# Course Offshore wind farm design OE 5662

## Module 4 Offshore Wind Climate

## Background document

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# General information on wind climate

### *1.1 Structure of the atmospheric boundary layer*

Wind is moving air caused by pressure differences in the atmosphere, initiated by temperature differences. At large heights (~1000 m) the wind is not perpendicular to the isobars but parallel to it due to the Coriolis force (caused by the rotation of the earth; perpendicular to the wind velocity). This wind is denoted the geostrophic wind.

| | | | |
|---|---|---|---|
| G | : pressure gradient force | Ug | : geostrophic wind |
| C | : Coriolis force | U | : wind at the ground |
| W | : drag force (friction) | | |

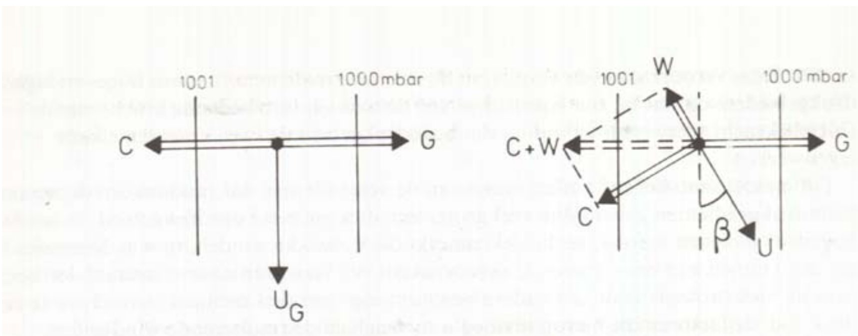



Fig. 1

At lower heights friction will lead to wind shear: a reduction of the wind magnitude (especially in the so-called surface layer, the first few 100 meters above ground level) and a change in the wind direction (especially above the surface layer: the Ekman layer).

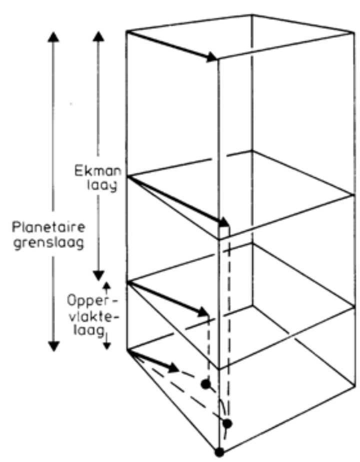



Fig. 2: Ekman layer in lower part of atmosphere

There are two causes of the friction:

a) Mechanical: the friction is a function of the terrain roughness, characterised by the roughness length $z_0$.
b) Thermal: the friction depends on the stratification of the atmosphere: an unstable atmosphere will lead to mixing of air layers (the warmed air above the hot surface will rise and lead to mixing of air layers with different velocities).

## 1.2 Stability of the boundary layer

The picture below shows the general built up of the temperature and the pressure of the earth atmosphere.

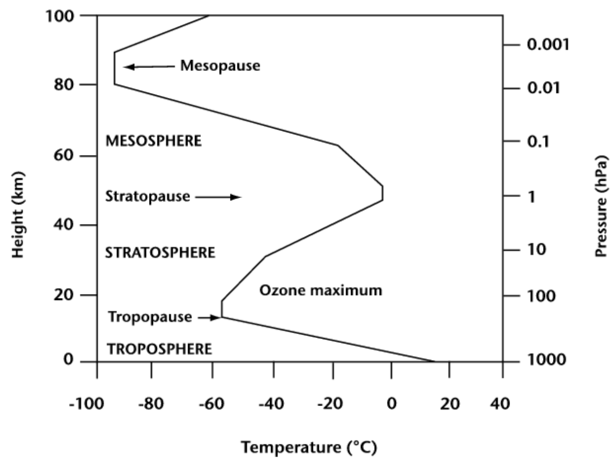



Fig 3: Temperature and pressure distribution in the atmosphere of the earth

An important aspect regarding the stability of the atmosphere is the temperature gradient in the surface layer of the earth atmosphere. As can be seen there is a fairly constant temperature gradient in the troposphere, the lower 10 km of the global atmosphere. A more detailed evaluation of the pressure and temperature gradients in the troposphere is necessary for the determination of the stability of the atmospheric boundary layer. The stability of the boundary layer is the determining factor for the wind speed gradients that are experienced the first few 100 meters above ground level.

### 1.2.1 Temperature and pressure in the boundary layers

One of the processes that are connected to vertical motions in the atmosphere is stability. This describes the tendency for the atmosphere to either resist or enhance vertical motions. The stability of the atmosphere is directly related to the changes of temperature with height, and evidently the changes of pressure with height.

The changes of **pressure** with height in still air (no motions) are described by

$$dp = -\rho(z) g dz \quad (1)$$

where $\rho$ is the density of the air, $g$ the gravitational acceleration (9,806 m/s$^2$) and $z$ the vertical coordinate.
Now consider the temperature changes experienced by rising air. This is best done with the paradigm of a “parcel of air”. Such parcels of air are large enough to neglect the amount of mixing with the surrounding air. As such a parcel of air rises, it moves into regions of lower pressure. This means that the surrounding air is pushing on the parcel with less force. So the air in the parcel will expand, and the volume will become larger.
When the air expands, the molecules must cover a larger volume. This means that the air in the parcel must perform work to inhabit the increased volume. Since there is effectively no transfer of energy between the parcel of air and the surroundings, the work done by the parcel will result in lower temperature. Such a system is called **adiabatic**. The term simply means that no exchange of energy with the outside environment. The relation between temperature and pressure gradient is then given by:

$$c_p dT = \frac{1}{\rho} dp \quad (2)$$

where $c_p$ is the specific heat at constant pressure (for "dry" air 1.005 kJ/(kg $^o$K)) and T the temperature [ $^o$K]. The relation between temperature and height is thus:

$$dT = -\frac{g}{c_p} dz \qquad (3)$$

An atmospheric boundary layer, in which the temperature distribution is according to the above equation, is known as neutral. In such a neutral atmosphere a parcel of air will not have the "natural" tendency to move vertically, since it experiences neutral "buoyancy". When such parcel rises its expansion and hence its temperature reduction matches exactly new the conditions (pressure and temperature) at the new height.

### 1.2.2 Dry adiabatic lapse rate

The **lapse rate**, or vertical temperature gradient, expresses the change of the temperature of the atmosphere with altitude (height). The **adiabatic lapse rate** is the rate at which the temperature of a parcel of descending or rising air would change due solely to compression or expansion associated with elevation change.
From the above equation (3) the **dry adiabatic lapse rate** can be determined. This is the change of temperature a parcel of unsaturated air will experience in a neutral boundary layer when it is moved to another altitude:
.

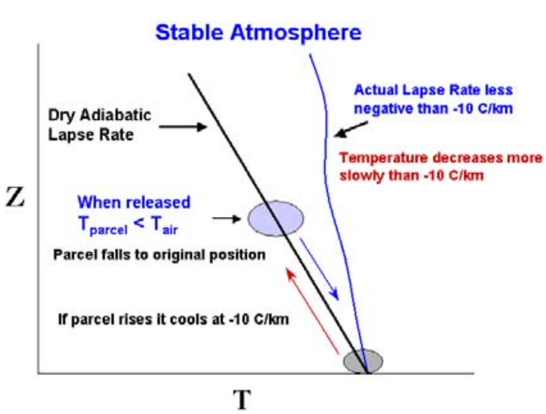
$$\frac{dT}{dz} = -\frac{g}{c_p} = -9.76 \quad [^o\text{K/km}] \qquad (4)$$

The dry adiabatic lapse rate, applicable for air containing no liquid water, is thus 9.76 $^o$K of cooling per 1000 meters that the air rises. It is thus valid for parcels of air in which no condensation of water occurs.

