



Energy research Centre of the Netherlands

Turbulence and Wind Turbines

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Turbulence and wind turbines

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Abstract. The nature of turbulent flow towards, near and behind a wind turbine, the effect of turbulence on the electricity production and the mechanical loading of individual and clustered wind turbines, and some future issues are discussed.

1. Wind energy conversion and turbulence

A wind energy conversion system extracts energy from the turbulent wind and while doing so creates extra turbulence. Wind energy conversion systems include horizontal axis wind turbines, vertical axis wind turbines, and other devices like kites or ladders, but in this paper the focus is on horizontal axis wind turbines. In the following these devices are referred to as wind turbines. Wind is motion of air in the planetary boundary layer. As shown in figure 1 it is a process at various time and space scales (Orlanski, 1975). This paper addresses small scale turbulence, which is all variation in time of wind speed and wind direction with periods less than ten minutes.

In this paper an overview is given of the effect of wind turbines on turbulence, and the effect of turbulence on wind turbines. In addition various modeling approaches are presented. First, in section 2 descriptions are presented of the turbulent flow towards, near and behind a wind turbine. Next, in section 3 the electricity production and the mechanical loading under turbulent conditions are addressed. Finally, in section 4 some future issues are presented.

2. Turbulent flow towards, near and behind a wind turbine

2.1. The flow towards a wind turbine

The flow towards a wind turbine is essentially turbulent, with wind speed variations originating from production of turbulent kinetic energy due to surface roughness in combination with production or destruction of turbulent kinetic energy due to atmospheric stability.

The modeling of the flow towards a wind turbine is based on classical assumptions on the time variation of wind speed (van der Hoven, 1957), the type of the probability density function of wind speed variations within ten-minute periods (Wyngaard, 1992), and the shape of the wind speed profiles under various atmospheric stability conditions (Businger et al., 1971). These assumptions are shown in the figures 2, 3 and 4. Recent insights challenge these assumptions: the spectral gap in the Van der Hoven spectrum is absent over land (Courtney and Troen, 1990) and under unstable maritime conditions (Gjerstad et al., 1994), the distribution of wind speed variation is non-Gaussian (Böttcher et al., 2006), and wind speed profiles under maritime conditions differ from the Businger-Dyer profiles (Gryning et al., 2007).

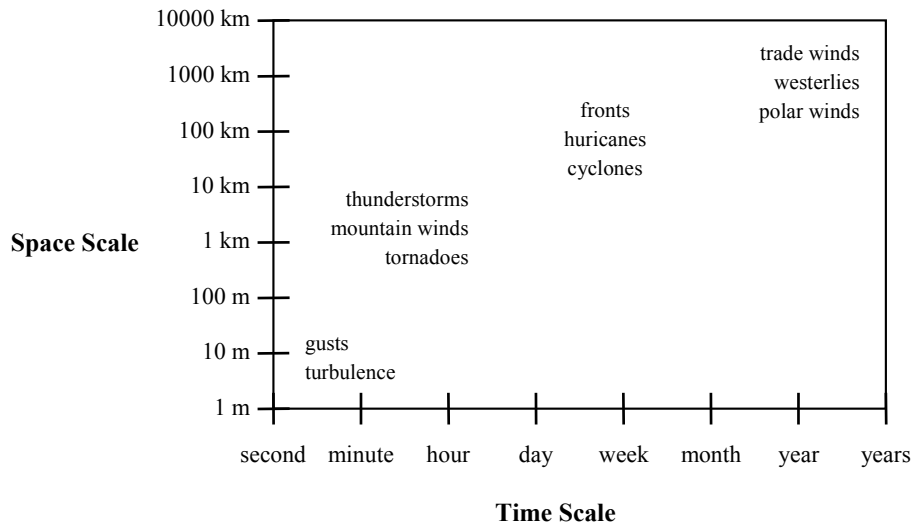


Figure 1. Processes in the planetary boundary layer according to the classification by Orlanski, 1975

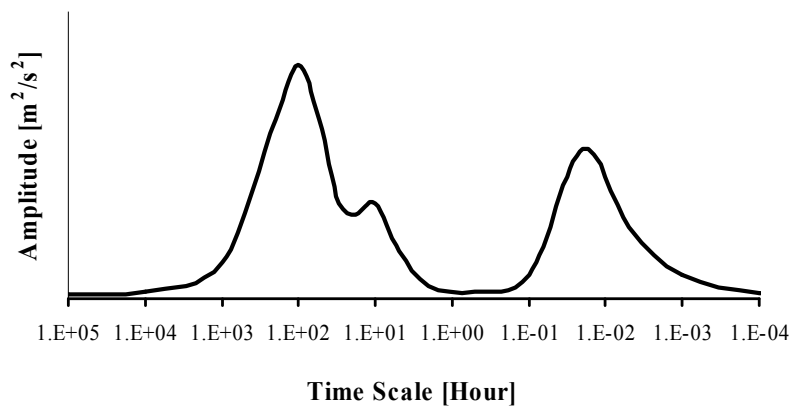


Figure 2. The classical assumption on the time variation of the wind speed. The spectrum of wind speed variation has a gap allowing for a separation of scales (van der Hoven, 1957)

The turbulence in the flow towards a wind turbine is modeled on basis of similarity theory in combination with computational fluid dynamics methods (Satoh, 2004; chapter 11). The computational fluid dynamics approaches employ closure models in order to treat the effect of scales smaller than the resolution of the numerical model. These closure models include the classic zero, one and two-equation turbulence sub-models as well as the modern Smagorinsky and Mellor-Yamada sub-models. The closure models are implemented in atmospheric models like the HiRLAM (Undén et al., 2002), the WRF (Skamarock et al., 2008) or EllipSys3D (Bechman et al., 2007).

