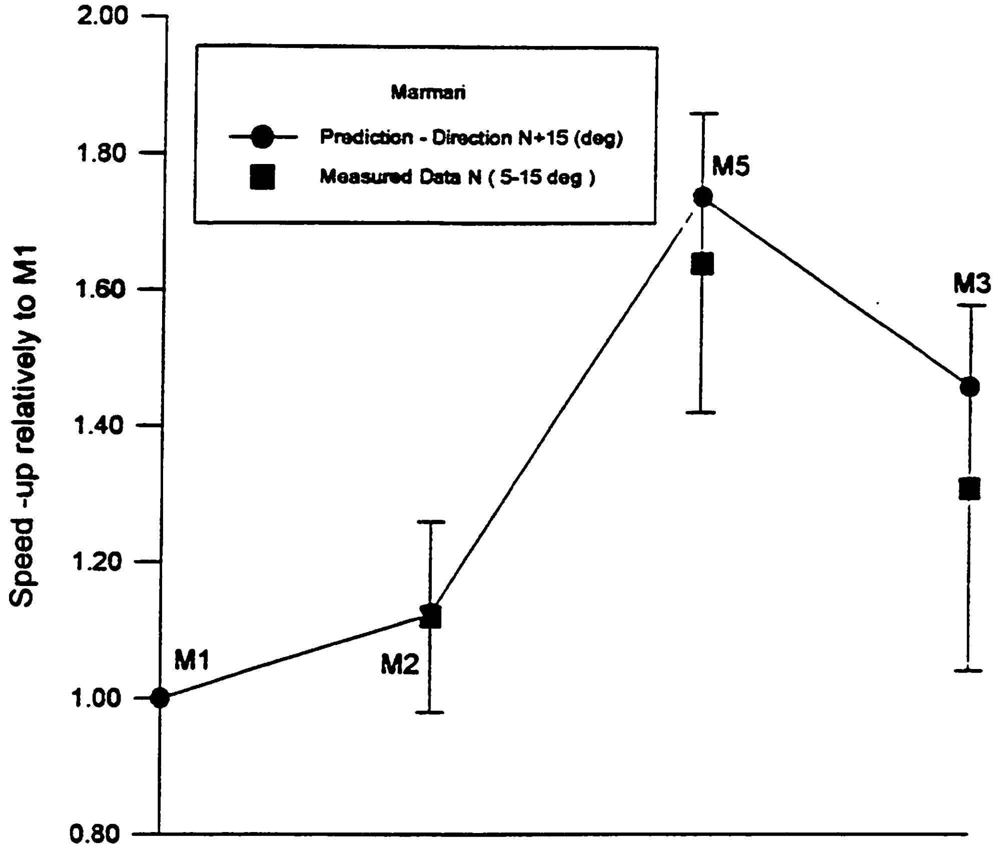
Marmari - 15^0 Wind Direction



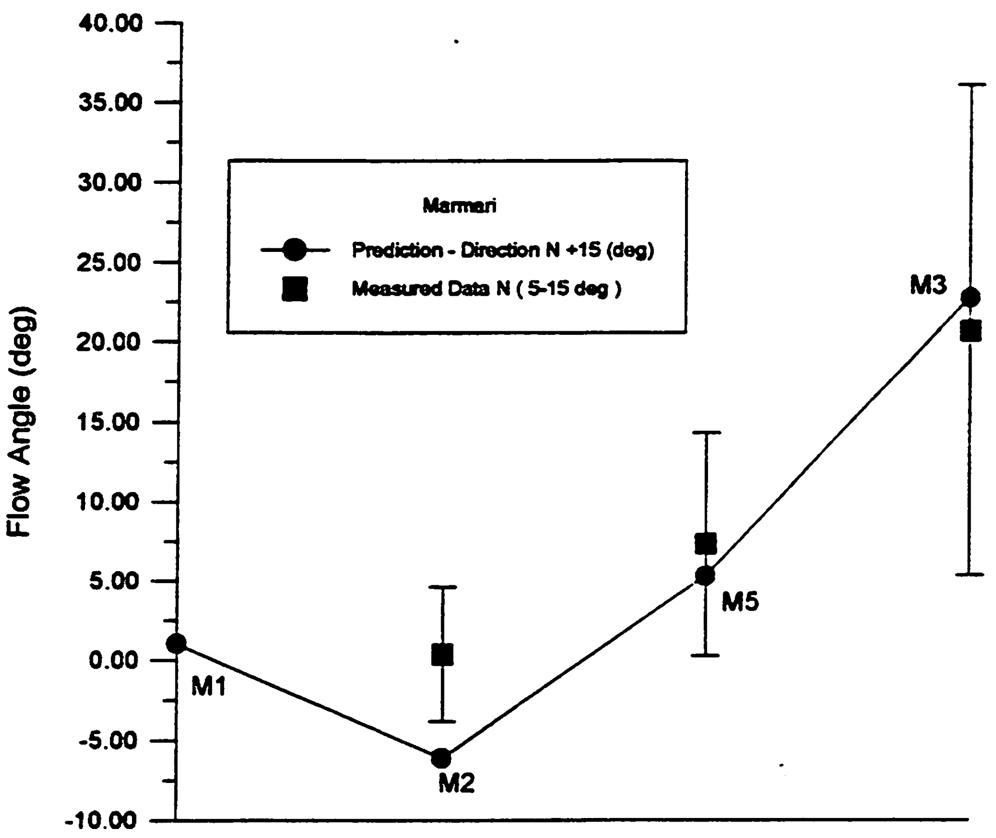
Terrain Contours



U Velocity Contours at 34 m

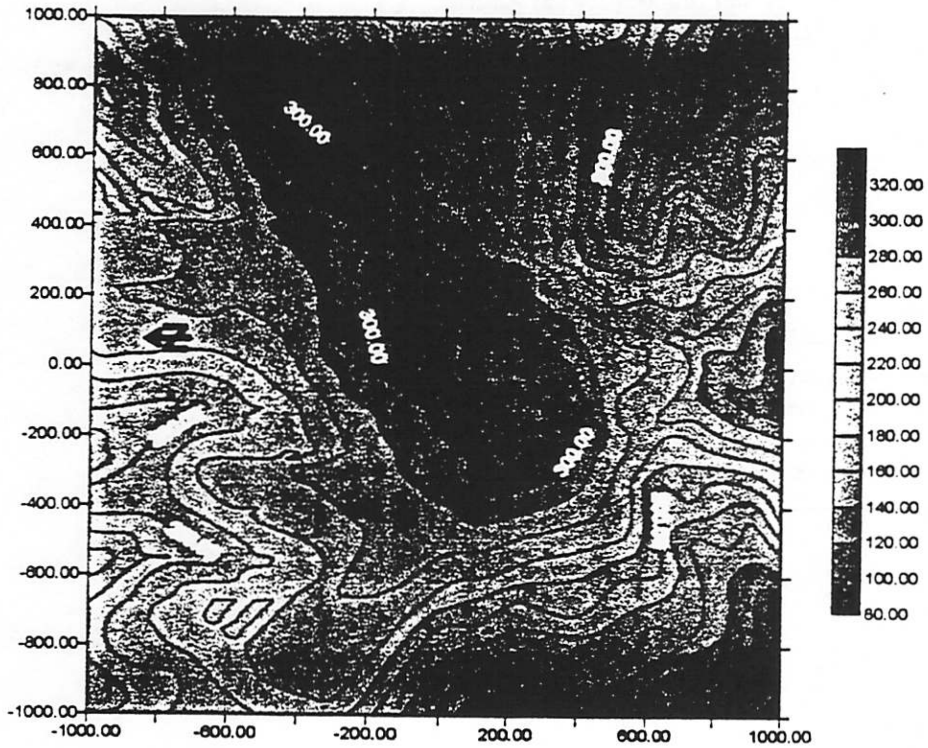


2.00
1.80
1.60
1.40
1.20
1.00
0.80
Speed -up relatively to M1
Marmari