### 1.2.3 Stable, neutral and unstable atmospheric boundary layers

An atmospheric boundary layer, in which the actual temperature distribution is according to dry adiabatic lapse rate, is known as a **neutral** boundary layer. In practice the atmospheric (or environmental) lapse rate (the variation of temperature with height) will differ from the dry adiabatic lapse rate. If the gradient is less negative than the adiabatic value of –9.76 $^o$K/km, then the atmospheric boundary layer is stable. Vertical movement of parcels of air are stabilised by the actual temperature gradient, since they cool adiabatically. Such situation is called a **stable** boundary layer.

When the actual gradient is more negative that the dry adiabatic lapse the boundary layer becomes **unstable.** A favourable ambient temperature encourages vertical movements of air parcels. A rising parcel will become relatively warmer with respect to its environment, and thus its buoyancy increases and it keeps rising.



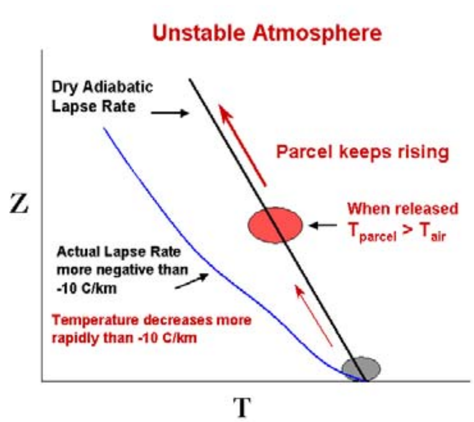



Fig 4: Lapse rate in a stable and in an unstable atmospheric boundary layer.

A stable atmosphere can usually be found above a cold surface, where hot surfaces will stimulate the development of unstable atmospheric boundary layers. Warmed air above such a hot surface will rise and will lead to mixing of air layers with different velocities.

### 1.2.4 Wind speed distribution in the atmospheric boundary layer.

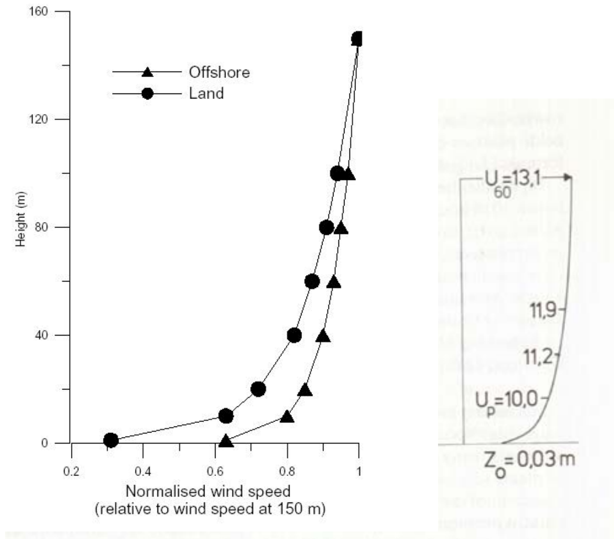



Fig. 5

The (mean) wind speed distribution in a neutral atmospheric boundary layer can best be described using a logarithmic profile. The following general equation is valid for the (mean) wind speed at some height $V(h)$ with respect to the wind speed at a reference height (e.g. a wind speed measured with a meteo mast at a certain height $h_{ref}$ ):

$$V(h) = V(h_{ref})\left(\frac{\ln(h/z_0)}{\ln(h_{ref}/z_0)}\right) \tag{5}$$

The logarithmic profile is a result of a physical description of the boundary layer equations; hence it is preferred above a power law, which is sometimes used in e.g. standards.
The value $z_0$ is called the roughness height and is a measure for the surface roughness.
Above land this roughness height typically varies between $z_0$ = 0.03 m. and $z_0$ = 1.00 m.
At sea the roughness height is significantly less. A typical value at open sea is $z_0$ = 0.0002 m.
Note that the value of $z_0$ is not a direct measure of the physical height of elements at the surface, but is a “fitting constant” in order to fit the logarithmic profile to the observed profile at higher altitude.
For non-neutral boundary layers a correction is usually applied upon the logarithmic wind profile:

$$V(h) = \frac{u_*}{\kappa}\left[\ln\left(\frac{h}{z_0}\right) - \Psi\right] \tag{6}$$

### *1.3 Estimation of the mean wind speed at a given location*

It is not possible to determine a map of the mean wind speeds due to the large local variations of the roughness length. To overcome this problem a so-called potential wind speed has been defined: this is the wind speed at a standard height of 10 m which would exist in case the local roughness length would be equal to the standard value of 0.03 m. The KNMI has processed such a map for the Netherlands based on several years of wind measurements. Similar maps exist for other countries.

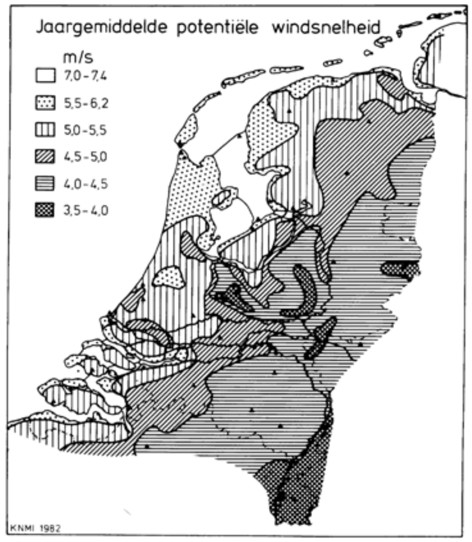



Fig. 6

As can be seen in the figure, there is a missing category, form 6.2 to 7 m/s. This is caused by the way in which this potential wind speed map has been produced. Wind velocities at larger heights have been translated downwards to the reference height of 10 m with a roughness length of 0.03 m at land, but with a roughness length of 0.0002 m at sea. This causes the discrete step between 6.2 and 7 m/s for coastal locations.

### *1.4 Wind statistics*

Wind is extremely variable: it fluctuates continuously in speed and direction. This variability extends over an enormous range of time scales. This variability results from the many different physical phenomena which influence the wind; each has its own characteristic effects and occurs over a characteristic range of time (and length) scales. The figure shows a (fictional, similar to Van der Hoven) power spectrum of wind speed variations (showing the contribution of different time scales to the total variability).

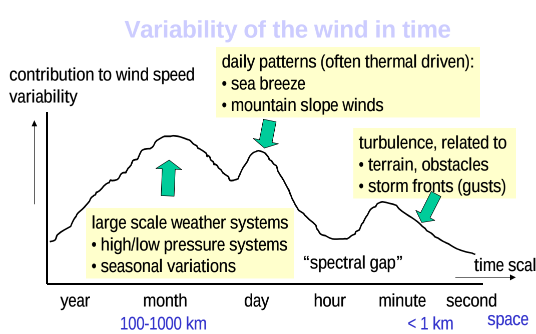



Fig. 7

- On the scale “second to minutes” : stationary turbulence, caused by friction of the wind with the surface, by wakes of obstacles, by thermal instability (warm air rises); non stationary “turbulence” related to cold fronts, hail storms etc.
- On the scale of “ hours to days”: passing of the above mentioned non stationary phenomena; thermally driven daily circulations as sea breezes, mountain slope winds
- On the scale of “days to weeks”: changes due to development and passing of large scale weather systems
- On the scale of weeks to months”: seasonal differences, related to regional and global temperature differences;
- On the scale of “years to years”: year to year differences caused by cyclic solar activity, “El Nino” type of phenomena, long term trends eg. global warming !).

The picture shows that time scales between “many minutes“ and “few hours” contribute much less to the overall variability than smaller and especially larger time scales. This means that if one compares an one hour average with the next one hour average, these values are likely to be more similar than comparing two successive week averages or second averages. The low variability around these middle time scales is called the spectral gap. The very existence of the spectral gap makes it possible to split the analysis of wind into two main parts A and B, where A is the variability due to “turbulence” and where B is the variability due to “climatology”. It has turned out to be convenient to separate these two parts by using a 10 minute average (or up to 1 hour, this choice is not very critical).