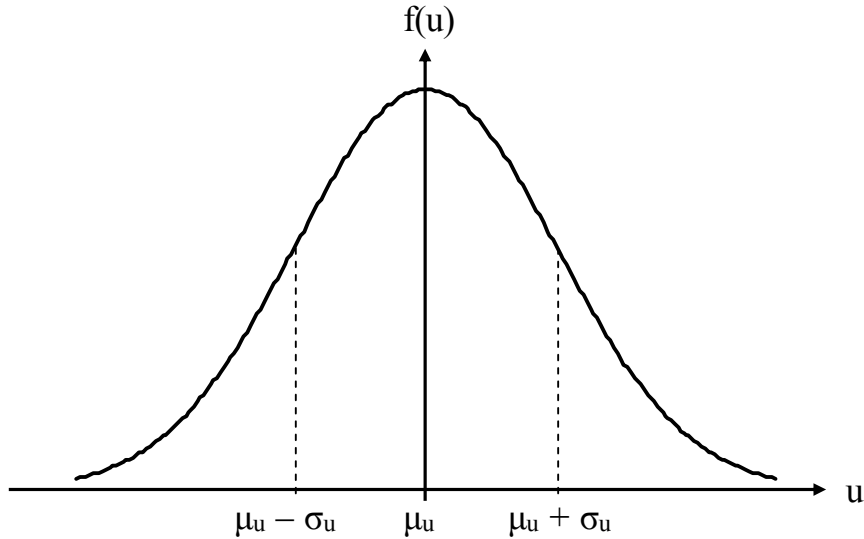


Figure 3. Sketch of the classical assumption of the probability density function $f(u)$ of the wind speed u within ten-minute periods. This distribution is Gaussian and is characterized by the average value μ_U and the standard deviation σ_U (Wyngaard, 1992)

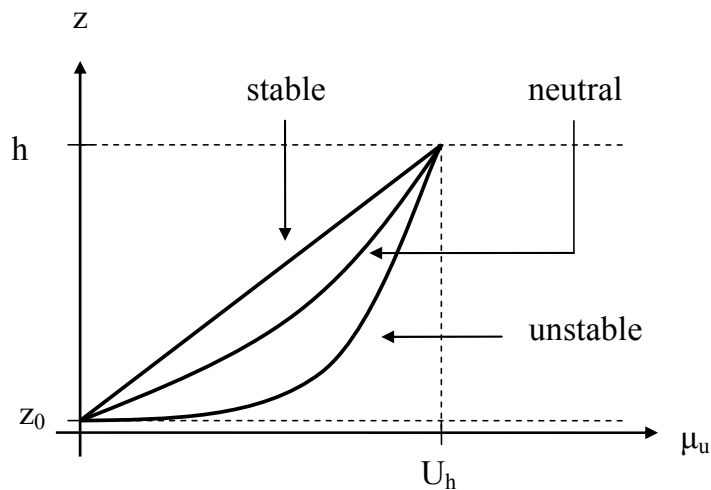


Figure 4. Sketch of the classical assumption on the shape of the wind speed profiles under various atmospheric stability conditions but for the same wind speed U_h at the top h of the atmospheric boundary layer. The average wind speed μ_U depends on the height z ; z_0 is the surface roughness length where the wind speed is zero (Businger et al., 1971)

2.2. The flow near a wind turbine

Upon approaching a wind turbine, the wind speed decreases and the turbulence increases in anticipation of the flow disturbing and energy extracting object. The flow near a wind turbine is modeled by using a rotor disk which contains the rotor blades.

The flow through the rotor disk traditionally is modeled homogeneously under the assumption that the wind speed and the turbulence do not depend on the position in the rotor disk, although it is not unusual to include some inhomogeneity in the form of a horizontal or vertical

wind gradient in order to model wind shear respectively yaw misalignment. The turbulence in a point in the rotor disk is modeled on basis of a spectrum, usually Kaimal (Kaimal et al., 1972), in combination with inverse Fourier transforms (Veers, 1984), or an approach based on rapid distortion theory (Mann, 1998).

A rotating rotor blade meets the incoming wind, and as a result feels an effective wind speed and an effective angle of attack (figure 5). Turbulent structures in the incoming wind are rotationally sampled by the rotor blade. The flow past a rotor blade is modeled by using blade-element/momentum theory and employing sectional airfoil data (Sørensen, 2011). The airfoil data have been found to depend heavily on unsteadiness (Devinant et al., 2002); for example a turbulent intensity of a percent considerably reduces the lift force and increases the drag force which effectively spoils rotor performance. The airfoil data traditionally originate from wind tunnel experiments but to date also from computationally fluid dynamics methods or aerodynamic design methods. If the computationally fluid dynamics method is based on the Reynolds-averaged Navier-Stokes equations, usually a $k\epsilon$ or $k\omega$ sub-model is used in order to calculate the flow over the airfoil section beyond transition. In the case of a Large Eddy Simulation method, the Smagorinsky-Lilly sub-grid model is used for this purpose. Aerodynamic design codes employ integral boundary layer formulations.

2.3. The flow behind a wind turbine

The flow behind a wind turbine is sub-divided in three regions, each requiring distinct modeling approaches (Vermeer et al., 2003). This is shown in the figures 6 and 7.

In the near wake the flow is dominated by the velocity deficit due to the energy extraction and the vortices created at the tip of the rotor blades, resulting in a wind speed deficit and extra turbulence. In this region the flow structure essentially depends on the aerodynamics of the rotor blades. On basis of solutions of this flow problem and empirical information the resulting flow is assumed to have a top-hat shaped wind speed profile and edge-concentrated turbulence.

In the intermediate wake the tip vortices gradually lose identity, and the undisturbed flow mixes with the core flow. As a result the wind speed deficit and the extra turbulence begin to decay.

In the far wake equilibrium is assumed between the convective forces and the gradients of the turbulent momentum fluxes. On basis of analytical solutions of the governing equations the profiles of the wind speed deficit are assumed to be Gaussian. On basis of empirical information the profiles of the extra turbulence are assumed to be Gaussian too, but with different values of the decay parameters. Both the velocity deficit and the extra turbulence decay with the streamwise and the spanwise distance until the limit situation of the upstream wind speed and the ambient turbulence is reached. Depending of the atmospheric stability, this takes a distance of 10 to 20 rotor diameters. The mechanism here is redistribution of energy between the mean and the turbulent wind field in combination with feed-in of undisturbed flow.