Prediction - Direction N+15 (deg)
Measured Data N (5-15 deg)
M1
M2
M5
M3

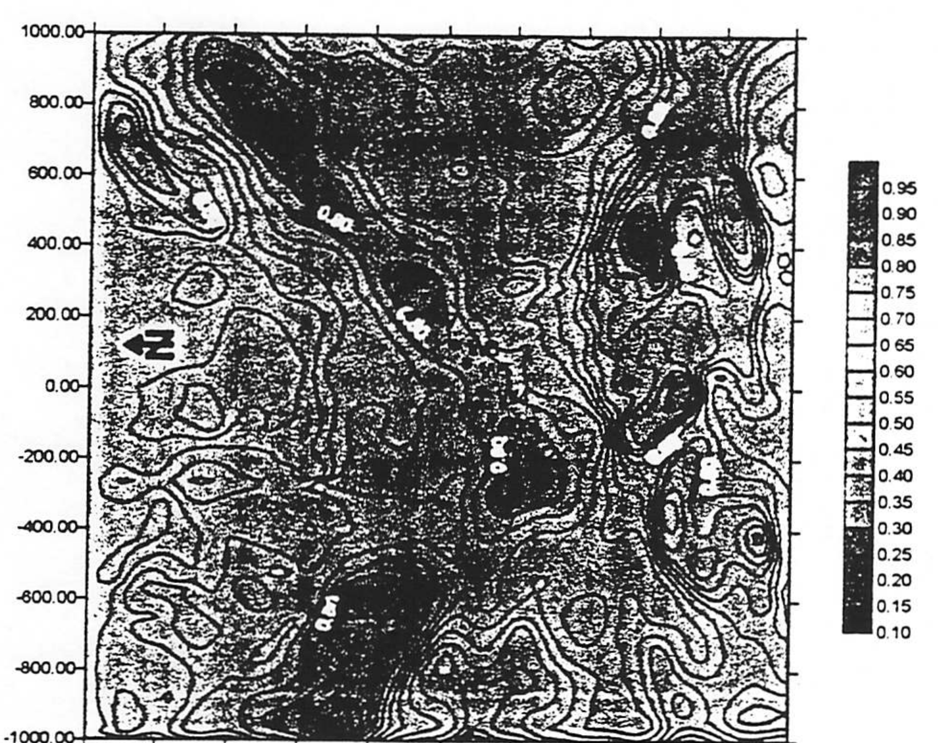


40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
Flow Angle (deg)
Marmari
Prediction - Direction N +15 (deg)
Measured Data N (5-15 deg)
M1
M2
M5
M3