The frequency distribution of the mean wind speed exhibits an important characteristic: it can be assumed to be distributed according to the cumulative Weibull distribution function which is determined by two parameters only:

$$F(U) = 1 - e^{-(U/a)^k} \tag{7}$$

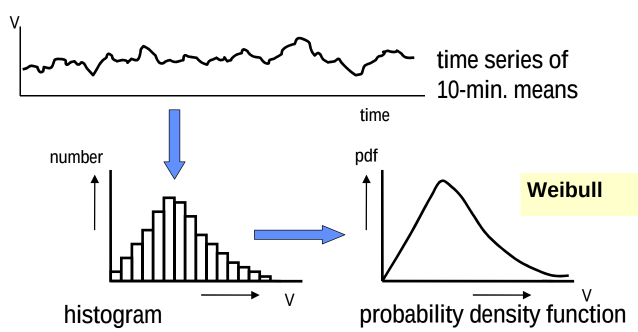



Fig. 8

Here F is the probability of a wind speed smaller than U, a is the Weibull scale factor and k is the Weibull form or shape factor. Another, maybe more familiar form is the following:

$$f(U) = \frac{k}{U}\left(\frac{U}{a}\right)^k e^{-(U/a)^k} \tag{8}$$

Here f is the continuous probability density function of wind speed U. The Weibull parameters a and k can be calculated by a fit matching the observed data (measured or hindcast). This can be done for each of the twelve wind direction sectors (of 30 degrees each).
The parameter a is proportional to the mean wind speed with a given k.

By straightforward combination of the Weibull distribution and the power curve of the wind turbine (power as function of the wind speed at hub height; both averaged over 10-min) the annual energy yield can be determined.

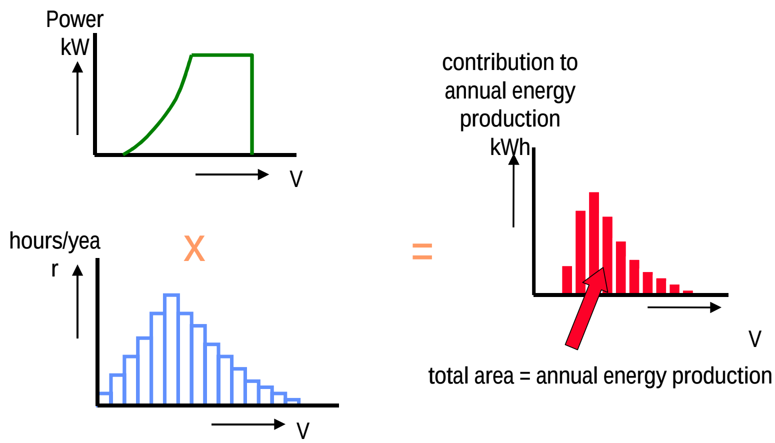



Fig. 9

There are basically two ways to obtain the Weibull distribution for a specific site: derive from existing data or measure. To derive from existing data is of course much cheaper and quicker than performing measurements. Because of the spatial variability, one can not assume that the wind speed at location A is equal to that of location B, even when they are only kilometres apart (effect of terrain shape, roughness, and obstacles). Correction methods have been developed to take account of these differences. These methods (grouped here under the name of “wind atlas correction methods”) have their limitations and are increasingly troublesome with increasing complexity of the terrain. Making measurements is than an option, in particular when wind atlas methods are expected to be not reliable enough and/or when the wind farm investment is so large that highly accurate data are needed.

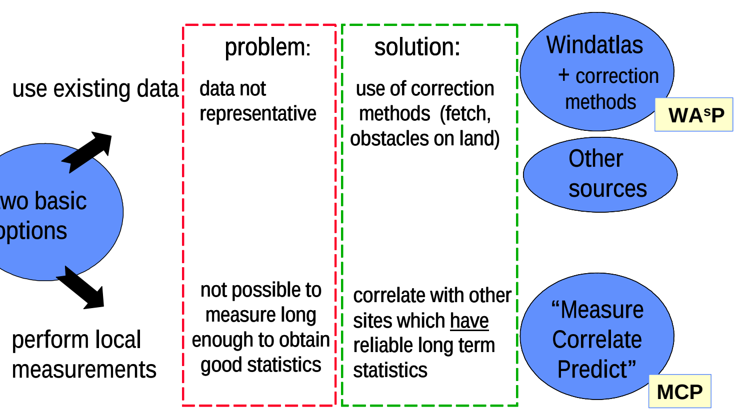



Fig. 10

Because the wind is so variable, also from year to year (annual average wind speed from one year can easily differ 20 % from another year) one needs to measure for many years to obtain a reliable average. This is both time consuming and costly. As a solution, the so-called MCP (Measure – Correlate – Predict) methods have been developed, which correlate the measurements with simultaneous measurements at a site where long term statistics are available. The required measurement period can thus be reduced. MCP methods have also their limitations, the obvious one being that the method requires a correlation (physical relation) between both sites. Without (or with only little) correlation it just spoils the quality of the short term measurements. When this is the case, one just has to measure long enough to develop a reliable long term picture. One should realise that both methods, in one way or another, need to use existing long term reliable wind statistics: MCP to transform the short-term (even one year is short term) measurements to long term and wind atlas methods to give the basis input. It is of course also useful to combine both methods and use the short term correlation to validate/calibrate theoretical methods.

In the offshore zone, close to the coast, several factors complicate the assessment of wind profile and wind resource. It can be expected that stability effects are important; very low roughness and large differences in temperature structures, both over the day and over the seasons. Three different cases are for instance: In the summer sea breezes can develop during the day and with onshore wind the air is in equilibrium with water surface temperature (1). The return flows at night results in relatively warm air flowing out over colder water (2). In the winter the water is usually warmer than the land, so when the wind flows from land to sea, cold air flows over warm water (3). It has turned out that current wind atlas methods ( ~1999/2000) can not accurately predict the wind resource in the coastal zone. Only when one is far enough from the land, the methods can more or less be applied, provided account is taken for the fact that the surface roughness is to some extent depending on the wind speed itself (high waves at high wind speeds give a somewhat higher roughness). Development work is yet going on to improve the modelling in the coastal zone, so-called Coastal Discontinuity Models.

## *1.5 Turbulence*

Variation of the wind speed within a period of 10-min is called turbulence. These fluctuations have a Gaussian (normal: 'bell-shaped') distribution. The ratio between the standard deviation and the 10-min. mean wind speed is called turbulence intensity. Turbulence does not effect the energy yield but it is vital for the dynamic wind turbine loading.

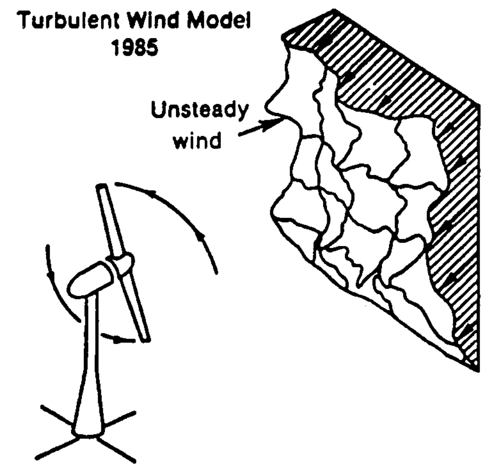



Fig. 11

The characteristic time scales of turbulence varies between a second to minutes; the corresponding length scales range from a meter to hundreds of meters. The spatial variation of turbulence is 'felt' by a rotating wind turbine blade as temporal ones; this phenomenon is denoted rotational sampling. It results in a dynamic wind loading with main frequencies equal to the rotor frequency (so-called '1P') and its multiples (2P, 3P, …nP). Apart from turbulence the following wind loads result in periodic wind loads which may lead to fatigue: wind shear, yawed flow and tower shadow. Note: also gravity acts as a periodic load (in the so-called lead-lag direction: parallel to the rotor plane).

