Review Article

Wind Power Meteorology.
Part I: Climate and Turbulence

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Key words: wind atlas; resource assessment; siting; wind climatology; wind power meteorology; wind profiles; turbulence; extreme winds; rotor wakes

Wind power meteorology has evolved as an applied science firmly founded on boundary layer meteorology but with strong links to climatology and geography. It concerns itself with three main areas: siting of wind turbines, regional wind resource assessment and short-term prediction of the wind resource. The history, status and perspectives of wind power meteorology are presented, with emphasis on physical considerations and on its practical application. Following a global view of the wind resource, the elements of boundary layer meteorology which are most important for wind energy are reviewed: wind profiles and shear, turbulence and gust, and extreme winds. ©1998 John Wiley & Sons, Ltd.

Preface

The kind invitation by John Wiley & Sons to write an overview article on wind power meteorology prompted us to lay down the fundamental principles as well as attempting to reveal the state of the art—and also to disclose what we think are the most important issues to stake future research efforts on. Unfortunately, such an effort calls for a lengthy historical, philosophical, physical, mathematical and statistical elucidation, resulting in an exorbitant requirement for writing space. By kind permission of the publisher we are able to present our effort in full, but in two parts—Part I: Climate and Turbulence and Part II: Siting and Models. We kindly ask the reader to be indulgent towards inconsistencies, which are inevitable in the process of dividing the work of five authors.

An ideal review paper is objective; however, this requires it to be written by someone not personally active in the field. This is a contradictory to the provision of the most up-to-date knowledge. Therefore, because all five authors are employees of Risø National Laboratory, the review is to a large extent the ‘Riso view on things’. It is our hope that these views are shared by many, but we invite discussions on any subject in the review.

Part I is an attempt to give an account of the advance of wind power meteorology, from the early days of modest wind turbines till today’s massive plans for large-scale power production by modern megawatt-size turbines. The historical development of the concept of ‘wind atlas’ is portrayed, followed by an introduction to the basic concepts of boundary layer meteorology, atmospheric turbulence and wind climatology.

Part II categorizes the relevant part of geography into workable schemes for the siting process by describing landscapes according to the consequences they have on the wind climate by various combinations of topography and climatology. The inevitable transformation of carefully obtained data, through numerical models based on fundamental physics, to useful statistics on the wind climates of specific places or of entire regions is deliberated in some detail. Finally, the necessity of research in areas of vital importance for the advancement of wind energy technology with respect to wind power meteorology is emphasized.

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CCC 1095–4244/98/010002–21$17.50
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Introduction

Wind Power Meteorology is not a term to be found in a standard glossary of meteorological terms. However, it is a discipline which has evolved under its own provisions. It can formally be described as applied geophysical fluid dynamics, but a more understandable definition would rest on a combination of meteorology and applied climatology. Meteorology is atmospheric science in its widest sense. It consists of atmospheric thermodynamics and chemistry, the qualitative and quantitative description of atmospheric motion, and the interaction between the atmosphere and the Earth’s surface and biosphere in general. Its goals are the complete understanding and accurate prediction of atmospheric phenomena. It is one of the most complex fields of both natural and applied science. Climatology is the scientific study of climate and its practical application. It uses the same basic data as meteorology and the results are particularly useful to problems in industry, agriculture, transport, building construction and biology. Many of the aspects of climatology make it a part of meteorology, but when the emphasis is on specific climate conditions at a particular point on the Earth’s surface, it is clearly part of geography. Wind power meteorology thus does not belong wholly within the field of either meteorology, climatology or geography. It is an applied science whose methods are meteorological but whose aims and results are geographical. It concerns itself with three main areas: micro-siting of wind turbines, estimation of regional wind energy resources, and short-term prediction of the wind power potential, hours and days ahead.

With respect to wind power meteorology, siting is defined as estimation of the mean power produced by a specific wind turbine at one or more specific locations. A full siting procedure includes considerations such as the availability of power lines and transformers, the present and future land use, and so on. However, these aspects are not considered here. To put ‘paid’ to the problem of proper siting of wind turbines with respect to the wind resource, we require proper methods for calculating the wind resource, the turbulence conditions, the extreme wind conditions and the effects of rotor wakes.

Regional assessment of wind energy resources means estimating the potential output from a large number of wind turbines distributed over the region. Ideally, this results in detailed, high-resolution and accurate resource maps showing the wind resource (yearly and seasonal), the wind resource uncertainty and areas of enhanced turbulence.

Forecasting of the meteorological fields, hours and days ahead is one of the great challenges of meteorology. The tremendous increases in computer power and in observational density (by satellites in particular) and quality have contributed to a marked increase in forecasting skills over the last decade. This, in turn, has made it possible to construct a methodology by combining numerical weather prediction models with micro-siting models to predict the power output from specific wind farms up to 48 h ahead.

These three topics and wind power meteorology in general are treated in the following sections. First, the history, status and perspectives are described. This description constitutes by no means a full account of what has been done by whom; admittedly, it gives a rather subjective view—the Risø perspective on matters. The next two sections set the stage for wind power meteorology with respect to meteorology and climatology, and the following section relates it to geography. Then, wind data are treated, in particular the means by which these data are obtained. Finally, a description of the numerical meteorological models—spanning from full, global circulation models over high-resolution, limited area models to microscale models—is given.

History, Status and Perspectives

The discipline Wind Power Meteorology has evolved together with the commercial evolution of the wind turbine and the large-scale utilization of wind for electricity generation. From the early 1970s, groups worldwide began to work with meteorological and climatological questions related to wind energy, and numerous publications can be found in the literature. The national wind energy programs, which were
initiated in a number of countries in the 1970s, typically included national wind resource surveys. Among these, probably the best known are the Wind Energy Resource Atlas of the United States by Pacific Northwest Laboratory\(^1\) and the Wind Atlas for Denmark by Risø National Laboratory.\(^2\) In addition to these atlases, a number of so-called siting handbooks were produced, most notably in the USA,\(^3,4\) Canada\(^5\) and the Netherlands.\(^6\) The Danish Wind Atlas and the later European Wind Atlas\(^7\) serve both purposes, as wind resource atlas and siting handbook.