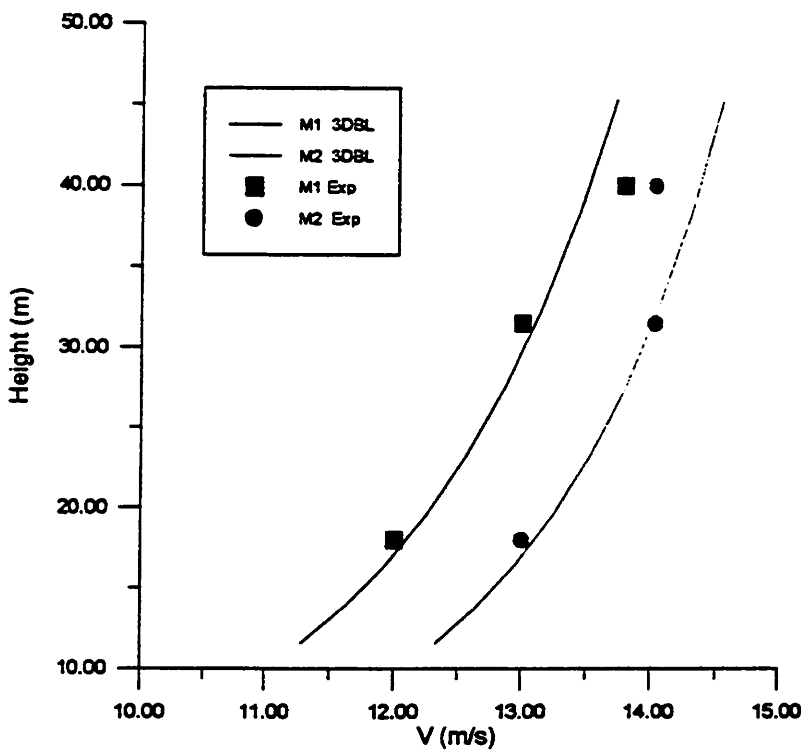
Andros - Topography Contours



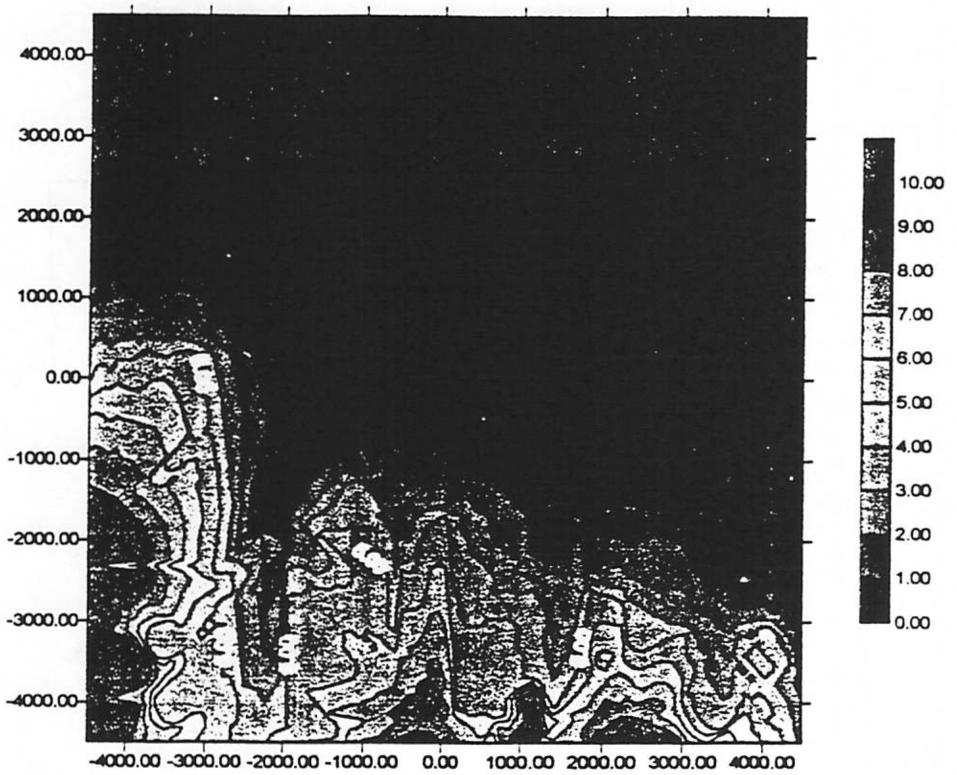
Iso u at 30 m



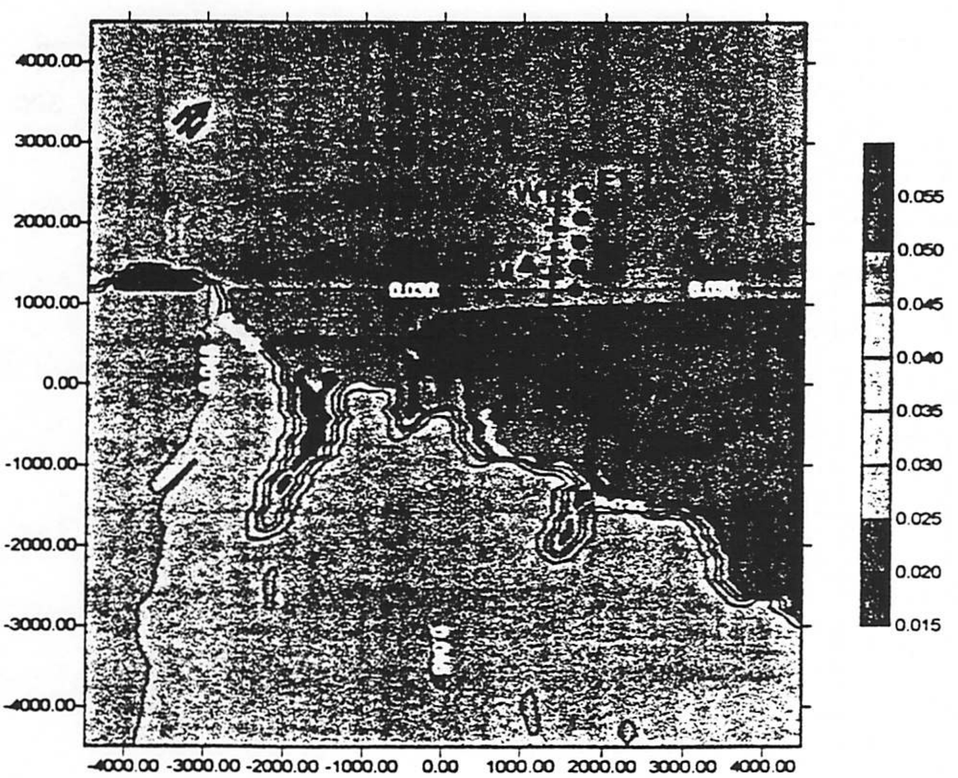
u velocity distributions for M1 and M2 locations at Andros.
Comparison between 3DBL Code Results and Experimental Data.