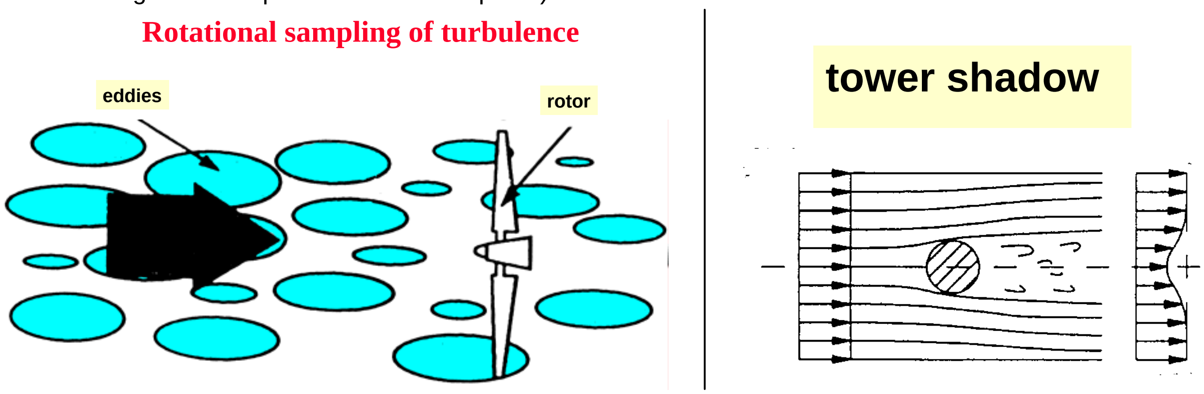



Fig. 12

Nowadays, it is common practice to generate 3D stochastic wind fields, for several mean wind speeds, to account for turbulence in the simulation of wind turbines. For such a simulation, the turbulence spectrum should be known as well as the turbulence intensity. The number of occurrences of each mean wind speed during the design lifetime of the wind turbine follows from the Weibull distribution.

## *1.6 Extreme wind speeds*

The KNMI has also compiled a map of extreme wind speeds (10-min. or 1 hour mean values). Usually a return period of 50 years is applied; i.e. the extreme wind speeds occur *on average* once in 50 years.

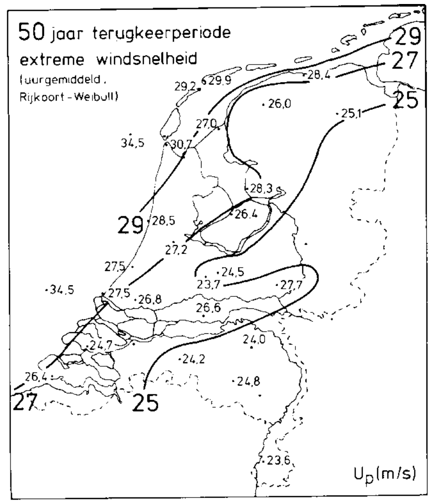



Fig. 13

For the determination of the extreme wind loads, the turbulence on top of the extreme wind speeds must be taken into account. For this purpose, standards specify deterministic wind gust shapes. Ongoing research aims at a more precise, stochastic description of gusts.

# Overview of existing offshore wind information

## *1.7 Overview of existing data*

For information on the offshore wind climate several sources of data are at hand.
However, the combination of detailed and long-term data of sufficient quality and availability is very rare. Therefore different types of data will probably have to be combined to achieve good results.
There are three main criteria that are important. For each type of data source the extent with which is complied to these criteria is shown in Table 1.

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| | **Accuracy** | **Duration** | **Resolution** |
|---|---|---|---|
| **Pressure data** | -- | ++ | - |
| **Data VOS** | - | + | ++ |
| **Light-ship data** | +/- | ++ | - |
| **Satellite data** | +/- | - | + |
| **Platform data** | ++ | +/- | + |
| **NESS** | ++ | + | ++ |

Table 1: Overview of characteristics of several data sources

### 1.7.1 Pressure data

The main problem with using pressure data is the fact that a conversion step is necessary to obtain wind speed data. Theoretically the geostrophic wind (also called “free” wind, because it is the wind that does not depend directly on the characteristics of the underlying surface) can be derived simply from pressure gradients. For the North Sea this has been done by Børresen, leading to the Wind Atlas for the North Sea and the Norwegian Sea. The underlying pressure data set had a duration of 27 years (1955-1981). The grid size was 150 km by 150 km, and the temporal resolution was 6 hours. The geostrophic wind speeds were reduced further to 10-minute mean wind speeds at 10 m height by using a geostrophic drag law.

The JOULE-project POWER uses similar methods to obtain geostrophic wind speeds over all European seas. The reduction to near-surface winds is carried out using WAsP.
In the table the accuracy does not score well, because the translation from pressure observation to near-surface wind speed inherently gives rise to uncertain results. The two main advantages of the use of pressure data are: the duration (can be over 100 years) and the large coverage.

### 1.7.2 Data Voluntary Observing Ships

The data of Voluntary Observing Ships are reliable and have been checked since 1960. They cover the entire globe and have high spatial resolution (0.1° × 0.1°). The individual observations probably have flaws, due to the variety of observers and methods of observation (visually or using instruments). It is not possible to check every observation, although there are standard procedures. But due to the abundance of the data they may prove very valuable. The data consist of wind speed and direction, wave parameters, visibility, temperatures of air and sea water and atmospheric pressure.
Several studies have been conducted using VOS data as a starting point. One is a JOULE project by Germanischer Lloyd and Garrad Hassan leading to the report Study of Offshore Wind Energy in the EC. For this project the Deutsche Seewetteramt has (re)analysed many VOS-data and derived a crude wind map for all European seas with wind speeds re-scaled to 25 m height.
In the past KNMI has published a report by Korevaar using VOS showing several results of analyses. E.g., exceedance of wind speeds expressed in Beaufort and of wave heights in m for the North Sea in several seasons and for a whole year. Furthermore, extremes of the wind and waves are given in return periods of 50 years. KNMI is willing to make the data available and suitable for an update of these analyses. The data comprises 40 years: 1960-2000.

### 1.7.3 Light-ship data

Data from light-ships have been used quite extensively in the past to gather information about the offshore wind and wave climate. Another report by Korevaar was devoted to this topic. This type of data was also used for Windklimaat van Nederland.
Light-ships are stationary and usually are installed for several decades. In recent years they have been removed and were replaced by unmanned light isles or otherwise. The observations at light ships were made by visual inspection, with the use of the Beaufort scale according to its strict definition. In a later stage the conversion from Beaufort classes to near-surface wind speeds was investigated and established.
Another study was conducted by RWS, in which observations of the period 1907—1980 were analysed from three light-ships: Haaks & Texel, Schouwenbank & Goeree and Noordhinder. Finally, the two light-ships Noord-Hinder and Texel were also described.

### 1.7.4 Satellite data

The technique of remote sensing has developed very rapidly in recent years. The use of satellites to gather data is now common practice. Over water surfaces it is possible to “measure” wind speeds by interpreting the wave appearance. This technique has the advantage of great spatial coverage, but the disadvantage of poor accuracy and temporal character (‘snapshots’). Furthermore, satellite images have become available during recent years so the length is not very long. However, this type of data source will become more and more widely used and may provide additional information to other available data sources at this moment.

### 1.7.5 Data from platforms and other offshore sites

Since the beginning of the eighties, just when the light-ships were being removed, KNMI and RWS have started to install meteorological instruments on various platforms and other offshore constructions called the Measuring Network North Sea. This Network is unique and supplies invaluable information. Both wind and wave characteristics are measured, and now already during more than 10 years at several locations. RWS is mainly responsible for operation and maintenance, KNMI for the calibration of the instruments, the quality of the data and the storage for later use.
About 10 years ago the first research project was undertaken to make use of the data of a platform for wind energy applications.