During the 1980s wind turbine development increased dramatically, and large demonstration wind turbines were erected and tested, but often dismantled after a few years of operation owing to unsuccessful design. In the meantime the small and privately produced turbines went on growing larger and more reliable, and—thanks to various political initiatives—a sometimes turbulent market was created. Best known is the growth of the European and American wind turbine industry—the eruption of the Californian market and the subsequent decline leading to multiple bankruptcies for the industry. Following this incidence, a slower but stronger growth of the European market developed: the wind energy community had learned its lesson from the Californian adventure. The importance of an accurate knowledge of the overall wind resource and reliable methods for the siting of wind turbines had become increasingly clear.

Through the 1990s the world has seen a continuous growth in the application of wind energy. The competition has become fierce, not only between specific brands of turbines but also between projects demanding large investments. Which project to select and on what grounds? Usually, economy and, consequently, the expectation of power production during the lifetime of the wind turbine are crucial parameters. Here the application of wind power meteorology plays an increasingly important role. It is interesting to note that this discipline has evolved over the last 20 years or more, turning a relatively ‘free’ academic discipline into ‘hard core’ research and development under the pressure from the wind energy community—with a strong and almost unrealistic demand for accurate and efficient methods. Many of the early methods put forward did not survive. The methods that are left are in return extensively used. With the wisdom of hindsight it is straightforward to explain what happened, why it happened and finally in what direction the development must go. The answer lies in the physics: the more relevant the physics that can be implemented in the methods, the more general and realistic the models and the more accurate and reliable the results. In the following we will go through simple physical arguments in support of this allegation.

**Physical Considerations**

The state of the atmosphere is well described by seven variables: pressure, temperature, density, moisture, two horizontal velocity components and the vertical velocity; all functions of time and position. The behaviour of these seven variables is governed by seven equations: the equation of state, the first law of thermodynamics, three components of Newton’s second law and the continuity equations for mass and water substance. These equations are mathematical relations between each atmospheric variable and their temporal and spatial derivatives. Mathematical models of the atmosphere can be obtained by integrating the relevant equations with special initial and boundary conditions. The equations can be solved numerically by forward marching in time, using the time rates of change of the variables; the derivatives are replaced by ratios of finite differences, and changes of the variables over a certain time interval are computed repeatedly as long as needed.

The atmosphere contains motions with scales varying from about 1 mm to thousands of kilometres. Ideally, mathematical models should be constructed from observations with 1 mm spatial and with a fraction of a second temporal resolution. Clearly, this is impossible in practice, and models are constructed separately for systems on different scales. Thus, for example, there are models for local circulations such as sea breezes, for flow over mountains, for weather developments over Europe or for the entire globe. Depending on the system modelled, the equations can be simplified, and, for the development of wind power meteorology, the starting point is the simplest model for motion in the atmosphere:
steady winds over very extensive plains under an overcast sky; or, in other words, a stationary wind field over an infinite flat plane of uniform roughness with neutral stratification. The only quantity of interest is the variation of wind speed with height. Straightforward physical considerations lead to the well-known logarithmic wind profile, which is determined solely by three variables: the height above ground, the roughness length and the friction velocity. The roughness length parametrizes the roughness of the surface, and the friction velocity parametrizes the frictional force between the moving air and the ground.

From the starting point of the infinite plate at rest we move to the rotating Earth. Far away from the ground the atmosphere cannot feel the friction, and the flow is in equilibrium with the pressure force and the Coriolis force. The latter is caused by the rotation of the Earth. The resulting wind is called the geostrophic wind. Moving down to the surface, the wind changes from geostrophic speed to zero speed at the height of the roughness length. At the same time the wind direction changes, rotating anticlockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The balance between the forces can be derived theoretically under the idealized conditions of stationarity, homogeneity and barotropic stratification (the pressure gradient being constant over the depth of the boundary layer). For conditions of neutral stability the balance can be expressed as a relation—the geostrophic drag law—between the surface friction velocity and the geostrophic wind, with the roughness length and the Coriolis force as parameters; see equation (3). The geostrophic wind can be calculated from the surface pressure gradient and is often close to the wind speed observed by radiosondes above the boundary layer. The combination of the logarithmic wind profile and the geostrophic drag law provides us with an easy-to-handle model atmosphere: the Coriolis parameter is known for a given location and the roughness length can be estimated from the characteristics of the ground cover. Hence, if we can determine the geostrophic wind, the friction velocity can be calculated from the drag law and, in turn, applied in the logarithmic profile to calculate the wind speed at a desired height.

Now we introduce weather and climate; the atmosphere is no longer assumed stationary, but characterized by ‘synoptic’ activity, i.e. the passing of high- and low-pressure systems. The geostrophic wind has a climatological variation which we need to estimate in order to get the climatology of the surface wind. This was the philosophy behind the Danish Wind Atlas work. Surface pressure data measured every third hour over 13 years at 55 stations in Norway, Sweden, Denmark, Germany and Poland were used to calculate a 13 year time series of the geostrophic wind over Denmark. This was then used to calculate time series of the surface wind at heights between 10 and 200 m for four values of the roughness length. Each value of the roughness length was assigned to a characteristic type of terrain, named a roughness class. Initially, the aim of the project was to produce maps over Denmark of the wind resources. Early in the project it became clear that in order for such maps to make any sense, they would have to be produced with an—at that time—impossibly high resolution. The reason for this is the dramatic variation of the wind conditions which, owing to the extreme dependence of the wind speed on the topographical features, can be experienced near the surface over short distances. Instead of producing maps, a method which could be used to produce maps of high resolution at particular locations was developed. More specifically, this method, which later became known as the Wind Atlas Method, was created such that a user, having specified the roughness classes in each of eight direction sectors (N, NE, . . . , NW), could use the tables and graphs in the Atlas to calculate the distribution function of the wind at the desired height. This was before the advent of the PC.