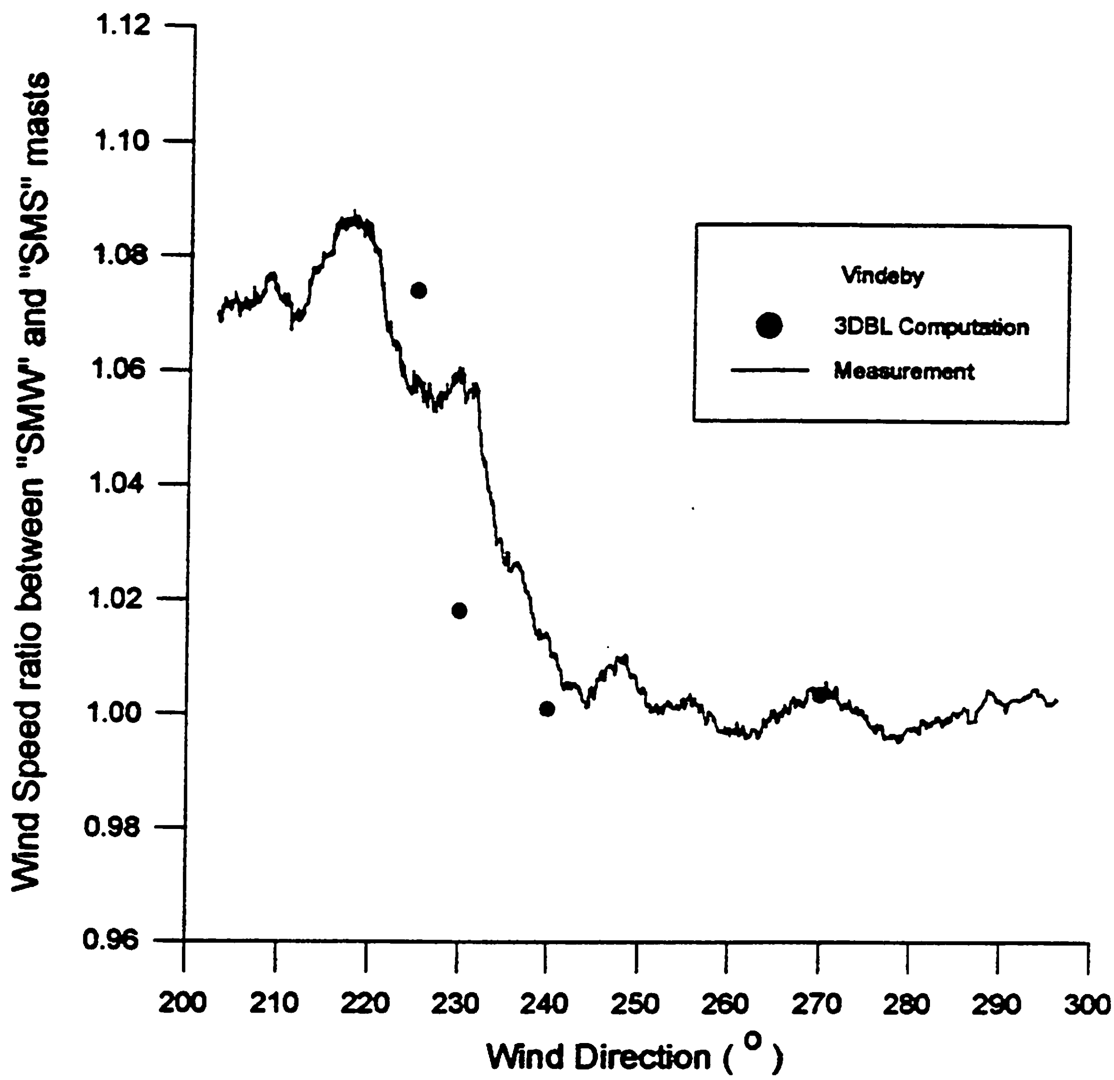
Vindeby - SW Wind Direction



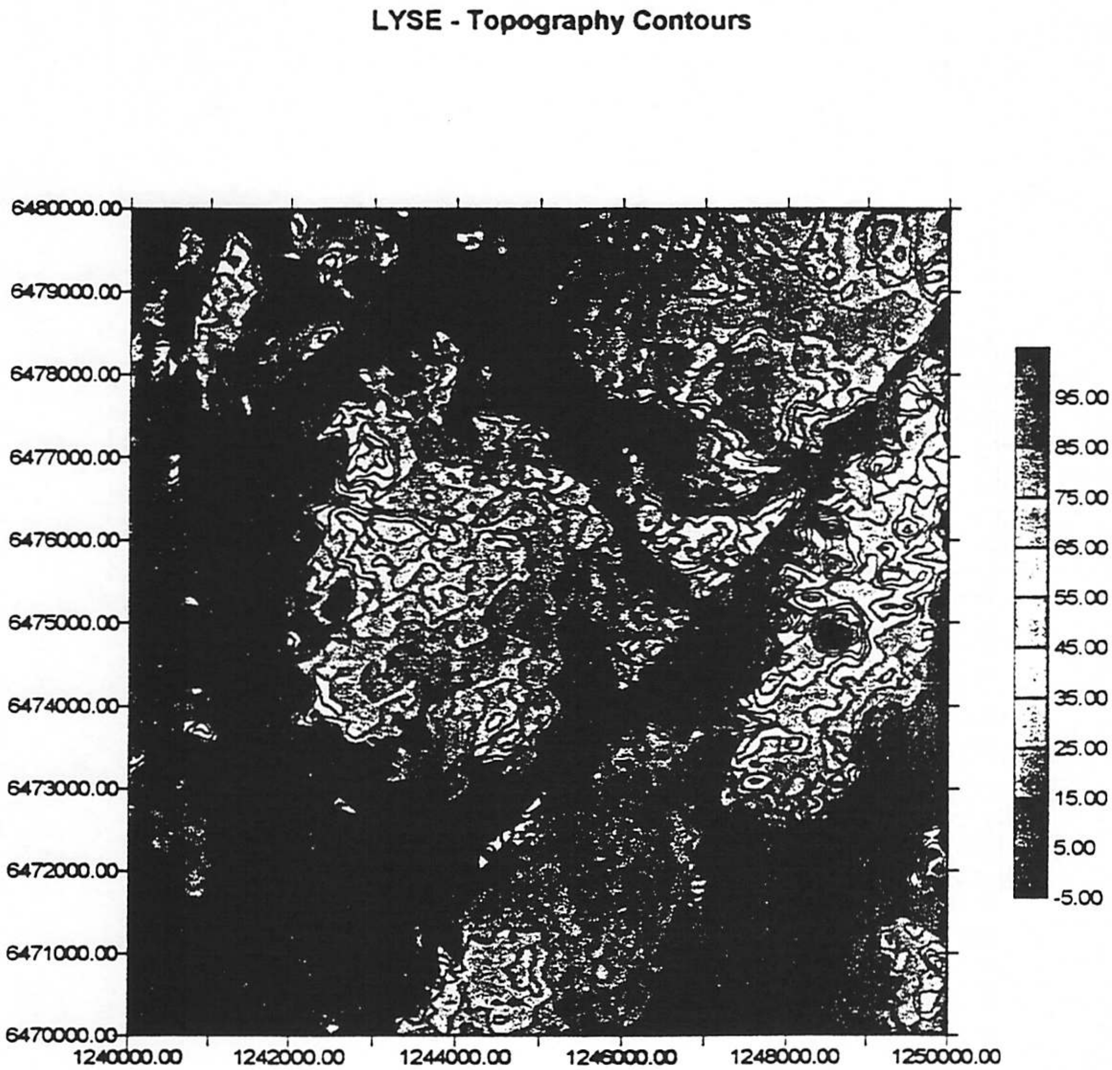
Terrain Contours



Friction Velocity Contours



Vindeby - Wind Speed ratio between two masts at 48m a.g.l.