In about the same period a similar network was established in the province of Zeeland by RWS. It is called the Monitoring Network ZEGE (ZEeuwse GEtijdewateren). In stead of using existing structures custom made measuring posts were used. Currently about 10 are in use that are equipped with anemometers. Also wave measurements are carried out at several locations by buoys. The data are gathered and stored for later use. Although the main focus is on the inland waters of Zeeland, some posts are located in the North Sea. Data form ZEGE were used for the feasibility study for the 100 MW Near Shore demonstration project.
In England the oil platform West Sole has been equipped for some time with instruments at several heights up to about 80 m above Mean Sea Level (MSL). The feature that makes this configuration unique is the fact that turbulence intensities were measured as well as wind speeds. Several publications have been devoted to the results of the measurement campaign conducted at West Sole. However, one conclusion drawn from a comparison with other platform data was that the situation just east of the English coast is not the same as west of the Dutch coast in terms of temperatures and therefore stability. In prevailing westerly winds the fetch at West Sole is mainly over land, while near the Dutch coast it is mainly over sea.

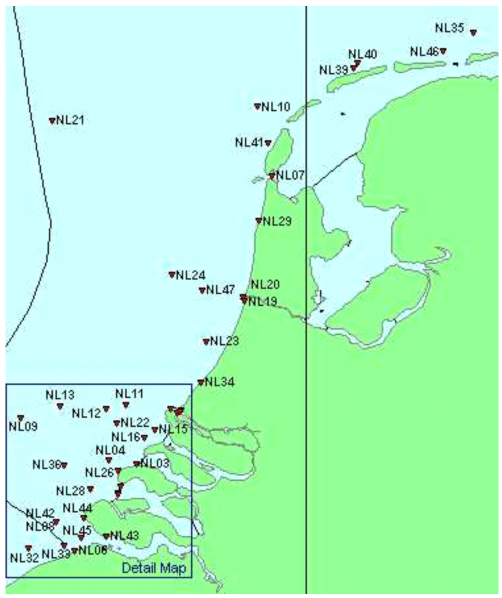


Fig. 14

| ID | Name | Code | Northing | Easting | Anemometer height[1] | Period | Water depth |
|---|---|---|---|---|---|---|---|
| NL20 | IJmuiden-harbour | IJM | 52º27'47" | 04º33'22" | 18.5 m | 1987—1997 | n.a. |
| NL24 | IJmuiden depot | IJM | 52º33'30" | 04º03'30" | n.a. | 1987—1997 | 21 m |
| NL23 | Measuring post Noordwijk | MPN | 52º16'23" | 04º17'50" | 27.6 m | 1987—1997 | 18 m |
| NL22 | Light Isle Goeree | LEG | 51º55'29" | 03º40'06" | 38.3 m | 1991—1997[2] | 22 m |
| NL13 | Euro platform | EUR | 51º59'55" | 03º16'35" | 29.1 m | 1987—1997 | 32 m |
| NL21 | K13 platform | K13 | 53º13'04" | 03º13'13" | 73.8 m | 1987—1997 | 30 m |
| NL01 | Auk platform | AUK | 56º23'59" | 02º03'56" | 103.3 m | 1987—1995 | 85 m |

Note: The location of the AUK platform is not shown in the figure as it is further north near Norway.

Table 2: Characteristics of the selected offshore locations with concurrent wind speed and wave observations of the Measuring Network North Sea.

### 1.7.6 Availability of data

Considerable effort has been devoted to obtain information about the availability of data. Knowing the existence of databases and of the owner or user is not enough to actually get hold of them. In general three routes for various databases can be distinguished.

The main institution collecting and distributing data in The Netherlands is KNMI. They have established an online database which can be assessed for wind energy applications. The project in which this database is set up and can be used by external parties is called the Hydra project (http://www.knmi.nl/samenw/hydra/index.html). Most of the information concerns onshore locations, but there is also data available for 7 offshore measuring posts.

## *1.8 Overview existing knowledge*

Many of the formulas given in this report depend on the stability of the boundary layer. Here it is assumed that the stability conditions are neutral. For the time being this seems justified because *on average* the influence of the stability on the wind profile seems to be very limited according to measurements at on offshore location.
By means of sensitivity studies, on energy yield and design loads, the validity of this assumption can be investigated. Furthermore, neutral conditions correspond with high wind speeds, so the assumption will probably lead to conservative design loads.

### 1.8.1 Wind resource

For the economics of a wind farm, the estimate of the average energy production is essential. For an accurate estimate of the energy output the following information is important. First the statistics of wind speeds are described, than an overview of methods to calculate the wind speed at hub height (wind profile) is given

*Statistical description*

One of the main drivers for offshore siting of wind turbines is the higher mean wind speed. In the figure the Weibull distribution onshore and offshore are compared.

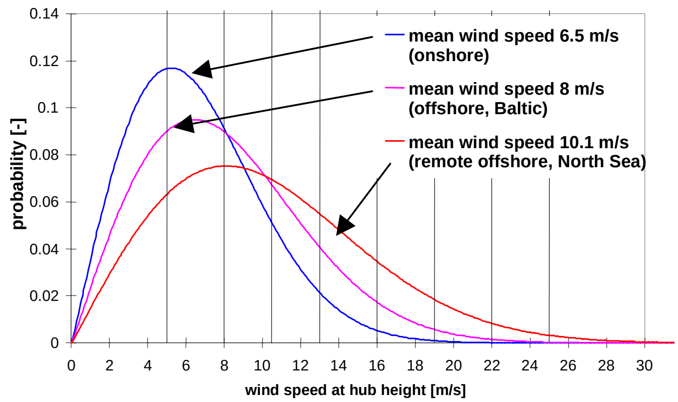


Fig. 13

The annual mean wind speed can vary considerably in different years. A standard deviation of annual mean wind speed of 11% is found for offshore locations, which is large compared to the 5.5% for onshore sites.

In order to determine the long term mean wind speed a database of 30 years or more is necessary; such long databases are not (yet) available for offshore locations. In case such a database becomes available for some locations, this will be also useful for locations nearby (for which only a limited data set is available). A correction factor can be determined based on the ratio of the annual mean wind speed for the two locations. Such method is standard practice for onshore situations.

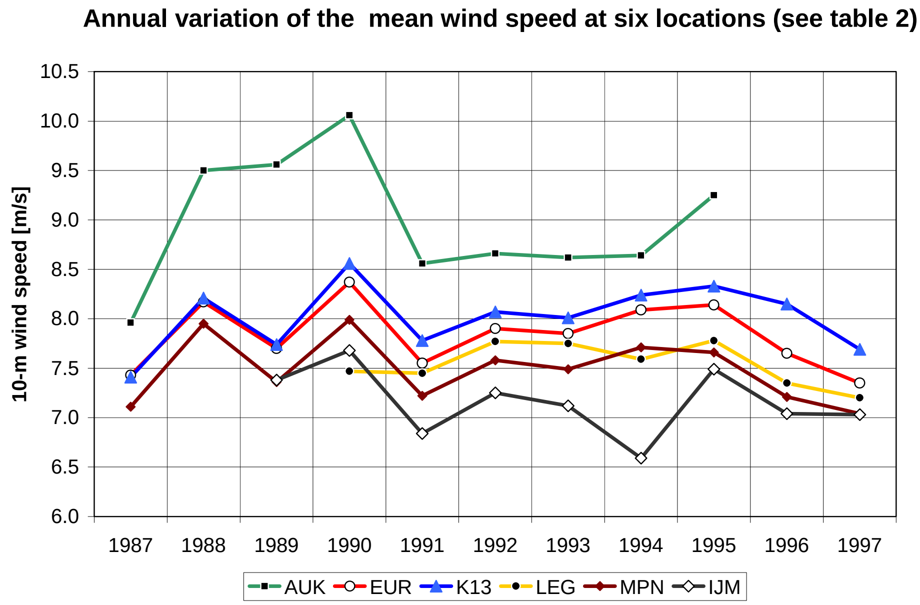


Fig. 14

*Wind profile*

Usually the wind speed at hub height has to be calculated from wind speed observations or models where the wind speed is given at a standard height of 10 m. The simplest relationship to describe the wind profile (i.e. the horizontal wind speed U as function of height Z) is a power law:

$$\frac{U(Z_1)}{U(Z_2)} = \left(\frac{Z_1}{Z_2}\right)^{\alpha} \qquad (9)$$

This is a non-physical expression which gives reasonable results for the correct value of $\alpha$ (usually in the order of 0.1, for offshore locations the exponent $\alpha$ is equal to 0.11 according to GL). The IEC uses a value of 0.2, KNMI uses a value of 0.13 for standard height corrections of offshore observations.