A wind turbine wake does not have a fixed position even if the mean wind direction is constant: it has been found to move in horizontal as well as vertical direction. This effect is known as wake meandering. A meandering wake smears the velocity deficit and the extra turbulence over a much larger volume than a fixed wake does. To date the process is not completely understood; hypotheses include stochastic wind direction variation (Bingöl et al., 2010), an analogy with bluff body vortex shedding (Medici & Alfredsson, 2006), and motion due to a spanwise wind speed component (Larsen et al., 2008). May this be as it is, a small number of empirical wake meandering models exist.

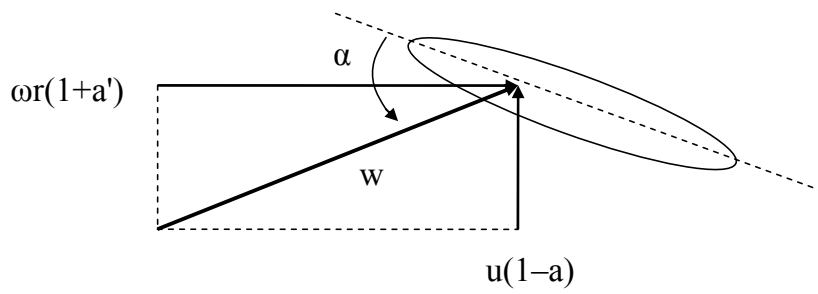


Figure 5. The effective wind speed w and the effective angle of attack α of a section of a wind turbine rotor blade is a function of the upstream wind speed u , the rotor speed ω and the radial position r . The induction factors a and a' represent the effect of the rotor blade on the flow

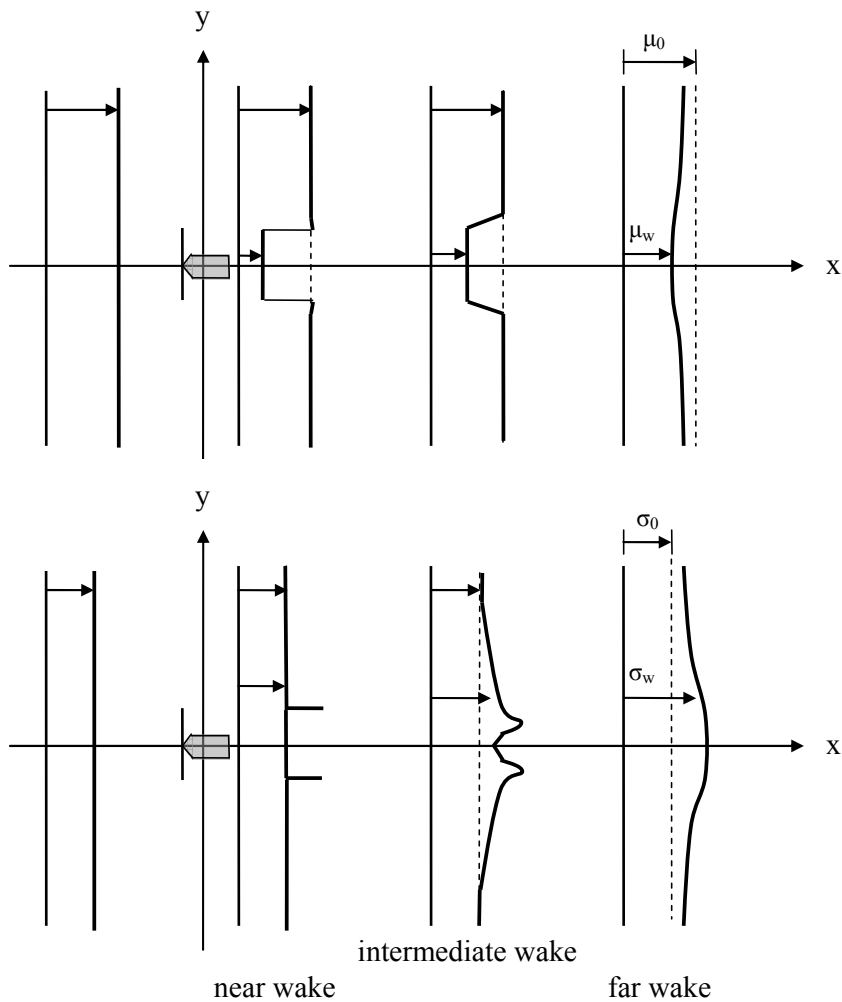


Figure 6. Top view of the average μ (top) and the standard deviation σ (bottom) of the wind speed at hub height near a wind turbine. The upstream values are μ_0 and σ_0 , and the downstream values are μ_w and σ_w . The streamwise and the spanwise directions are x and y , respectively