LYSE - Topography Contours
6480000.00
6479000.00
6478000.00
6477000.00
6476000.00
6475000.00
6474000.00
6473000.00
6472000.00
6471000.00
6470000.00
1240000.00
1242000.00
1244000.00
1246000.00
1248000.00
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75.00
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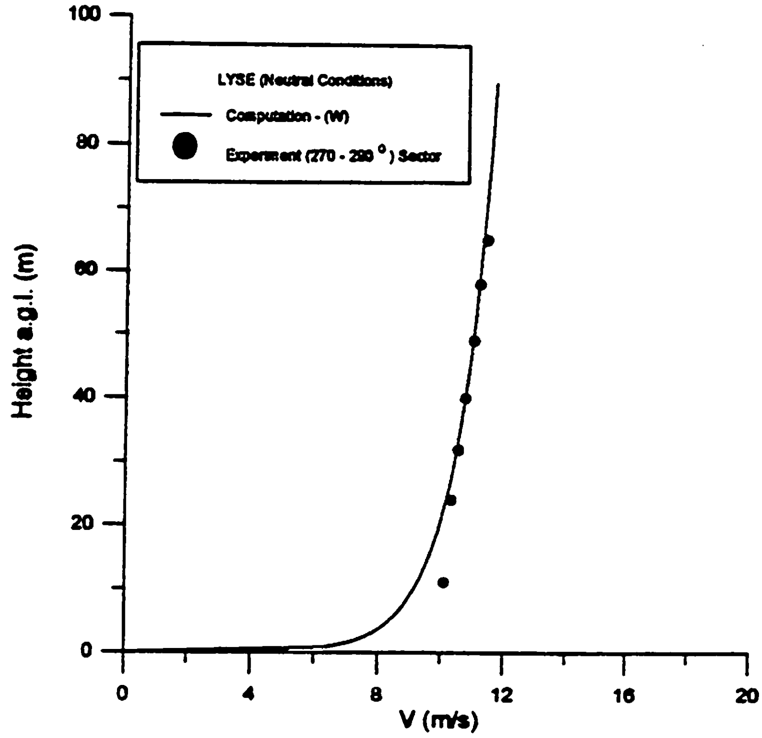
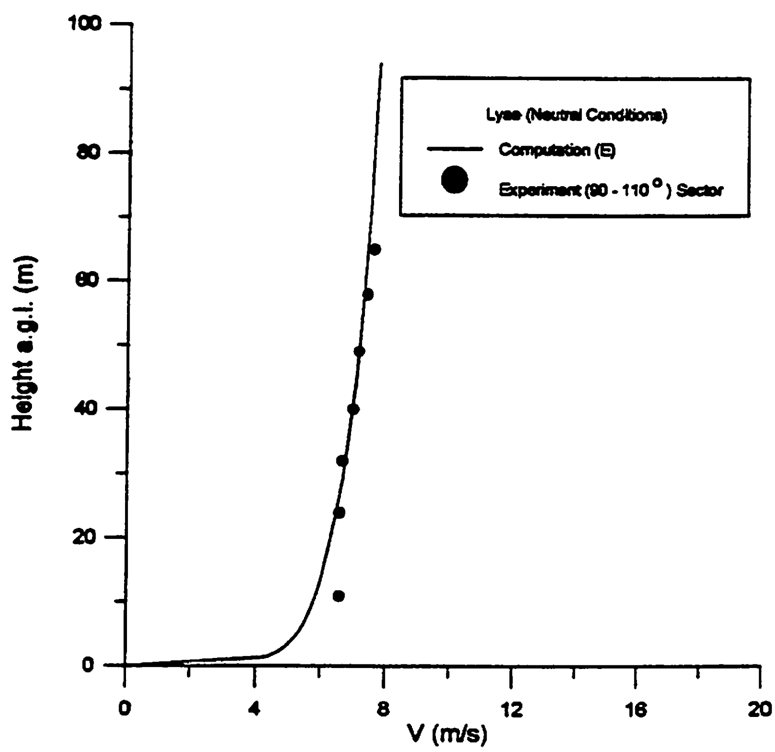
45.00
35.00
25.00
15.00
5.00
-5.00


LYSE (Neutral Conditions)
Computation - (W)
Experiment (270 - 290 °) Sector
Height a.g.l. (m)
V (m/s)
0
20
40
60
80
100
0
4
8
12
16
20


Lyse (Neutral Conditions)
Computation (E)
Experiment (90 - 110 °) Sector
Height a.g.l. (m)
V (m/s)
0
20
40
60
80
100
0
4
8
12
16
20

APPENDIX II

3-D Reynolds Averaged Navier-Stokes Solver

CRES

GOVERNING EQUATIONS

- **Incompressible Reynolds averaged N.S.**

$$\nabla \cdot \mathbf{V} = 0$$

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} - \frac{1}{\mathrm{Re}} \nabla \nu_T \cdot \nabla \mathbf{V}^T - \frac{1}{\mathrm{Re}} \nabla \cdot [(1 + \nu_T) \nabla \mathbf{V}] + \nabla p = 0$$

- **Turbulence closure is achieved using the standard k-ω model**

$$\frac{\partial k}{\partial t} + \mathbf{V}.\nabla k - \frac{1}{\mathrm{Re}} \nabla.[(1+\sigma^* \ \nu_T)\nabla k] = \frac{1}{\mathrm{Re}} P_k - \beta^* k\omega$$

$$\frac{\partial \omega}{\partial t} + \mathbf{V}.\nabla \omega - \frac{1}{\mathrm{Re}} \nabla.[(1+\sigma \ \nu_T)\nabla \omega] = \frac{1}{\mathrm{Re}} \alpha P_k \frac{\omega}{k} - \beta\omega^2$$

where

$$P_k = \frac{1}{2} \nu_T \, [\nabla \mathbf{V} + (\nabla \mathbf{V})^T]^2$$

$$\nu_T = \mathrm{Re} \frac{k}{\omega}$$

- **Wall functions**

$$u / u_T = \frac{1}{\kappa} \ln(z / z_0), \ k = \frac{u_T^2}{\sqrt{\beta^*}}, \ \omega = \frac{|u_T|}{\sqrt{\beta^*} \kappa z}$$

- **k-ω model constants**

$k / u_T^2 \cong 5.5 \quad \Rightarrow \quad \beta^* = 0.033$

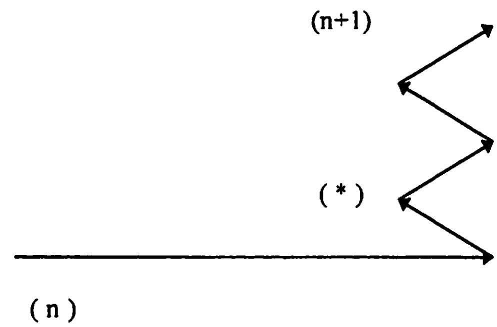
$\beta^* / \beta = 1.25$ Townsend, decaying turbulence

$\alpha = \beta / \beta^* - \sigma\kappa^2 / \sqrt{\beta^*}$ Compatibility condition

$\alpha=0.371$, $\beta=0.027$, $\beta^*=0.033$, $\sigma=1/2$ and $\sigma^*=1/2$.