A first step towards a physical description of the wind profile is the logarithmic law. It incorporates the roughness length $z_0$, and gives therefore more information, in this case about the underlying surface:

$$U(Z_1) = \frac{u_*}{\kappa}\ln\left(\frac{Z_1}{z_0}\right) \Rightarrow \frac{U(Z_1)}{U(Z_2)} = \frac{\ln\left(\frac{Z_1}{z_0}\right)}{\ln\left(\frac{Z_2}{z_0}\right)} \qquad (10)$$

The value of the Von Kármán constant $\kappa$ is 0.4, while $u_*$ is the friction velocity, a measure for the effectiveness of vertical exchange of momentum. In this expression it is assumed that there is no heat exchange (adiabatic conditions), and the wind profile is completely determined by mechanical turbulence. This assumption is certainly true for high wind speeds, and appears to be true *on average* for offshore conditions.

Onshore the value of $z_0$ depends on the terrain conditions only and is not influenced by the wind speed. It can of course be dependent of the wind direction because it reflects the characteristics of the upwind terrain only.

In offshore conditions the value of $z_0$ *does* depend on the wind speed. Due to the generation of waves by the wind there is a strong correlation between the wind speed and the roughness length. In a simple form this relation was formulated by Charnock as follows:

$$z_0 = \alpha \frac{u_*^2}{g} \tag{11}$$

Here g is the gravitational constant, and $\alpha$ is a constant with a value of 0.01-0.02. In neutral conditions there are two equations, (5) and (6), with two unknowns (U and $z_0$) that can be solved numerically.

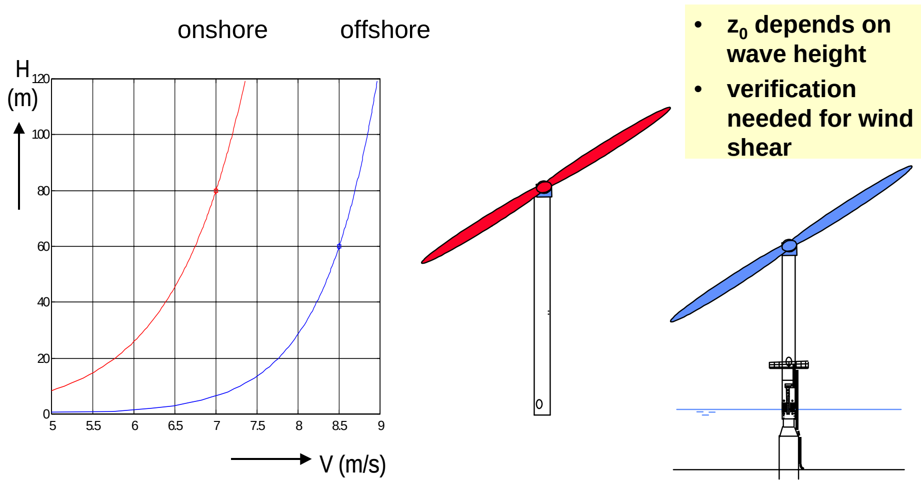


Fig. 15

*Stability effects*

Finally thermal effects can be introduced into the picture. In general this is done by extending the earlier given logarithmic profile relationship with an extra term:

$$U(h_1) = \frac{u_*}{\kappa}\left[\ln\left(\frac{h_1}{z_0}\right) - \Psi\left(\frac{h_1}{L}\right)\right] \tag{12}$$

The term $\Psi$ is the so-called stability function. It depends on the ratio of the height and the Obukhov length L. The value of L gives an indication of the stability conditions. For negative values of L the atmospheric conditions are unstable (warm surface, cold air, much vertical mixing), for positive values of L conditions are stable (cold surface, warm air, little vertical mixing, strong stratification). If the absolute value is large (>1000) the conditions are (near-)neutral (adiabatic conditions).

Although this framework appears to be rather simple (i.e. we now have three equations with three unknowns which have to be solved numerically), there are a few snags.

The first is that the form of the function $\Psi_m$ has to be determined, and the value of L has to be calculated. Basically the same equations are used for land or sea surfaces but with different parametrisations and input parameters. In the literature several formulations for this can be found. For conditions over sea the following input parameters are needed: wind speed and direction, air and seawater temperature. The second is that the validity of the used expressions is limited to a certain layer. In this layer (the atmospheric boundary layer) the conditions are subject to the physics as expressed in the previously given equations. However, the depth or height of this layer is dependent on several conditions. Especially in the case of very stable conditions (small positive values of L) the atmospheric boundary layer may be very thin, less than the (upper) tip height of a large wind turbine. In this case strong wind shear may occur due to uncoupling of the wind speed close to the surface and above the height of the boundary layer. Therefore care has to be taken with the use of the given equations and the interpretation of the results.

Moreover, a model is always a simplification of the reality and is in itself a possible source of errors. When it comes to exploring the outer limits of the model validity, it is important to have experiments to corroborate the theory. In the case of the theoretical description of a wind profile beyond 100 m above ground level there are hardly or no experimental data to rely on.

*Comparison of conditions onshore vs. offshore*

Looking at the general situation onshore compared to that offshore the following characteristics can be identified (see Table 3).
The reason for differences is as follows: first of all the sea water has a higher heat capacity than the soil onshore. Furthermore it is vital that the irradiated energy is mixed down. This results in a sea surface temperature which is constant during the day, but has a seasonal pattern which lags behind the pattern of the air temperature over land. This will not influence the energy yield as such but may be important with respect to the economic value of offshore wind energy on a free electricity market.
On land the irradiated heat leads to the warming of only the top of the surface. During the night this heat is radiated with long wavelengths, resulting in a cooling of the surface. So therefore the diurnal pattern of the surface temperature follows the solar irradiation (with a time lag of maybe a few hours). During the day the surface heats up leading to more mixing and therefore a wind speed maximum in the afternoon.

| | **onshore** | **offshore** |
|---|---|---|
| **diurnal pattern** | daily maximum | uniform |
| **seasonal pattern** | less pronounced | more pronounced |
| **stability** | diurnal pattern | seasonal pattern |
| **wind profile** | “unstable” on average | “neutral” on average |
| **mean wind speed** | decreasing inland | higher than on land |