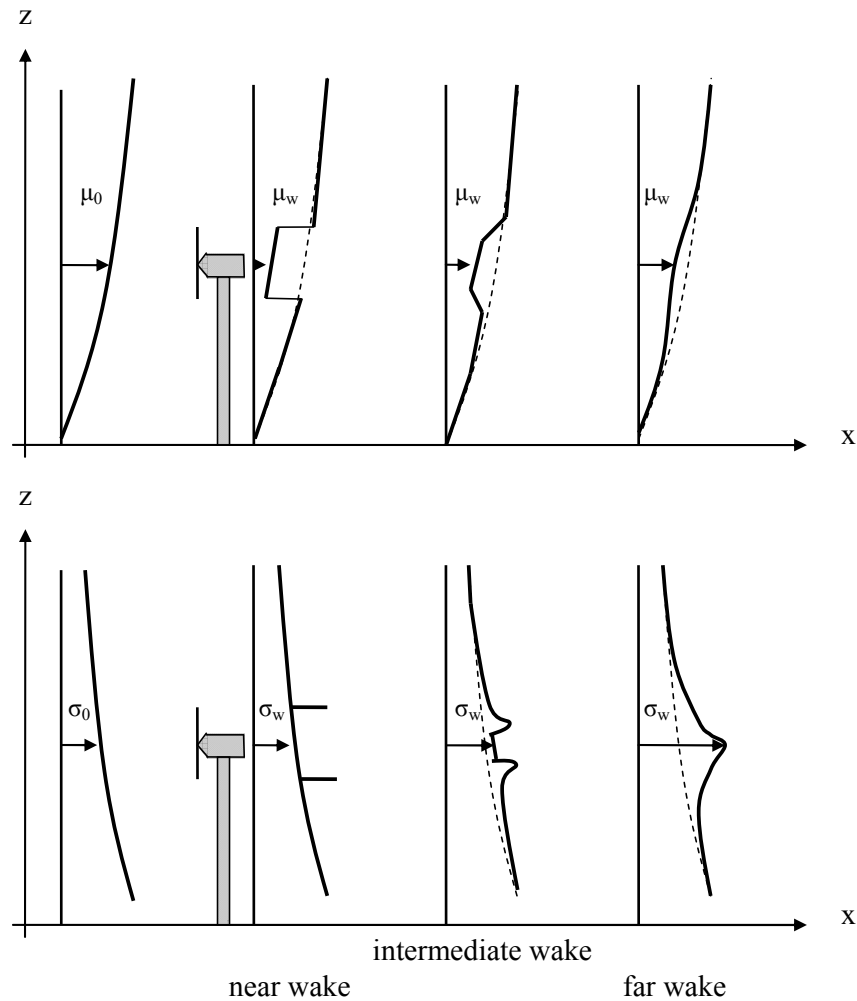


Figure 7. Side view of the average μ (top) and the standard deviation σ (bottom) of the wind speed near a wind turbine as a function of the height. The upstream values are μ_0 and σ_0 , and the downstream values are μ_w and σ_w . The streamwise and the vertical directions are x and z , respectively

3. Effect of turbulence on electricity production and mechanical loading

3.1. Individual wind turbine

The wind exerts forces on the rotor blades of a wind turbine. When rotating, the in-plane components of the aerodynamic force on the rotor blades cause torque about the rotor axis. Similarly, the out-of-plane components cause thrust on the rotor. Turbulence now leads to time variations in the rotor shaft torque and the rotor thrust.

The aerodynamic power is the product of the rotor shaft torque and the rotor speed. Turbulence therefore gives rise to variations in the power and consequently the electricity production. In fact, turbulence is believed to be essential in assessing energy yield (Gottschall & Peinke, 2008).

The mechanical loading of the components of a wind turbine, like the blades or the shaft, originates from the aerodynamic force on the rotor blades. Turbulence therefore causes variations in the mechanical loading; in other words: it causes fatigue loading. To date fatigue loading is

considered the primary factor which determines the life time of a wind turbine, and several methods for designing for a given life time exist. Understanding and characterizing turbulence before and behind a wind turbine is believed to be essential here (Mücke et al., 2010).

3.2. Cluster of wind turbines

In a cluster of wind turbines the flow towards a given wind turbine is affected by the velocity deficit and the extra turbulence due to any upstream wind turbine. Such a cluster usually is referred to as a wind farm. In general, this interaction leads to a complex structure of the flow in and behind the wind farm. For example, depending on the wind direction and the layout of the wind farm, regions with multiple velocity wakes and multiple turbulence wakes may be identified. In this section of the paper the focus is on the relatively simple case where the wind direction is parallel to a row of wind turbines.

The limit situation of the upstream wind speed and the ambient turbulence only is reached after the most downstream turbine of a row of wind turbines. In the row a different limit situation is reached (Barthelmie et al., 2004). If the separation distance between the turbines is smaller than a critical value, the power deficit at the second turbine is the largest in the row and the power deficits in the subsequent turbines are constant. In this case beyond the second turbine equilibrium is reached between the mean kinetic energy extracted by a wind turbine and the vertical fluxes of the turbulent kinetic energy (Cal et al., 2010). On the other hand, for separation distances larger than the critical value, the power deficit smoothly increases with position in the row and a constant power deficit is not obtained. The mechanism in this case is superposition of the individual values of the velocity deficit and the added turbulence, without replacement from above. The consequences for the mechanical loading of the turbine components are less clear, but in general the loading has been found to increase with the position in the row.

4. Future issues

In the preceding sections of this paper it has been shown that a wind turbine produces turbulence at a scale of the rotor size (diameter as well as chord) and the corresponding frequency (rotor speed) and induced velocity, and that this turbulence decays to smaller scales when traveling in downstream direction and eventually dissipates to a level which can not be discriminated from the background turbulence. In addition it has been shown that a wind turbine adds turbulence to the inhomogeneous turbulence in the atmospheric boundary layer, which turbulence is created by the always present roughness of the surface but usually also by the thermal structure of the atmospheric boundary layer. In the remainder we address three outstanding issues.

First, the classic turbulence sub-models that were addressed in the section 2 have been found to perform poorly in validations on basis of full-scale data. This has to do with the limitations of the experimental techniques (usually point measurements), but it also points to a limited understanding of the complex structure of the flow towards, near and behind a wind turbine.

Second, as already explained in section 2.1, the modeling of the flow towards a wind turbine is based on classical assumptions on the variability of wind speed which have been challenged by recent insights.

The third issue is the assumed homogeneity of the wind field in the rotor plane (section 2.2). This assumption has been found to be reasonable for wind turbines which are small compared to the length scales of the coherent motions in the atmospheric boundary layer. (These coherent motions include – but are not limited to – flow induced by thermal instability, low-frequency/large-scale structures due to weather systems, and short-lived and local bursts.) Since the scales of larger rotors are of the same order as those of the coherent motions, the wind field in the rotor plane of such a wind turbine is expected to be inhomogeneous.