NUMERICAL ASPECTS

• Linearization & time stepping



$$\nabla \cdot \mathbf{V}^{n+1} = 0$$

$$\frac{\mathbf{V}^{n+1} - \mathbf{V}^{n}}{\Delta t} + \mathbf{V}^{*} \cdot \nabla \mathbf{V}^{n+1} + \nabla p^{n+1} - \frac{1}{\mathrm{Re}} \nabla^{2} \mathbf{V}^{n+1} = 0$$

$$\mathbf{V}^{n+1} = \mathbf{V}^{*} + \delta \mathbf{V} \quad ; \quad p^{n+1} = p^{*} + \delta p$$

<u>momentum equation</u>

$$N(\delta \mathbf{V}) + \nabla(\delta p) = -\mathbf{R} \Leftrightarrow \delta \mathbf{V} = -N^{-1}\{\mathbf{R} + \nabla(\delta p)\}$$

with

$$N \equiv \{\frac{I}{\Delta t} + \mathbf{V}^{*} \cdot \nabla - \frac{1}{\mathrm{Re}} \nabla^{2}\} \ ;$$

$$\mathbf{R} \equiv \{\frac{\mathbf{V}^{*} - \mathbf{V}^{n}}{\Delta t} + \mathbf{V}^{*} \cdot \nabla \mathbf{V}^{*} + \nabla p^{*} - \frac{1}{\mathrm{Re}} \nabla^{2} \mathbf{V}^{*}\}$$

<u>continuity equation</u>

$$\nabla \cdot \delta \mathbf{V} + \nabla \cdot \mathbf{V}^{*} = 0 \Leftrightarrow \nabla \cdot \{N^{-1} \nabla(\delta p)\} = \nabla \cdot \{\mathbf{V}^{*} - N^{-1}\mathbf{R}\}$$

NUMERICAL INTEGRATION ALGORITHM

STEP0 : Initialize (*) quantities by (n) quantities.

STEP1 : Compute [N] and factorize it to obtain [M], (incomplete LU decomposition, MSIP).

STEP2 : Compute an intermediate velocity field through

$$\bar{\mathbf{V}} = \mathbf{V}^{*} - M^{-1}\mathbf{R}$$

STEP3 : Solve the pressure correction equation for δp using the restarting GMRES(m) algorithm and update the pressure field

$$\nabla \cdot M^{-1}\nabla(\delta p) = \nabla \cdot \bar{\mathbf{V}}$$

$$p^{n+1} = p^{*} + \delta p$$

STEP4 : Update the velocity field through

$$\mathbf{V}^{n+1} = \mathbf{V}^{*} + \delta\mathbf{V} = \bar{\mathbf{V}} - M^{-1}\nabla(\delta p)$$

STEP5 : Replace current (n+1) values by (*) and go to STEP1. Iterate until the unsteady momentum and the continuity residuals satisfy the convergence criterion.

STEP6 : If convergence is achieved proceed to the next time level starting from STEP 0.

RESULTS

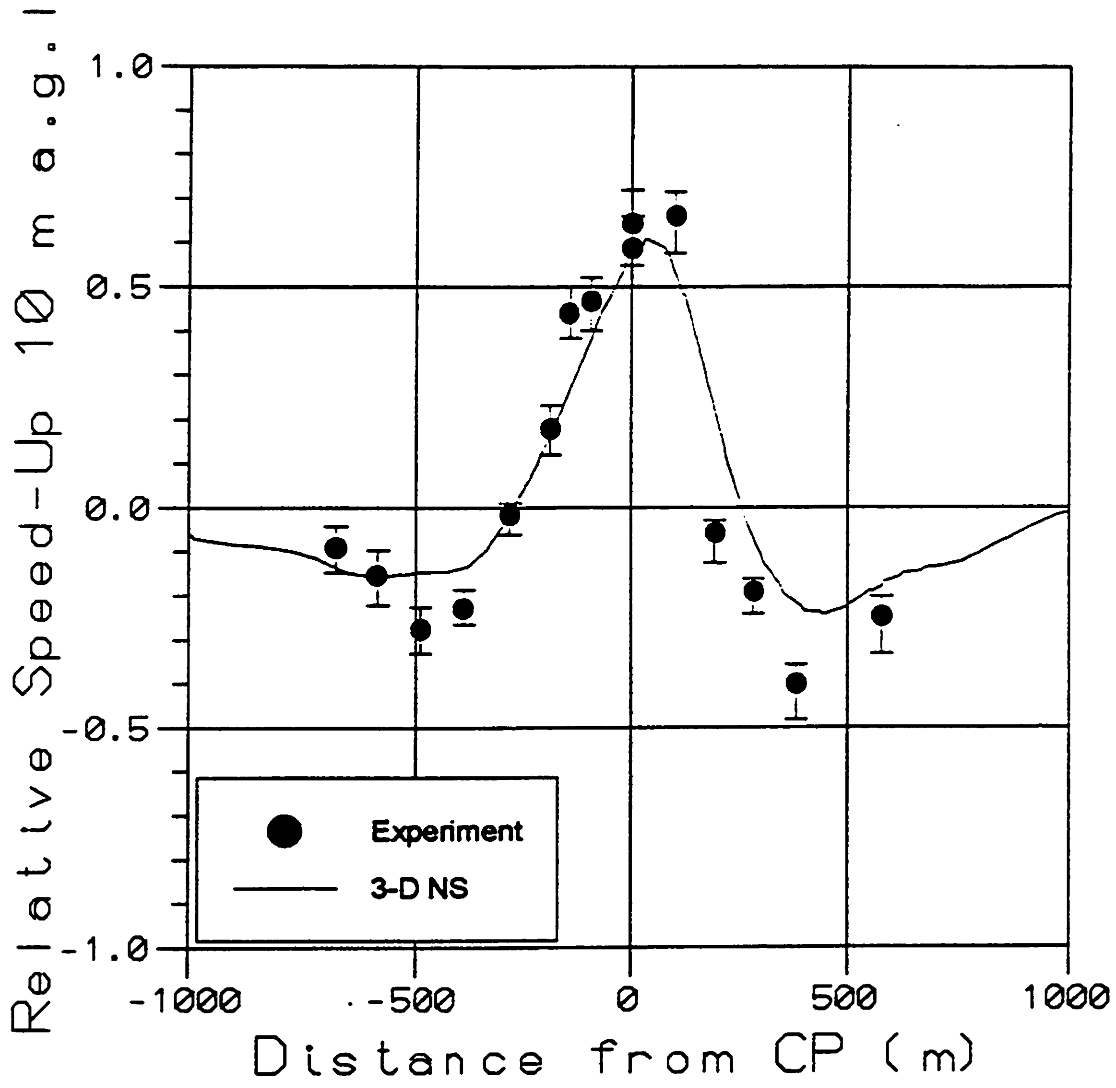
The Askervein hill

- A (75 X 45) X 40 grid is used with two blocks of 37 X 45 X 40
- Uniform inflow corresponding to a boundary layer height of 500 m
- The roughness length is 0.03 m (standard roughness)
- logarithmic grid expansion in the vertical direction, 1^{st} grid point at 10 roughness lengths