One of the assumptions used in the development of the wind atlas method was that the distribution of wind speeds is well approximated by the Weibull distribution function. Several investigations before the Atlas had hinted at this, and the general experience today is that well-measured data at locations with moderate to high winds can almost always be approximated by the Weibull function. The time series of the geostrophic wind calculated from the pressure data had a near-perfect Weibull distribution as shown in Figure 1(a). The distribution functions of the surface wind speed time series, calculated as described above, were then fitted with the Weibull distribution, and the resulting two parameters describing the distribution, the scale parameter and the shape parameter , were plotted for five heights, four roughness classes and eight direction sectors. A typical graph is shown in Figure 1(b). More than 6000
wind turbines operating in Denmark and Germany have been sited using this method; hence there is an immense amount of experience behind its use.

In the construction of the Danish Wind Atlas it was necessary to move a step away from the idealized world. It was essential to include the effects of changes from one roughness class to another and from height variations in the terrain. In other words, it was inevitable to construct models which, on the basis of simple information extracted from standard topographical maps, could calculate the effect on the wind from topographical features. This was achieved by combining contemporary theories with experimental investigations. The Atlas contains a method for calculating the effect of a change of roughness class, the so-called roughness change model, and a model for calculating the speed-up which occurs when the flow passes over a hill, the so-called hill model. Further, it was necessary to construct a model for the effect of sheltering obstacles in the terrain, such as houses and shelter belts, the so-called shelter model.

In 1981 the European Commission launched its first wind energy research program. In the plans was the creation of a European wind atlas, based on the Danish Wind Atlas methodology for non-mountainous terrain and on the application of a mass-consistent model for mountainous terrain. An assembled working group immediately deemed this approach impossible. Not only was the necessary collection of pressure data prohibitively immense, but so were the requirements for computer power, also. Furthermore, the influence on the pressure measurement from the actual heights of the synoptic stations above mean sea level could introduce such large errors in the calculation of the geostrophic wind that the resulting statistics would most likely be useless. The use of a mass-consistent model for the mountainous areas had the problem that because the physics is extremely simplified—basically, only the continuity equation—it requires a network of measurements with unrealistic density. Therefore a methodology was established in which the first step was to give a systematic description of the various types of landscapes in Europe and the next to provide methods and data to be used in each landscape type. Five distinct landscape types were recognized and the topography and wind climatology were described. For the creation of the European Wind Atlas the strategy was to adopt parts of the methodology from the Danish Wind Atlas for the relatively simple landscapes, and for the complex landscapes to collect as many high-quality wind records as possible and develop a method to describe and classify the stations in a unified way.

As mentioned above, the Danish method could not be used straightforwardly because of the insurmountable difficulties in the pressure analysis. Instead, another method was put forward: the double vertical and horizontal extrapolation method. The idea behind this is quite simple: if we have measured the wind speed at a height of 10 m at one station and we are able to estimate the distribution of the roughness length around the station, then we can find the friction velocity from the logarithmic profile and apply this in the geostrophic drag law to calculate the geostrophic wind. Having determined the geostrophic wind in this way, we can proceed as in the Danish Wind Atlas method to calculate the Weibull

\[ \begin{align*}
  G & = 10.2 \ \text{m s}^{-1} \\
  A & = 11.48 \ \text{m s}^{-1} \\
  k & = 1.75
\end{align*} \]

Figure 1. (a) The distribution of the geostrophic wind over Denmark. (b) Weibull $A$ and $k$ parameters as functions of height over roughness class 2. The values shown at 1000 m correspond to the geostrophic wind.

statistics. These statistics can then be used to estimate the wind statistics at specific locations up to 200 m a.g.l. The procedure is illustrated in Figure 2.

However, with the introduction of the double extrapolation method the assumption about the uncomplicated neutral atmosphere had to be relaxed. This is so because the climate of the surface heat flux is an important parameter for the vertical extrapolation of the wind distribution with height. Even at moderate wind speeds, deviations from the logarithmic profile occur when the height exceeds a few tens of metres. Deviations are caused by the effect of buoyancy forces in the turbulence dynamics; the surface roughness is no longer the only relevant surface characteristic, but has to be supplemented by parameters describing the surface heat flux. With cooling at night, turbulence is lessened, causing the wind profile to increase more rapidly with height; conversely, daytime heating causes increased turbulence and a wind profile more constant with height. In order to take into account the effects of the varying surface heat flux without the need to model each individual wind profile, a simplified procedure was adopted which only requires the climatological average and root mean square of the surface heat flux. This procedure introduces the degree of ‘contamination’ by stability effects to the logarithmic wind profile when conditions at different heights and surfaces are calculated.

Owing to the complexity of the European landscape and the large number of stations used for the analysis, it was necessary to replace the roughness change model and the hill model by much more general computerized models which were able to handle topographical map information in digital form. These
models had to be developed, verified and applied. The result was a flow-over-hill model with an expanding polar grid centred at the point of interest, enabling a very detailed description of the terrain around a specific location. Because the terrain elevations closest to the location exert the strongest influence, this is very much desired feature. The roughness change model was initially expanded to multiple roughness changes and subsequently developed into a more general model capable of handling roughness areas extracted directly from topographical maps. The European Wind Atlas was published in 1989, a year after the calculational methods had been made publicly available in the PC program WASP: the Wind Atlas Analysis and Application Program. Subsequently, a number of similar studies were undertaken in e.g. Norway, Jordan, Western Australia, Switzerland, Algeria, Finland, Sweden, Germany and Egypt, and similar efforts are in progress in Libya, Syria, Russia and elsewhere.