In order to resolve these issues and to identify the consequences for the design of wind turbines, there is a need to describe the physical processes which are relevant to the production, the transport and the dissipation of the turbulence due to the wind turbine and their interaction with the turbulence in the atmospheric boundary layer. New experiments will play an important role in this research (Knebel et al., 2010). In addition there is a need to develop a comprehensive model of this kind of turbulence for application in wind turbine and wind farm design.

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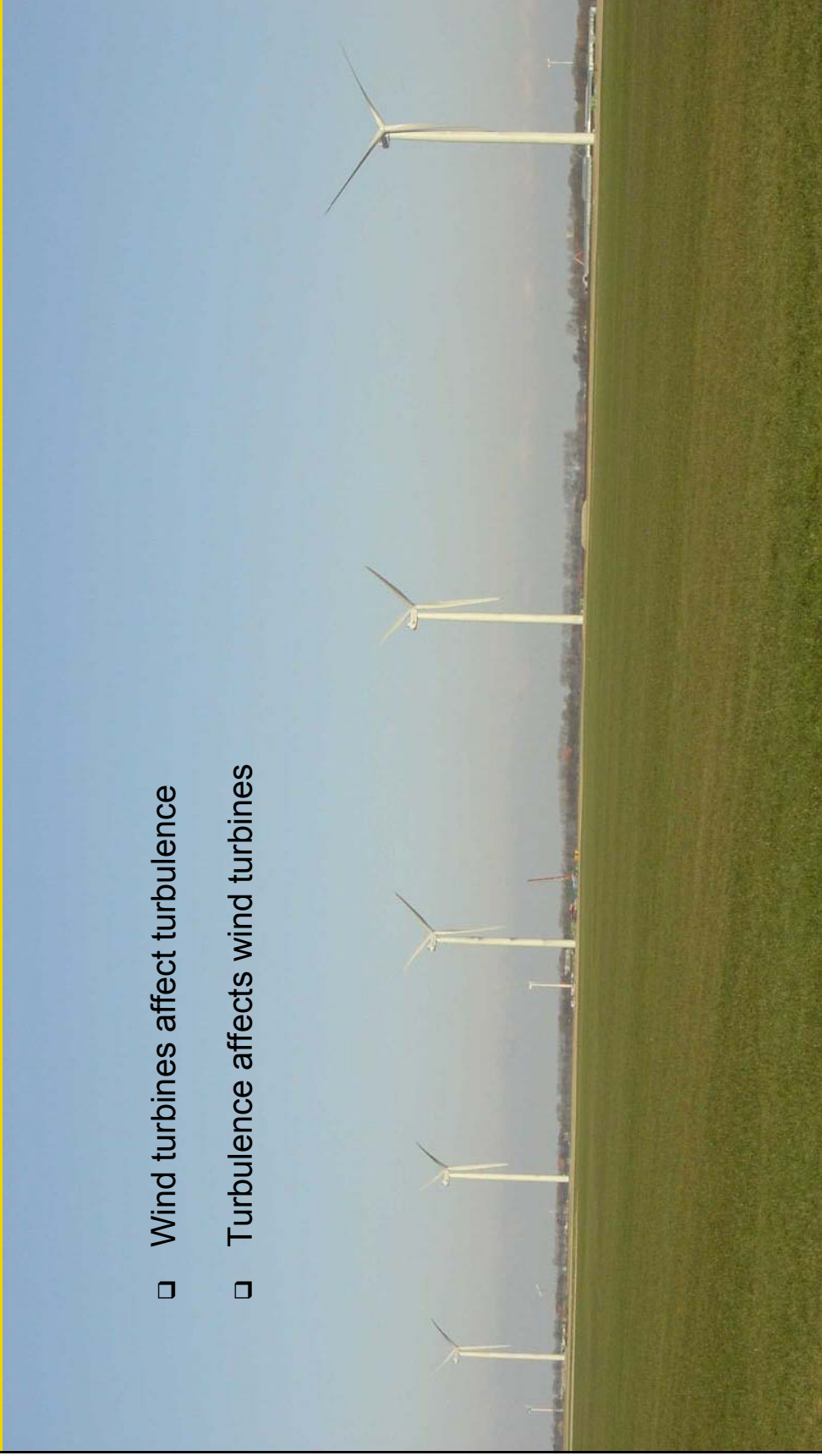
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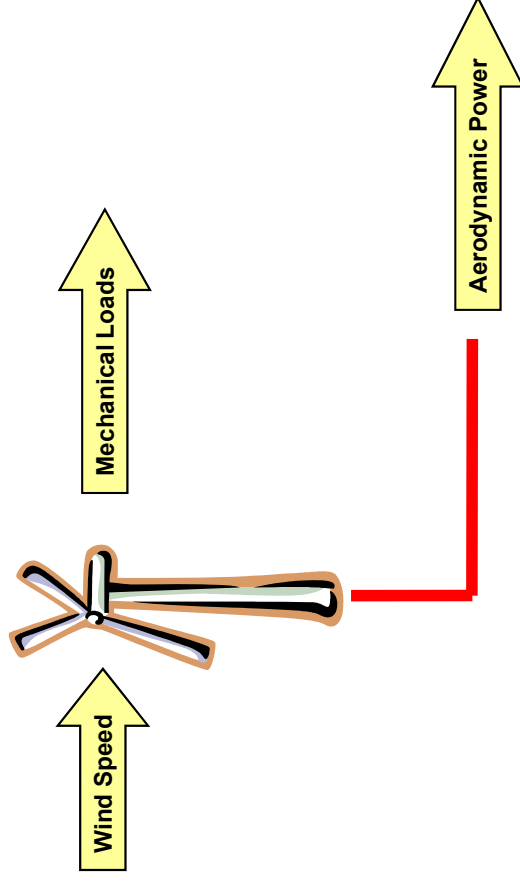