Wind park at Andros island

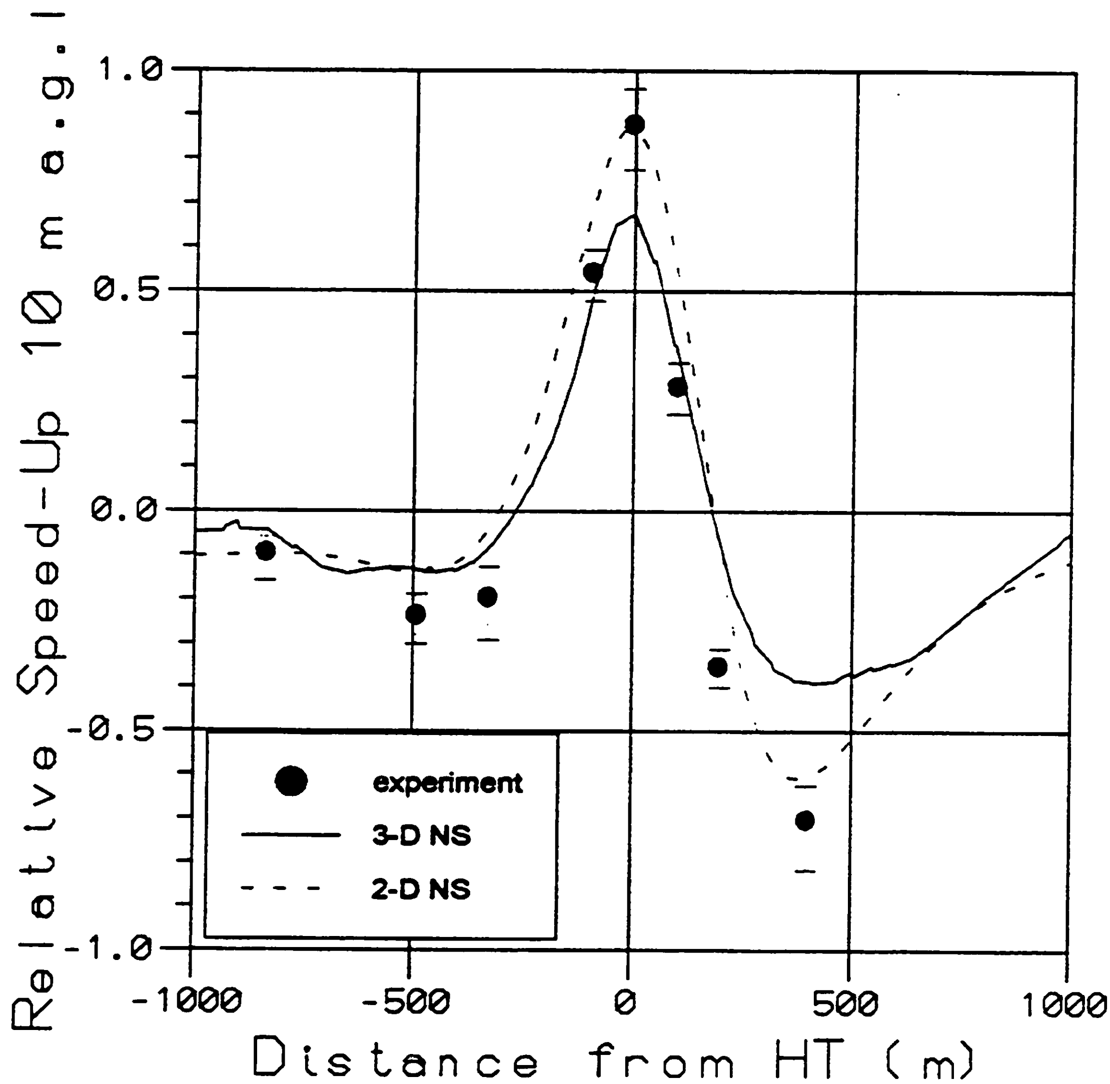
- A (100 X 87) X 40 grid is used with four blocks of 51 X 44 X 40
- The roughness length is 0.15 m

ASKERVEIN HILL



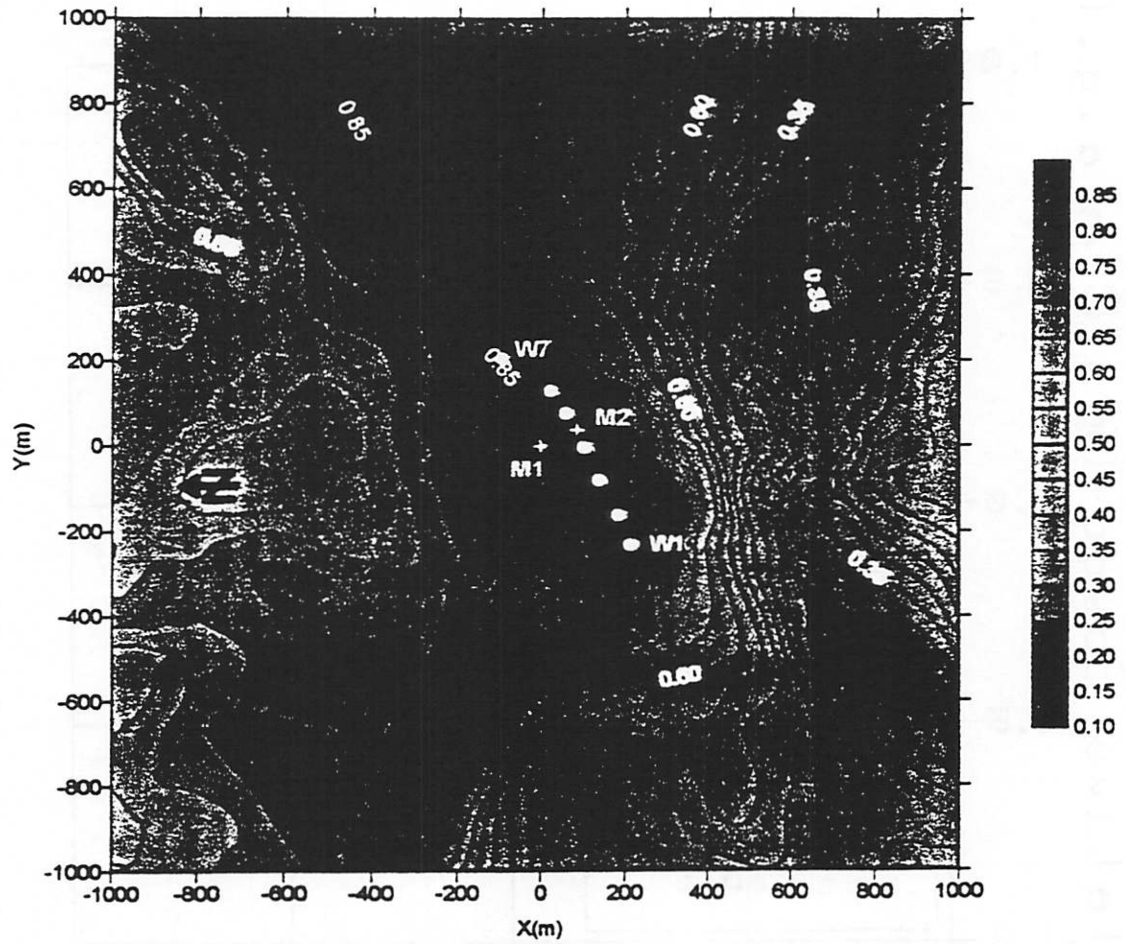
Relative speed-up along the AA line at 10m height