The primary use of WASP has been for siting of wind turbines worldwide, singly or in farms. Over the decade it has been in use, it has developed into a generally accepted standard for micro-siting. However, it has its well-recognized limitations: the more complicated the situation is with respect to topography, climatology or both, the more uncertain are the results from the calculations. Many of the procedures that constitute the method are strictly applicable only under an idealized and limited range of conditions. The most severe problems are encountered in mountainous terrain, where large-scale effects render the model increasingly deficient because of the importance of dynamics which is at present not accounted for in the model. The only way forward is to use more complete physical models. The next level consists of the so-called mesoscale models. They build on the full set of equations and are therefore—formally—capable of modelling all types of flow in complex situations. Their disadvantage lies in the difficulties encountered in prescribing the initial and boundary conditions accurately. Furthermore, they typically model an area of the order of $10^2 \times 10^3$ km$^2$ with a resolution of 5–10 km. To zoom in on specific locations, it is necessary to apply a high-resolution model such as WASP. This line has been followed in a number of studies. The European Wind Atlas work was followed up by the EU Commission with a study called ‘Measurements and modelling in complex terrain’. The aim was to be able to calculate the available wind resources in mountainous terrain with an acceptably low uncertainty. The project encompassed model development and measurements in several mountainous regions of Europe for verification and demonstration. The result is produced by a combination of the Karlsruhe Atmospheric Mesoscale Model (KAMM) and WASP.

The perspectives for further progress of wind power meteorology are good: the ever-increasing computer power and efficiency of numerical methods allow for continuous development of the models involved, and the public availability of large databases on long-term global wind climatology and high-resolution topography (orography and land use) allows for production of worldwide reliable wind atlas data and for accurate siting of wind turbines.

**Weather and Wind Climate**

It is the wind in the lowest part of the atmosphere that is the most important atmospheric variable for wind power meteorology. During this century a scientific discipline named boundary layer meteorology evolved with the aim of describing the atmospheric process in the atmospheric boundary layer. The application of this discipline has mainly been aimed at the study of air pollution, agriculture and engineering. Wind power meteorology has been fortunate to be able to draw from the acquired knowledge of boundary layer meteorology, but until recently it is fair to say that wind turbine designers have not been able to make full use of it. However, this has now changed, and the requirement for detailed and highly realistic models, e.g. a three-dimensional quantitative description of the turbulence over a rotor plane, is a tremendous challenge to wind power meteorology.

The atmospheric boundary layer is the layer of air directly above the Earth’s surface. The layer extends to about 100 m above the ground on clear nights with low wind speeds, and up to more than 2 km on a fine summer day. The lower part of this layer is called the surface layer and is sometimes defined as a fixed fraction, say 10%, of the boundary layer depth. For the purpose of climatology relevant to wind power...
utilization we can often neglect the lowest wind speeds, so situations where the atmospheric boundary layer extends to approximately 1 km are of primary concern. It is in the lowest 100 m—the surface layer—that the logarithmic law for the wind profile and other relations described in the next section apply.

The wind profile we observe at any particular time is one measure of the elements of the current weather. If we continue to observe the same wind profile over years, we make up its climatology. It is worthwhile for discussions ahead to reproduce here the generally accepted definitions of weather and climate.\(^{21}\)

- **Weather** is the totality of atmospheric conditions at any particular place and time—the instantaneous state of the atmosphere and especially those elements of it which directly affect living things. The elements of the weather are such things as temperature, atmospheric pressure, wind, humidity, cloudiness, rain, sunshine and visibility.
- **Climate** is the sum total of the weather experienced at a place in the course of the year and over the years. Because the average conditions of the weather elements change from year to year, climate can only be defined in terms of some period of time—some chosen run of years, a particular decade or some decades.

**Wind Climates of the World**

The climate varies greatly around the globe. We are not concerned here with elements other than the wind and the wind resource, but note in passing that other climate elements, such as humidity, precipitation, temperature, and also average concentration of particles, sea spray, etc., would be required for other purposes. An example of this is a ‘Corrosion Atlas’, which would be an appropriate thing for a wind turbine designer to have.

An overview of the global wind climate is illustrated in Figure 3, where the mean wind energy flux at 850 hPa (\(\approx 1500\) m.a.s.l.) is shown. The picture is a familiar one, displaying clearly the ‘roaring forties’ in the Southern Hemisphere.

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\(^{21}\) Weather and climate definitions are from the World Meteorological Organization (WMO).
the Southern Hemisphere and the extratropical cyclonic activity over the North Atlantic and North Pacific. Furthermore, the southwest monsoon can be seen, with the Somali Jet standing out.

Evidently, this is a very coarse picture of the wind regimes of the world: it does not display local wind systems on scales less than a few hundred kilometres, and larger-scale systems with strong yearly variations are suppressed too. For a detailed description of the global climate, see References 22 and 23. However, as a starting point for regional wind resource estimation worldwide, the database used for the map is extremely useful in combination with adequate meteorological models.

The wind climatological description/classification of a particular location is not a simple matter. Many different types of wind statistics could be considered for a description of wind climates, local or regional. For the European Wind Atlas a graphical representation called the wind climatological fingerprint was developed. Experience has shown that the collective information in the various statistics usually provides a good representation of the wind climate. Figure 4 elucidates the usefulness of parts of the fingerprint characterization; three widely different wind climates from the Arctic, the westerlies and the trade winds are shown. The dramatic differences between these climates are obvious, especially for the yearly and daily variations.

![Figure 4. (a) Yearly and (b) daily variations of the mean wind speed for three different wind climates. (c) Frequency distributions of the wind speed at the same three locations](image)

**Climate Variability and Change**

Variability is an intrinsic feature of climate, because the weather changes from year to year and between consecutive decades. The data which form the basis of any wind resource study cover a limited period of time, which in many cases is about 10 years. The question therefore arises: to what extent is that period representative for the longer-term climate and, more importantly, how large a deviation must be expected in future decades? A study of climatic variability in Northern Europe shows that variations in wind energy of up to 30% can be expected from one decade to another; see Figure 5. In another study it was found from an analysis of the expected power output for a 45 m high wind turbine over a 22 year period that the interannual variation in power corresponds to a mean relative standard deviation of approximately 13%.