Table 3: Comparison of atmospheric characteristics onshore and offshore

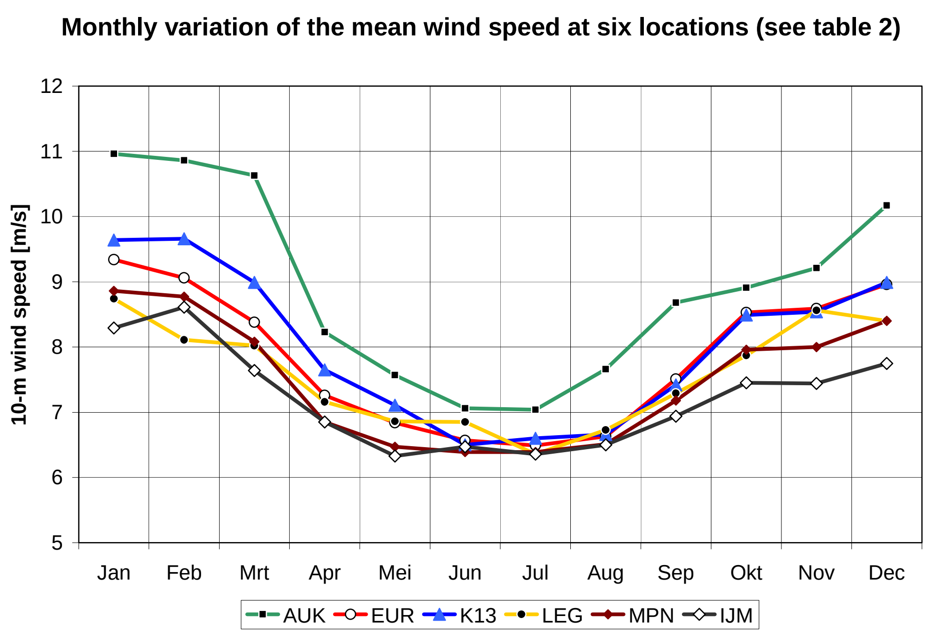

Fig. 16

**Hourly variation of the mean wind speed at six locations (see table 2)**

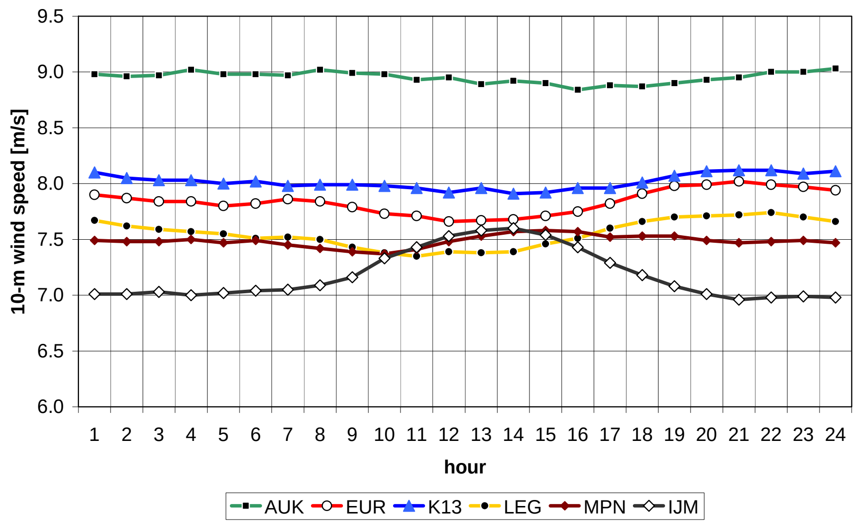


Fig. 17

Looking at a larger scale two types of climates can be distinguished: offshore vs onshore. It is clear that in the coastal zone there is a transition between the two types where mixed features will occur, mainly depending on the wind direction. Some work has been devoted to determine to what distance such a coastal zone extends, and it is generally believed to be some tens of kilometres.

*WAsP*

The model WAsP by Risø is commonly used for calculating energy productions in many countries. Several parameters used in the underlying model are tuned to yield correct results *on average* during average conditions. In principle WAsP can be used for offshore purposes, but the tuning of the parameters is not adapted for offshore applications yet. However, several publications have shown encouraging results in certain particular conditions.

*Models at KNMI*

At KNMI an operational model is being tested which is capable of describing the wind field offshore. This means that wind speeds offshore can be predicted from onshore data. These situations represent only a limited number of weather situations, but these are the most difficult to model. Westerly winds have a sea fetch which is modelled far more simply. Another interesting trend is the increasing use of so-called mesoscale models. At KNMI the meso-scale model Hirlam is available and is undergoing constant development.

### 1.8.2 Design Parameters – Fatigue

The design process requires different input of the environmental conditions. A distinction has to be made between the design against fatigue and the design against extremes. For the fatigue calculations the distribution of the mean wind speed is mandatory. Moreover, for the simulation of the turbulence, the spectra of the wind turbulence have to be specified.

In the different design codes, the spectra specification differs. There is no specific guideline for the offshore turbulence spectrum and by lack of sufficient and reliable offshore measurements, it is generally assumed that it can be expressed with the conventional spectra. One example is the von Kármán spectrum for the longitudinal component of the wind speed:

$$\frac{f \cdot S_{uu}}{\sigma_{uu}{}^{2}} = \frac{4\tilde{f}}{(1+70.8\tilde{f}^{2})^{5/6}} \tag{13}$$

$S_{uu}$ is the auto power spectral density of the wind speed

$\sigma_{uu}$ is the standard deviation of the wind speed

$f$ is the frequency (Hz)

$\tilde{f}$ is the dimensionless frequency

$$\tilde{f} = \frac{{}^{x}L_{u} f}{\overline{U}}$$

Here, the turbulence length scale ${}^{x}L_{u}$ can be defined as

$${}^{x}L_{u} = \frac{25 z^{0.35}}{z_{0}^{0.0063}} \tag{14}$$

The turbulence intensity is the governing measure for fatigue loads. According to the ESDU the turbulence intensity can be formulated as

$$I_{t}(z) = \frac{F(z)}{\ln(z / z_{0})} \tag{15}$$

with $F(z) = 0.867 + 0.556 \cdot \log_{100}(\mathrm{z}) - 0.246(\log_{10}(\mathrm{z}))^{2}$ (it can be assumed that F(z)≈1).

This equation is also given in the Danish Standard (DS 472). This expression is to be preferred above i.e. the equations for the turbulence intensities as given in the IEC code, which are applicable for whole regions (indicated by WTGS classes). The latter are based on turbulence measurements at a very broad range of sites and conditions (e.g. atmospheric stability) which therefore show a lot of scatter. The surface roughness length is a function of the mean wind speed according to Charnock's relation, thus the turbulence intensity is also dependent of the mean wind speed. The GL offshore regulation prescribes a turbulence intensity of 12%. Measurements show a range of 8 to 12% depending on the mean wind speed and stability conditions.

For the design of an offshore wind farm at some specific site, it is recommended to use the turbulence intensity at that site, in case measurements (of say at least 1 year) are available; otherwise equation (10) may be applied. A certification based on the actual site conditions seems justified in respect to the large number of wind turbines of an offshore wind farm; application of the turbulence intensities as given in the IEC code will lead to far more conservative designs.

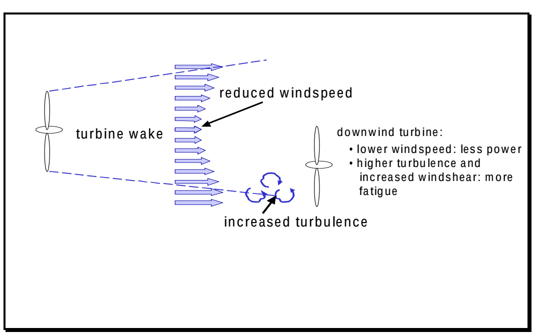

Fig. 18

The efficiency of the wind farm and the loads are strongly influenced by the wake structure. The increase of turbulence due to the presence of the wakes produced by the upstream turbines is considerable and can be approximated as

$$I_{eff} = \sqrt{\frac{0.4C_T}{s_t^2} + I_0^2} \tag{16}$$

where,
$C_T$ is the thrust coefficient of the closest wake generating turbine
$s_t$ is the non-dimensional turbine separation x/D (D is the diameter of the rotor)
$I_0$ is the ambient turbulence of the free flow.