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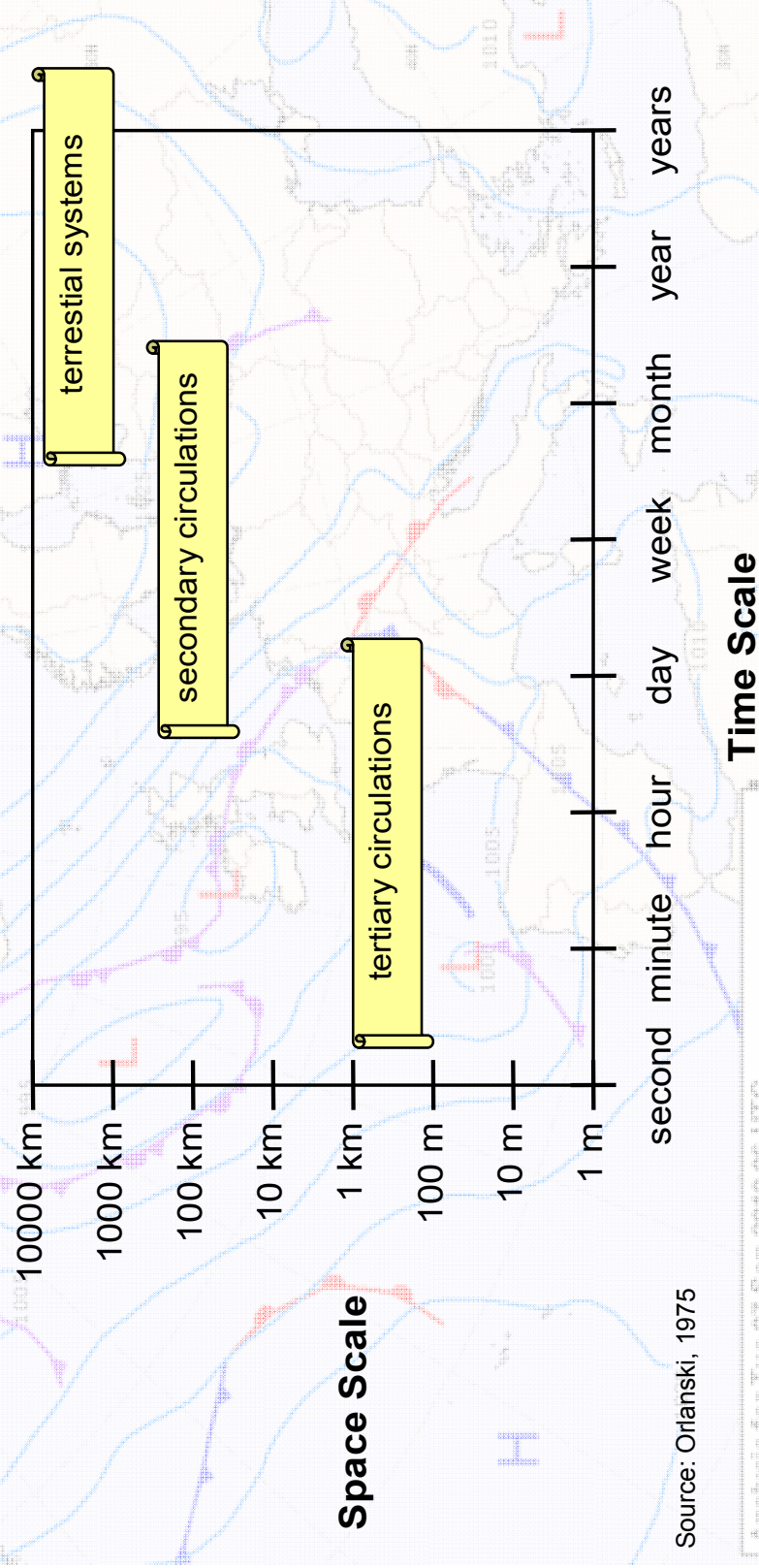
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- Wind energy conversion
- Flow towards, near and behind a wind turbine
- Effects of turbulence
- Modelling issues

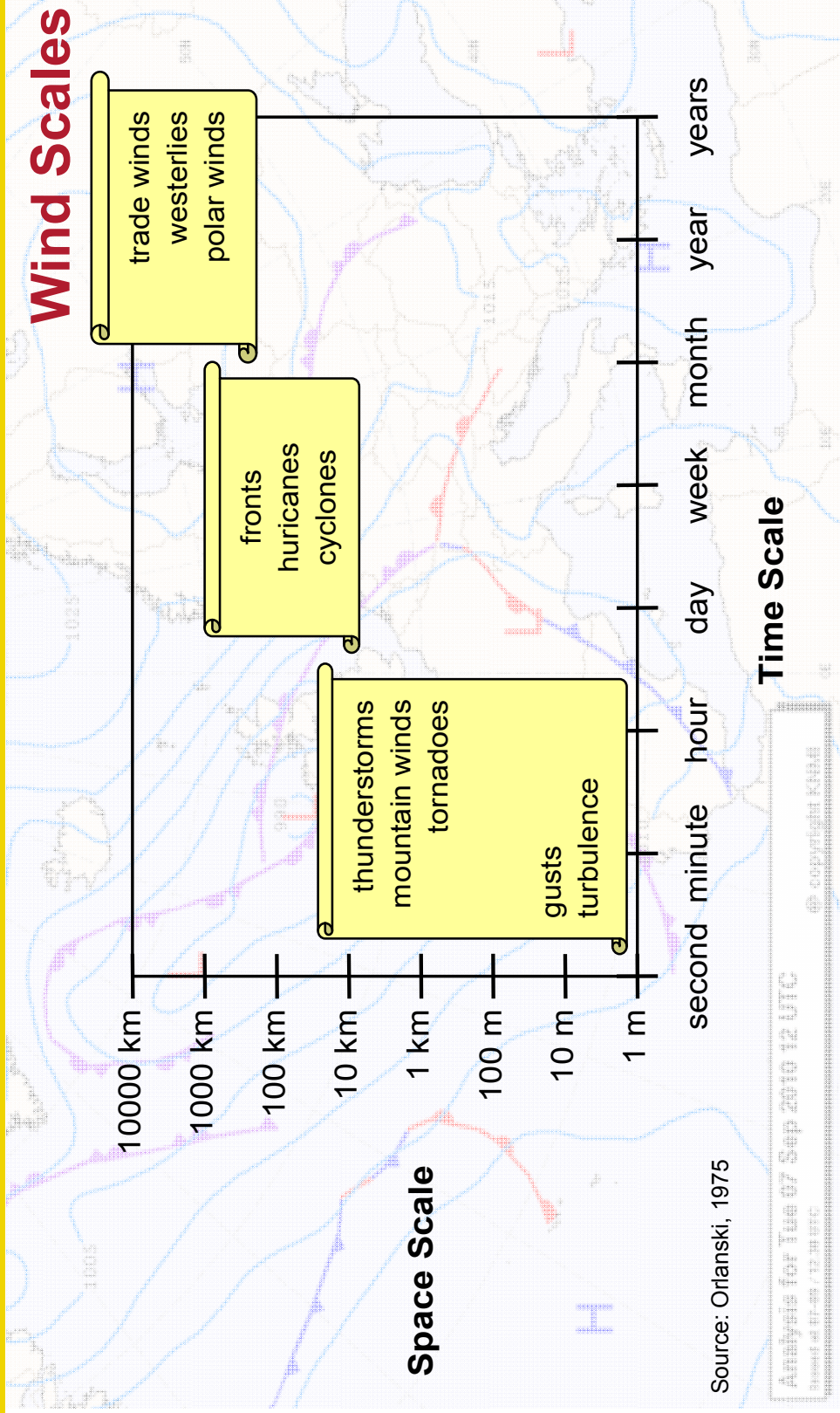
- Wind turbines affect turbulence
- Turbulence affects wind turbines