For the proper assessment of the economics of wind power utilization, such variability must obviously be borne in mind. In comparison with other important factors such as rates of interest and prices of other fuels, the uncertainty in the wind resource is not large over the lifetime of a wind turbine of, say 20 years. Based on the studies cited above, one can estimate the variation of the mean power from one 20 year period to the next to have a standard deviation of 10% or less. The possible effect of the increasing CO₂ content in the atmosphere might be a gradual change in the global climate. If this happens, both a change in the magnitude of climate mean levels and climate fluctuations of the wind energy can be expected. However, as for now, no firm evidence of global change has been given.
Winds in the Atmospheric Boundary Layer

The scientific discipline boundary layer meteorology has produced a wealth of knowledge, especially concerning the dynamics of the flow in the atmospheric boundary level. Below, some of the aspects most important to wind power meteorology are described and the basic equations given.

Wind Profiles and Shear

The behaviour of the natural wind field over flat terrain of uniform roughness and a long upstream fetch is well known, both from a large number of field measurements and from theoretical treatments, and a description can be found in any textbook on turbulence.\(^{24}\)

The mean wind profile, i.e. measurements of wind speed as a function of height, averaged over periods of 10–60 min, is often described for engineering purposes by a power law approximation

\[
\frac{U(z_1)}{U(z_2)} = \left(\frac{z_1}{z_2}\right)^p
\]

where \(U(z_1)\) and \(U(z_2)\) are the wind speeds at heights \(z_1\) and \(z_2\) respectively and \(p\) is the power law exponent, with a typical value of 0.14. A serious problem with this approach is that \(p\) varies with height, surface roughness and stability, which means that Equation (1) is of quite limited usefulness. A more realistic expression for the mean wind speed at height \(z\), with much more general validity, can be obtained from the so-called logarithmic wind profile with stability correction. This expression, which is well supported by theoretical considerations, is written

\[
U(z) = \frac{u_\ast}{\kappa} \left[ \ln \left(\frac{z}{z_0}\right) - \psi \right]
\]

where \(u_\ast\) is the friction velocity, \(\kappa\) is the von Kármán constant (\(\sim 0.4\)), \(z_0\) is the roughness length and \(\psi\) is a stability-dependent function, positive for unstable conditions and negative for stable conditions. The wind speed gradient is diminished in unstable conditions (heating of the surface, increased vertical mixing) and increased during stable conditions (cooling of the surface, suppressed vertical mixing); see Figure 6(a).

\(^{24}\) John Wiley & Sons, Ltd.

\(Wind\ Energ.,\ 1, 2–22\ (1998)\)
In stable conditions, significant changes in wind direction with height are also observed. A wind turbine operating under such conditions experiences both a wind speed shear and a wind direction shear. An example of a large-shear case is given by the measured wind profile from the Nørrekær Enge II wind farm shown in Figure 6(b). The wind speed at hub height was quite moderate, but the very large shear across the rotor was comparable with the shear found with a hub-height speed of about 30 m s$^{-1}$ in neutral conditions and a roughness length of 0.03 m. This situation gave rise to large loads at the rotation frequency. In fact, we first observed the anomalous loads, subsequently checked the data and then found the large-wind-shear situation.

As another example, typical values of mean wind shear across a 50 m rotor at 50 m hub height for low wind speeds in stable conditions can be of the same magnitude as the wind shear at very high wind speeds in neutral conditions, i.e.

- neutral, $z_0 = 0.03$ m, $U_{hub} = 8$ m s$^{-1}$, $U_{75} - U_{25} = 1.2$ m s$^{-1}$;
- stable, $z_0 = 0.03$ m, $U_{hub} = 8$ m s$^{-1}$, $U_{75} - U_{25} = 4.8$ m s$^{-1}$;
- neutral, $z_0 = 0.03$ m, $U_{hub} = 32$ m s$^{-1}$, $U_{75} - U_{25} = 4.8$ m s$^{-1}$.

The wind is generated by large-scale pressure differences, and under certain simplifying circumstances a fictitious wind speed, the geostrophic wind, which is representative for the wind speed driving the boundary layer, can be calculated from the pressure field. Using information about surface roughness and stability, it is then possible to calculate the wind speed near the surface using the geostrophic drag law

$$G = \frac{u_*}{\kappa} \sqrt{\left[ \ln \left( \frac{u_*}{fz_0} \right) - A \right]^2 + B^2} \quad (3)$$

where $G$ is the geostrophic wind, $f$ is the Coriolis parameter and $A$ and $B$ are dimensionless functions of stability (for neutral conditions $A = 1.8$ and $B = 4.5$). If the geostrophic wind is known, it is quite simple to calculate $u_*$ for a given $z_0$ and use equation (2) for the calculation of the wind speed at a certain height. This is basically the double vertical extrapolation method described in the previous section.
In sloping terrain and over hills, certain layers of the flow accelerate, leading to different shapes of the wind profiles. The shear in local height ranges may then be much higher than that applied by equation (2); see Figure 7(a). In-depth treatment of flow in changing terrain can be found in Reference 27, and simple engineering approaches in References 24 and 28.

In the wake of an operating wind turbine the mean flow speed decreases downstream of the rotor, giving rise to the formation of strong shear layers near the edges of the wake, especially near the top of the wake. Initially, the wake diameter is close to the rotor diameter, but as the flow moves away from the rotor, turbulent mixing gradually increases the wake diameter and decreases the velocity deficit. At a distance of about 10 rotor diameters downstream the flow has almost recovered and the wind profile is close to the upstream profile. An example of the wind profile five rotor diameters downstream of a wind turbine is shown in Figure 7(b) (see also Figure 10).