ASKERVEIN HILL



Relative speed-up along the A line at 10m height

ANDROS



Velocity contours at 10m height

NOTES FROM THE ROUND-TABLE DISCUSSION

prepared by

Helmut P. Frank and Gregor Giebel

The aim is a global wind atlas or wind map to give a first impression on the wind resource for developers of wind power plants. However, it must be emphasized that it cannot give binding recommendations because local effects may result in good sites, even in regions of generally poor wind regions.

It was not clear whether an atlas, like the European Wind Atlas, of regional climatologies with a resolution of several 10 km should be made, or a wind map of actual expected resources on a grid of the order of 1 km. Both products have their advantages, and might be included on a CD-ROM.

Most experts agreed that a global overview should be created. However, regions with generally very low winds require no detailed information. Whether to include deep water regions was disputed.

The final format could be a CD-ROM, or a web site.

One would need maps of mean speed and expected wind power, hence also the Weibull shape-parameter; maybe also figures on extreme winds (or frequency of tropical cyclones), or icing in arctic climates should be included.

Perhaps later, corrected data (similar to the WAsP LIB-files), could be included for validation using models. It should be possible for people to make their data easily available for validation and/or calibration.

It is very important to give some idea about the accuracy of the atlas/map. This will vary for different regions of the earth. Also, as more experience is gained with the atlas/map, recommendations for corrections for different regions could be given.

A collection of data was proposed: First step are reanalysis data, or other data from weather forecasting and GCM simulations. Over oceans, satellite data could also be used.

One major problem remains in understanding surface winds in the tropics (no expert on tropical meteorology was present), which leads to less accuracy for these regions.

Financing of a global wind atlas/map could be provided by:
- -UN, UNDP, WMO, National Energy Agencies, IPCC, EU, IEA (if not too expensive),
- -EWEA, AWEA, Wind Turbine manufacturers,
- -Mulinationals (e.g. Shell, BP, Enron, ...)

Everybody should provide:
- -A printed version of his/her presentation.
- -References of existing wind atlases or maps.
- -References to methods for making wind atlases or maps.
- -Recommended books and review articles
- -Models used for wind resource assessments (including web-links)

31st IEA Meeting of Experts
State of the Art on Wind Resource Estimation

RISØ, Denmark, October 29. - 30., 1998

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IEA R&D WIND - ANNEX XI
TOPICAL EXPERT MEETINGS

1. Seminar on Structural Dynamics, Munich, October 12, 1978
2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979
3. Data acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, September 26 - 27, 1979
4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21 -22, 1980
5. Environmental and Safety Aspects of the Present LS WECS, Munich, September 25 - 26, 1980
6. Reliability and Maintenance Problems of LS WECS, Aalborg, April 29 - 30, 1981
7. Costings for Wind Turbines, Copenhagen, November 18 - 19, 1981
8. Safety Assurance and Quality Control of LS WECS during Assembly, Erection and Acceptance Testing , Stockholm, May 26 - 27, 1982
9. Structural Design Criteria for LS WECS, Greenford, March 7 - 8, 1983
10. Utility and Operational Experiences and Issues from Major Wind Installations, Palo Alto, October 12 - 14, 1983
11. General Environmental Aspects, Munich, May 7 - 9, 1984
12. Aerodynamic Calculational Methods for WECS, Copenhagen, October 29 - 30, 1984
13. Economic Aspects of Wind Turbines, Petten, May 30 - 31, 1985
14. Modelling of Atmospheric Turbulence for Use in WECS Rotor Loading Calculations, Stockholm, December 4 - 5, 1985
15. General Planning and Environmental Issues of LS WECS Installations, Hamburg, December 2, 1987
16. Requirements for Safety Systems for LS WECS, Rome, October 17 - 18, 1988
17. Integrating Wind Turbines into Utility Power Systems, Virginia, April 11 - 12, 1989

18. Noise Generating Mechanisms for Wind Turbines, Petten, November 27 - 28, 1989

19. Wind Turbine Control Systems, Strategy and Problems, London, May 3 - 4, 1990

20. Wind Characteristics of Relevance for Wind Turbine Design, Stockholm, March 7 - 8, 1991

21. Electrical Systems for Wind Turbines with Constant or Variable Speed, Göteborg, October 7 - 8, 1991

22. Effects of Environment on Wind Turbine Safety and Performance, Wilhelmshaven, June 16, 1992

23. Fatigue of Wind Turbines, Golden Co., October 15 - 16, 1992

24. Wind Conditions for Wind Turbine Design, Risø, April 29 - 30, 1993

25. Increased Loads in Wind Power Stations, "Wind Farms", Göteborg, May 3 - 4, 1993

26. Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems, Milan, March 8 - 9, 1994

27. Current R&D Needs in Wind Energy Technology, Utrecht, Sept. 11 - 12, 1995

28. State of the Art of Aeroelastic Codes for Wind Turbine Calculations, Lyngby, Denmark, April 11 - 12, 1996

29. Aero-acoustic Noise of Wind Turbines,Noise Prediction Models, Milano, Italy, March 17 - 18, 1997

30. State of the Art on Power Performance Assessments for Wind Energy Conversion Systems, Athens, Greece, Dec.8 - 9, 1997

31. State of the Art on Wind Resource Estimation, RISØ, Denmark, Oct. 29 - 30, 1998