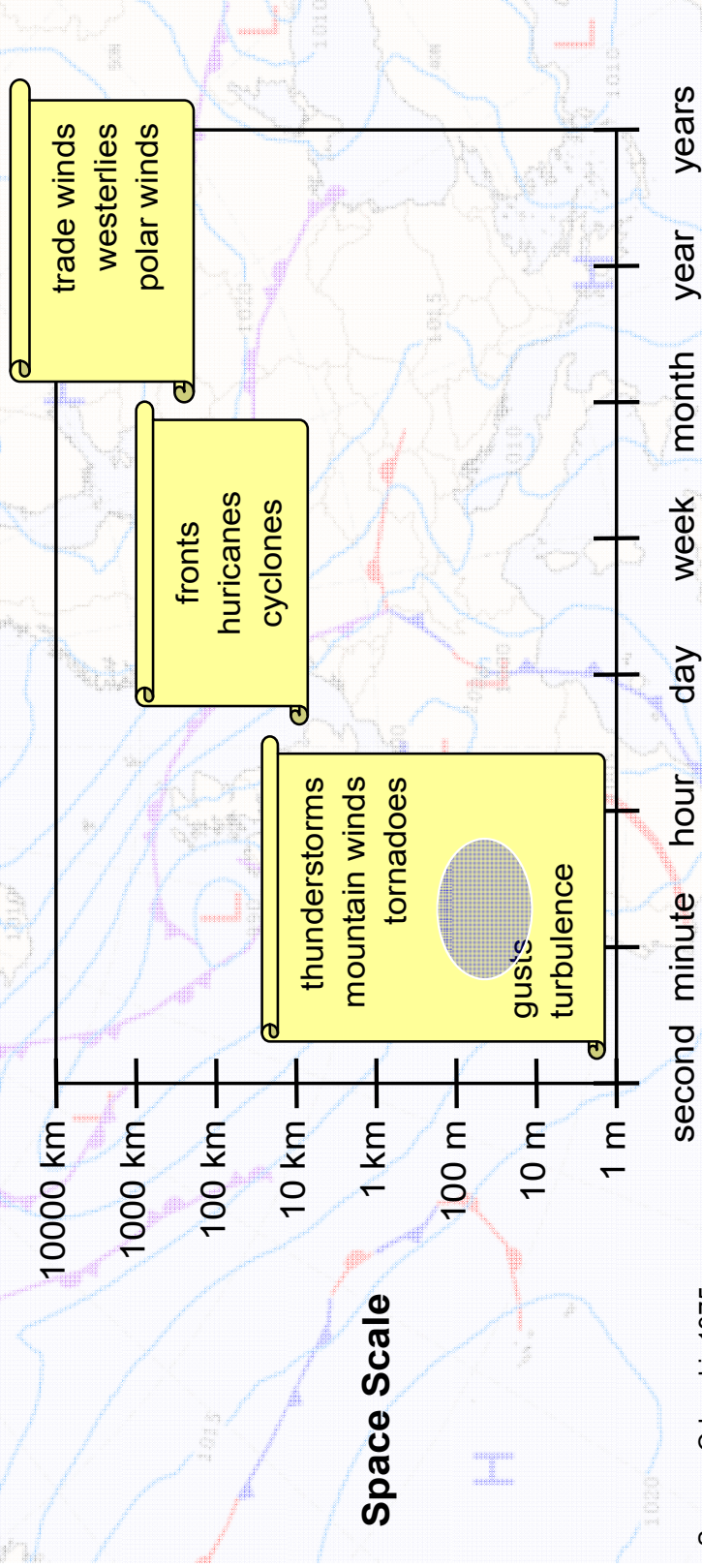


Wind Scales





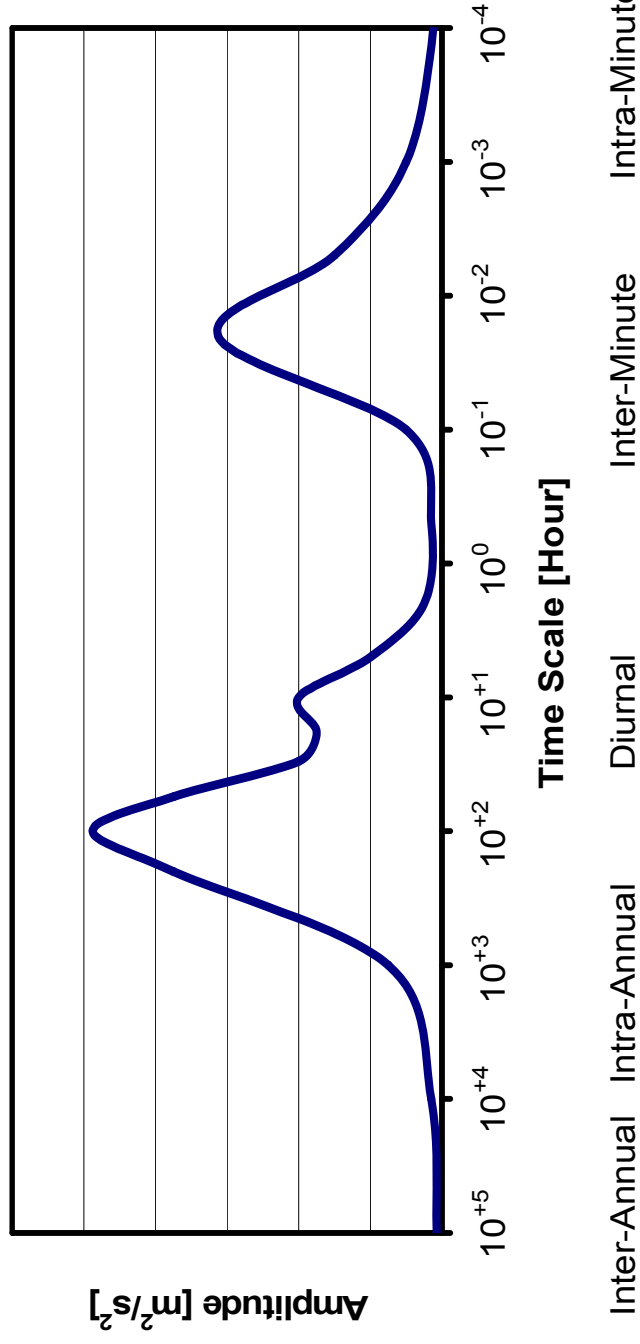
Rotor and Wind Scales



Source: Orlandi, 1975

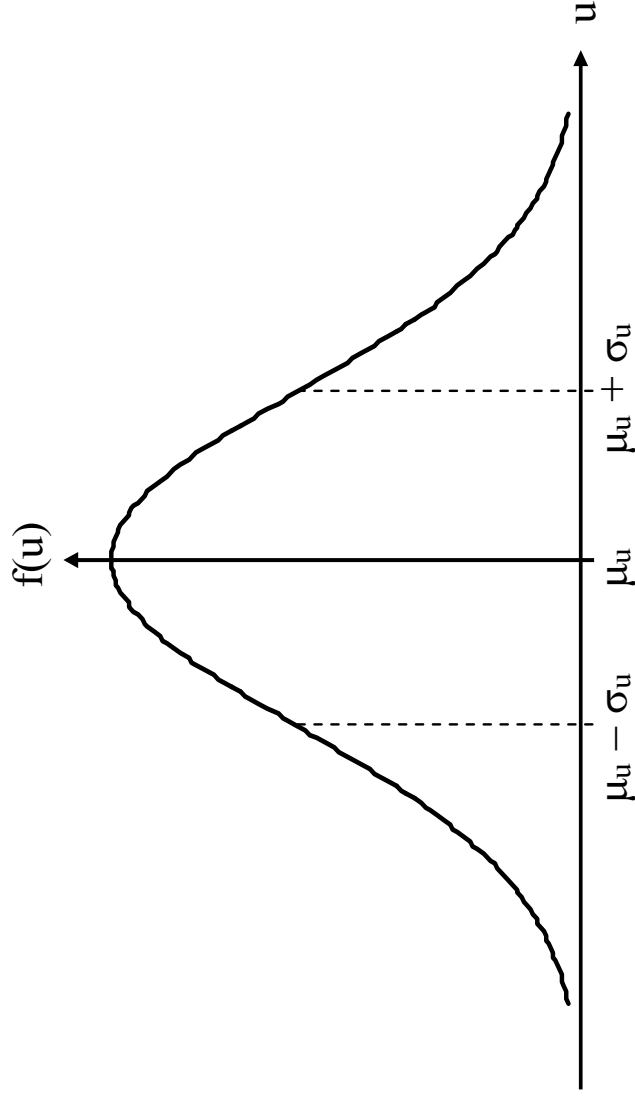