**Turbulence and Gusts**

The turbulent variations of the wind speed are typically expressed in terms of the standard deviation $\sigma_u$ of velocity fluctuations measured over 10–60 min, normalized by the friction velocity or by the wind speed. The variation in these ratios is caused by a large natural variability, but also to some extent because they are sensitive to the averaging time and the frequency response of the sensor used. In horizontally homogeneous terrain the turbulence intensity $I_u = \sigma_u / U$ is a function of height and roughness length in addition to stability, whereas $\sigma_u / U_*$, not too far from the ground, may be considered a function of stability only. A typical value for neutral conditions is $\sigma_u / U_* = 2.5$ for homogeneous flat terrain, often larger for inhomogeneous terrain, but with very large local variations.

The turbulence intensity is a widely used measure, and for neutral conditions with a logarithmic wind profile over flat terrain we find $I_u \approx 1/\ln(z/z_0)$. Typical values of $I_u$ for neutral conditions in different terrains are: flat open grassland, 13%; sea, 8%; complex terrain, 20% or more.

Measurements from a number of sites were shown in Reference 29. The variations with stability can also be considerable, especially at low to moderate wind speeds, with smaller resulting turbulent intensities in stable conditions and larger values in unstable conditions; values of 25% are not unusual in flat open grassland for moderately unstable conditions. The variances are quite sensitive to the averaging
time, because much of the turbulent kinetic energy appears at quite low frequencies, both in unstable and particularly in stable conditions. In the latter case the variance can be completely dominated by large-scale slow variations in wind speed and direction overlaid with very little turbulence.30

In wakes we see increased turbulence levels together with decreased mean wind speeds, leading to significantly larger turbulence intensities than for the free flow.26,31–33

The turbulent velocity fluctuations can be described as a result of stochastic broadband processes. We see variations in velocity in a broad range of frequencies and scales, and numerous models have been used to describe the distribution of energy over different scales as a function of stability and height. These models can be subdivided into two ‘families’: the so-called Kaimal spectra and their generalizations,34–36 providing good empirical descriptions of observed spectra in the atmosphere, and the von Kármán spectra, which may provide a good description of turbulence in the tube flows and wind tunnels but are less realistic for atmospheric turbulence.37 The popularity of the latter can mainly be attributed to the fact that they feature simple analytical expressions for the correlations. Examples of spectra in flat homogeneous terrain are shown in area-conserving representations in Figure 8(a). Typical spectra (at near neutral and not too close to the ground) are dominated by broad maxima and falling off towards high frequencies as \( f^{-5/3} \). The very-low-frequency behaviour is typically characterized by a large amount of variation and statistical uncertainty. Note the quite large differences in variances for different stabilities, with large variances in the unstable boundary layer and much smaller variances in the stable boundary layer.

The traditional way of relating length and time scales in turbulence is through the so-called Taylor ‘frozen turbulence’ approximation, i.e. the turbulence statistics can be regarded as a result of a frozen picture of turbulence advected past the observer by the mean wind, such that \( \lambda = U/f \), where \( \lambda \) is a length scale and \( f \) is the corresponding frequency observed in a fixed frame of reference. In the simple Kaimal formulation for neutral conditions, approached from stable conditions, spectra close to the ground have a dominating length scale of about 22 times the height above the ground. This is a fair approximation at low heights and moderate wind speeds, but above 30–40 m and for high wind speeds38 the length scale approaches a constant value, typically 500–1500 m.

Terrain inhomogeneities may locally give rise to very large changes in the spectra. In flow over hills the pressure field perturbations induced on the flow by the presence of the hill lead to an (almost) instantaneous redistribution of energy from the streamwise component of the wind to the vertical component by rapid distortion39 (see Figure 9). In situations with changing roughness the turbulence changes gradually downstream, first at small scales (high frequencies) and later also at larger scales. Because it can take

![Figure 8](image-url)
considerable amounts of time (tens of minutes to hours) to change the large, energy-containing eddies, the turbulence of the flow ‘remembers’ the upstream conditions far downstream.40 The general effect of inhomogeneous terrain is to increase turbulence, typically at length scales comparable in size with characteristic terrain features.41 In this way the shape of the spectrum approaches that of the unstable spectrum in Figure 8(a), where typical length scales of the energy-containing range are of the order of several kilometres.

Neutral conditions are very rare events, typically occurring only as transitions between stable and unstable conditions. However, near-neutral conditions occur also during overcast skies and moderate to high wind speeds. This variation in stability means that at a particular site a wide range of dominating length scales are seen, from tens of metres to several kilometres, the distribution of which depends very much on the local stability climatology. The probability distribution of length scales at a coastal site is shown in Figure 8(b). Here the length scale was defined as the scale for which half of the variance of the streamwise component is distributed on larger scales and the other half on smaller scales. This length scale does not coincide exactly with the peak of the power spectrum—the difference being < 10% for a typical spectrum—but the length scale defined in this way is much easier to measure reliably. In Figure 8(b) the most common length scale is 500–600 m, but the distribution is skewed (almost symmetric in the logarithmic representation) and the average length scale is about 1000 m. Length scale distributions are presented also for other heights in Reference 33; from 15 m and above these are very similar (for the 7 m level the scales were found to be significantly smaller), with a slight tendency towards smaller scales closer to land. Also, it has been observed at the offshore location, 2 km from the coast, that the scales are smaller for offshore flow and larger for onshore flow.