For the calculation of the fatigue load the logarithmic wind profile mentioned above should be applied. Furthermore, the variation of the wind direction with height should be taken into account. For this purpose the geostrophic drag law may be applied (in line with WAsP). It is standard to use such an expression for scaling of the wind speed and direction to hub height for energy yield calculations; it is yet to be determined how to incorporate this in a fatigue analysis.
Sensitivity studies show that the turbulence intensity is by far the dominant factor in fatigue loads.
For simulation of the wind velocities at different locations the knowledge over the cross correlation function is indispensable. The non-symmetrical cross correlation function results in a complex spectrum; however the quad-spectrum is usually neglected.
As is the case for spectra, there is no specific coherence model specified for the offshore wind, nor enough and reliable measurements. Conventional coherence models can be found in the IEC draft or ESDU.

*Turbulence*

Due to the lower mechanical friction at the sea surface less turbulence is created above the sea and turbulence levels are therefore lower than over land. The turbulence level is given by

$$I(z) = \frac{\sigma_u}{U} = \frac{(12 - 0.5 \cdot z_i/L)^{1/3} \cdot \kappa}{\ln(z/z_0) - \Psi(z/L)} \tag{17}$$

where $z_i$ denotes the height of the planetary boundary layer, L the Obukhov length and $z_0$ the roughness length.
Under the condition that the boundary layer is in equilibrium with the underlying surface these parameters can be derived using local conditions such as wind speed, sea and air temperature. For offshore wind conditions (wind coming from sea) this assumption is true if the fetch of water is sufficiently long. In nearshore conditions with wind flowing from land, this is not longer the case. Erbrink describes measurements at Meetpost Noordwijk, in situations with Easterly winds, where there is hardly found any correlation between the turbulence and the local wind speed and stability parameters. A better correlation is found when the land-sea transition is modelled and land conditions are used to initialise the calculations.
Offshore wind measurements suggest that the wind profile is influenced by upstream land conditions up to 30 km offshore. The adaptation of turbulence to the underlying sea conditions is expected to take place at an even slower pace. This suggests that one should consider land-based turbulence in those cases where winds have their origin over land.
Measurements of turbulence in offshore conditions are scarce. Larsen et al. have analysed wind data from a wind measuring mast at Vindeby wind farm. The mast is situated in shallow water erected very close to the shoreline. The data are recorded at a level of 37.5 m. In the paper only the sea fetch is considered. The sea fetch is characterised by having more than 15 km of sea upstream. The available data constitutes 5566 10-minute time series with an overall mean wind speed equal to 7.92 m/s. A design turbulence level (weighted average based on fatigue loads) is derived from the measurements. It should be noted that these

values have been derived for shallow water and a limited sea fetch of 15 km, and that the results are not automatically valid for Dutch offshore conditions.

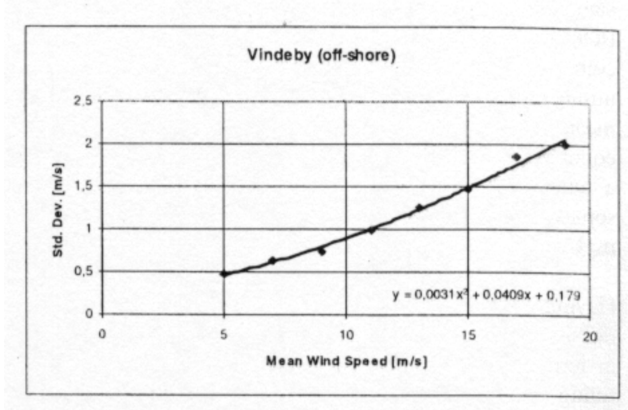


Fig. 19: Design standard deviation as a function of wind speed found at Vindeby (offshore sectors, sea fetch >15 km).

*Low Level Jets*

A Low Level Jet (LLJ) is a phenomenon in which a wind maximum occurs at relatively low levels in the atmosphere (150 m).

Onshore, the phenomenon of the Low Level Jet typically occurs during stable night-time conditions, in which case it is also known as a nocturnal jet. During clear nights, a stable, cold layer develops near the ground. In this layer, turbulence is damped and the vertical exchange of momentum is limited. The layer above the stable layer is effectively de-coupled and not any longer pulled back by the lower layer. It therefore accelerates, sometimes reaching velocities that are even higher than the geostrophic wind speed. The maximum wind speed occurs at heights between 100 and 150 m. The nocturnal jet is hence a time-dependent phenomenon in which the development of a stable boundary layer is a prerequisite. Since the diurnal course of the temperature over the sea is much smaller than over land the likelihood of such a type offshore nocturnal jet seems small.

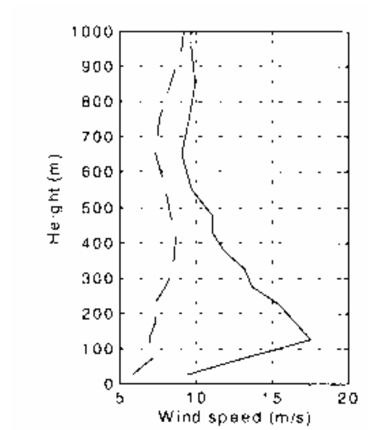


Fig. 20

An offshore LLJ is reported in the Baltic Sea, where it is rather common. The figure shows two wind speed profiles taken from a pibal tracking. The solid line shows the LLJ. The figure shows that during the phenomenon the wind speed can reach a considerable value. One consequence of the non-logarithmic behaviour is that extrapolations from one height to the other height result in erroneous wind speeds and that the wind potential in the Baltic is underestimated. Another consequence is the rather strong wind shear, which can an effect on the wind turbine’s life.

### 1.8.3 Maintenance and installation

The main concern for maintenance and installation operation is the accessibility delimited by the Met-Ocean variables. Generally for a location with 10 to 20 km distance from the coast, an accessibility of 75% percent can be assumed.
For development of an optimal maintenance strategy, detailed data has to be available in order to determine the weather windows. Depending on the means of transport and the equipment employed the specific criteria for these windows are different; maxima allowed values of the wind speed and wave height (and visibility).

# Literature

Main parts of this document are extracted from:
J.P. Coelingh (ed.), Wind and wave data compiled for the DOWEC concepts study, Section Wind Energy IW-00162R, Delft University of Technology, 2000.

Recommended literature on wind climate are (focus on onshore):

Wieringa, J. , Rijkoort, P.J., Windklimaat van Nederland [In Dutch], KNMI, 1983.
Troen, I., Petersen, E.L., European Wind Atlas, Risø National Laboratory, 1989.
Petersen, E.L. et al., Wind Power Meteorology, Wind Energy, number 1 and 2, 1998.

Information on the offshore wind climate can be found in the OWEMES proceedings, final reports of general offshore wind energy projects and specialised papers, e.g.:
Coelingh, J.P., Van Wijk, A.J.M., Holtslag, A.A.M., Analysis of wind speed observations over the North Sea, J. Wind Engin. Industr. Aerodyn., Vol. 61, Nr. 1, pp. 51—69

In the near future information will become available on several European offshore wind energy projects: POWER, MAST-III and ENDOW (wake effects offshore).
Wind and offshore wind turbine load measurements are currently performed at one of the two offshore wind turbines at Blyth (UK); at a.o. Vindeby and Horns Rev (Denmark) wind measurements have been performed. Similar measurements are scheduled for the coming Dutch Nearshore Windfarm (for the coast of Egmond).

For an introduction to the aerodynamic loading of wind turbines see a text book on wind energy, e.g.:
Freris, L.L. (ed.), Wind Energy Conversion Systems, Prentice Hall, 1990.

Figures
1, 2, 5,6 and 13 from:
Wieringa, J. , Rijkoort, P.J., Windklimaat van Nederland [In Dutch], KNMI, 1983.

4 "The Stratosphere." Met Office of the United Kingdom. http://www.met-office.gov.uk/research/stratosphere

8, 9 and 18: Renewable Energy Course Materials Tackling Market Barriers, Altener Project AL 98-022.

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