The spectral coherence $\text{Coh}(f)$ is a useful measure of the normalized spectral distribution of spatial correlations. Note, however, that the integral of $\sqrt{\text{Coh}(f)}$ over all frequencies is different from the correlation. The spectral coherence is defined as

$$\text{Coh}(f) = \frac{Q^2_{12}(f) + C_{12}(f)}{S_1(f)S_2(f)}$$

where $Q_{12}$ is the quadrature spectrum, $C_{12}$ is the cospectrum and $S_1$ and $S_2$ are the power spectra measured at the physically separated positions 1 and 2. The coherence is an important quantity when translating Eulerian spectra into spectra in a rotating frame of reference, such as that ‘seen’ at a fixed position on a rotating wind turbine blade.42,43 It is quite difficult to measure coherences with sufficient
statistical significance, and consequently there is a lot of scatter in measured values. Traditionally, very simple exponential models have been used to describe the coherence functions, for coherences along the wind and perpendicular to the mean wind, in the lateral and in the vertical. The coherence for separations perpendicular to the mean wind in neutral conditions is described well by the following model, even in wake situations:

\[
\text{Coh}(f, \Delta s) = \exp \left( -\frac{a_i f \Delta s}{U} \right)
\]

where \(\Delta s\) the separation and \(a_i\) depends on the velocity component and the direction of separation (vertical or lateral). For the \(u\)-component, \(a_i = 12 + 11\Delta z/z_{\text{avg}}\) for vertical separation and \(a_i = 12 + 11\Delta y/z\) for lateral separation, where \(\Delta z\) is the height difference, \(z_{\text{avg}}\) is the average of the two heights and \(\Delta y\) is the lateral separation at the same height \(z\). In the literature, several other models of varying degrees of sophistication can be found.

The coherences also depend on stability: the decay constant \(a_i\) increases significantly in stable conditions and decreases slowly with increasing instability. In strongly stable conditions the picture is somewhat blurred by the fact that the low-intensity, small-scale turbulent fluctuations are masked by the presence of slow, large-scale, highly coherent, two-dimensional structures. Except for minor differences in average stability (slightly more stable over the sea), there is no reason to believe that the coherences should behave differently over the sea. In complex terrain, however, where we typically see excess turbulence at large scales, one might expect that, as for unstable conditions, the coherences will increase somewhat.

The presence of operating wind turbines in the flow has significant impact on the flow properties close to the rotor (within 10 diameters).

- The wind speed is decreased inside the wake, giving rise to large shear at the top of the wake.
- Turbulence levels are increased inside the wake and, since the mean wind speed is decreased, there is a considerable increase in turbulence intensity.
- The length scale of turbulence is decreased inside the wake, because the turbulence produced by the shear layers in the wake is created at length scales of the same magnitude as the cross-wind dimensions of the wake, which are typically an order of magnitude smaller than the length scale of the turbulence in the free flow.
- Because of the wake-imposed length scale, turbulence length scales in the wake for the different components of wind speed approach each other.
- In general, second-order statistics are quite perturbed inside the wake, and the usual boundary layer approximations for variance, etc. become quite different in the non-equilibrium turbulence in the wake.
- Spectral coherence in the wake seems to be well described by the usual models, except for the near wake (distances \(\lesssim 5D\)).

Examples of changed mean and turbulence quantities are shown in Figures 10 and 11.

The turbulent velocity fluctuations, defined as the deviations of the instantaneous velocity from the average value (averaging time 5–60 min), are not the manifestations of a Gaussian process. Although probability distributions of wind speed fluctuations to a good approximation follow a normal distribution, accelerations are in general observed to have wider distributions (‘longer tails’). Despite these deviations and because of the lack of a better description, the gust, defined as the maximum wind speed during a measurement period of 5–60 min, is often calculated using a Gaussian process as an approximation. Using assumptions of stationarity and that a wideband process results in a joint Gaussian description of \(u\) and \(du/dt\), the expected gust value during time \(T\), where we have first block-averaged data over time \(\tau\), is

\[
\frac{U_{\text{max}} - \bar{U}}{\sigma_u} = \sqrt{2 \ln \left( \frac{T}{2\pi \sigma_u(\tau)} \right)}
\]
where $\sigma_u(t)^2$ is the variance of wind speed fluctuations with a lower cut-off at the frequency $1/T$ and block-averaged over time $\tau$, and $\sigma_f(t)^2$ is the filtered variance of wind accelerations.

The results of such a calculation, using the Kaimal spectrum, are shown in Figure 12(a), which also shows the results of simulated Gaussian turbulence plotted as a function of the length scale (spectral peak) of the turbulence. Measured data from the Finnish Kopparnäs site are shown in Figure 12(b) for different heights, plotted as a function of wind speed. These measurements are quite consistent with the model results and show very little variation with height. The scatter around the curves is larger at low wind speeds and decreases towards higher speeds; typical standard deviations are 0.5 at 5 m s$^{-1}$ and 0.4 at 15 m s$^{-1}$.

Figure 10. Profiles of (a) standard deviations of wind speed fluctuations and (b) length scales upwind and 5-3 rotor diameters of an operating wind turbine. Hub height is 31 m and rotor diameter 28 m. Averages of 17 half-hour series with hub-height speeds of 6-8 m s$^{-1}$ in near-neutral conditions were selected.

Figure 11. Downstream development of turbulence intensities at (a) hub height and (b) hub height + 0.5D for three different wind speeds. The smooth curves were drawn through averaged data at 2D, 7.5D and 14.5D; undisturbed data correspond to 24 diameters downstream. Hub height is 31 m and rotor diameter 28 m.
Another school of gust modelling takes its starting point in different characteristic shapes of gust events, that vary depending on the data set used. Some typical examples are described in Reference 53.

For calculations of the mechanical loads on a wind turbine rotor it is necessary to have detailed information about the spatial structure of the 3D wind field. Many load models use the Veers model, but in recent years the more efficient, realistic and flexible Mann model has been developed.55

**Extreme Winds and Exceedance Statistics**

The proper design of a wind turbine for a specific wind climate must take into account the number of times, or the probability, that large loads and resulting large responses may occur over the lifetime of the turbine. As for other engineering applications, it is useful to use the return period $T$, which is the average time interval between excursions beyond a certain load. The largest loads are caused by the strong winds which occur in connection with severe weather phenomena. Most severe are undoubtedly tornadoes, where it is claimed that wind speeds up to 100 m s$^{-1}$ occur. A tornado is very localized, with a horizontal extent of typically 500 m and a lifetime of tens of minutes. It is therefore almost impossible to estimate the probability that a specific location will be hit by a tornado. However, it is well known that tornadoes are more prevalent in North America than in other places on the Earth; about half of the world’s tornadoes occur there and most of the other half occur in about 20 other countries. Very violent winds are also encountered in connection with the about 80 large-scale, severe storms—tropical cyclones, hurricanes and typhoons—that occur each year. The polar front in the northern latitudes is the cause of cyclones of large extent, 1000 km, and with winds occasionally reaching the wind speeds of hurricanes and perhaps even tornadoes.

Good instrumental records are a necessary requirement for determining exceedance statistics. So are adequate statistical methods to determine the appropriate statistics, and methods by which the statistics can be transformed from the location of the measurements to other locations. In the engineering literature, extreme value statistics are often expressed as the average return period—typically 50 years—for a 10 min average wind speed of a certain (large) magnitude. Below, we illustrate a procedure for obtaining these statistics$^{56}$ by means of data from the Faroe Islands. The data series are all too short, but the analysis shows the principle of as well as possible problems with the method. Data were measured on several islands in order to study the wind conditions at a range of typical topographical sites. The measurements during a severe storm are shown in Figure 13(a) for the two islands of Nordradalsskard and Glyvursnes.
The first station is situated at a saddle point 267 m a.s.l. and is strongly affected by the orography, whereas the other station is considered not to be influenced by the local topography. The largest 10 min mean wind speed at 10 m at the first station was 58.1 m s$^{-1}$, and the lattice tower carrying the instrumentation collapsed when the 2 s gust value reached 76.7 m s$^{-1}$. The highest 10 min value at the second station was 39.2 m s$^{-1}$. The data series for the latter station covering 7 years is used for the extreme value analysis. First, the standard procedure is followed by plotting ranked extreme events versus the double logarithm of their relevant probabilities and fitting a straight line. This gives the speed which on the average is exceeded once in the period $T$ considered. The result is given in Figure 13(b). The double exponential form of the accumulated probability function implies that for large (rare) events the probability density function itself is nearly an exponential of the form $p(u) \approx \exp(-u)$. For such processes it can be shown that the average number of exceedances $\eta$ per unit time of a certain speed $u$ is proportional to $p(u)$. This can be used to extrapolate the above return period to another return period $T$. Thus, for one exceedance on the average, $T \eta$ is constant, i.e. $T_1 e^{-u_1} = T_2 e^{-u_2}$, or

$$u_2 = u_1 + x \ln \left( \frac{T_2}{T_1} \right)$$

where $x$ is the slope of the regression line in the ranking plot. Approximately the same results are obtained when other common statistical methods, e.g. selecting the events as individual storms, are used. The result is also rather insensitive to whether the analysis is carried out on the wind speed itself or on the wind pressure. Finally, the estimated extreme value which is valid for conditions of 10 m above fairly open terrain can be extrapolated to other topographical conditions and other heights on the island by applying the wind atlas method.

Figure 13(b) depicts a problem of the analysis: the storm event from Figure 13(a) is completely off the regression line. If we use the parameters of this, calculated without the data from 22 October 1988, we obtain an average return period of approximately 300 years. However, this is an irrelevant and useless prediction. The only conclusion we can draw is that this singular event must belong to a different
phenomenon than the rest of the extreme value ensemble. We do not have a solution to such problems, except to state that in order to get reliable extreme value statistics such as 50 year return periods, only long time series of well-measured data from a homogeneous statistical ensemble might suffice.

**Areas of Further Research**

It is our hope that this overview article on wind power meteorology will initiate a number of articles on central topics by authors well versed in this discipline. It is also foreseen that contributions will come from basic disciplines such as meteorology, climatology, geography, fluid dynamics, time series analysis, stochastic processes, etc. Overall, it is essential that the contributions add to the general knowledge on the utilization of wind energy. Well-undertaken and well-described research will help the wind energy community to accelerate progress by avoiding wasting time and effort.

The following list of areas of further research reflects our view and therefore cannot be complete. A more general view can be found in Reference 59, where the European wind energy research community has put forward a ‘road map’ for future R&D in wind energy.

**Weather and wind climate:**

- Systematic methods for the description of the ‘large-scale’ climate.
- The variability of the wind climate, temporally and spatially, i.e. how much the expected energy output varies from year to year in different parts of the world.
- Extreme winds as a function of location, locally (influence by local topographic features) and globally.

**Winds in the atmospheric boundary layer:**

- Realistic models for the turbulence in real terrain. How can the results from simplified models be applied to real-life conditions, and how large variations are to be expected around ‘standard conditions’?
- Wind turbine wake models are used routinely for modelling the mean flow, but some of the pertinent questions remain only partly answered or unanswered. What are the merits and drawbacks of the different models? How do we model turbulence realistically in the wake?
- Disturbed wind and turbulence fields close to obstacles, forests, cliffs, etc., modelling and measurements, and their effects on wind turbines.

**Acknowledgements**

Much of the work by Risø National Laboratory on wind energy in general and wind energy resources in particular has, since 1981, been supported by the Commission of the European Union, Directorate-General for Science, Research and Development. The Danish Energy Agency of the Ministry of the Environment and Energy has supported many of the national wind energy and wind power meteorology projects through the EFP-program. The offshore measurements at the Vindeby site were further sponsored by the Office of Naval Research, the Danish Technical Research Council and the Danish utility ELKRAFT. The wind data from the Faroe Islands are presented by courtesy of S. P. Heinesen, Landsverkfrødingurin (Office of Public Works), Faroe Islands. H.P.F. is sponsored by the European Commission through the program ‘Training and Mobility of Researchers’.

Last, but definitely not least, we would like to thank Dr L. Kristensen, Risø, for his review of and comments on an early draft of the paper.
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