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Wind Speed Spectrum



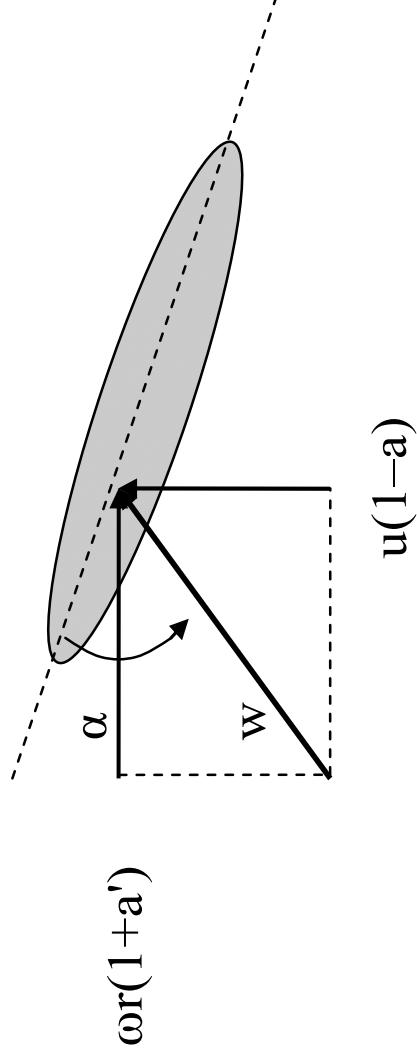
Source: van der Hoven, 1957

Distribution of Wind Speed Variation

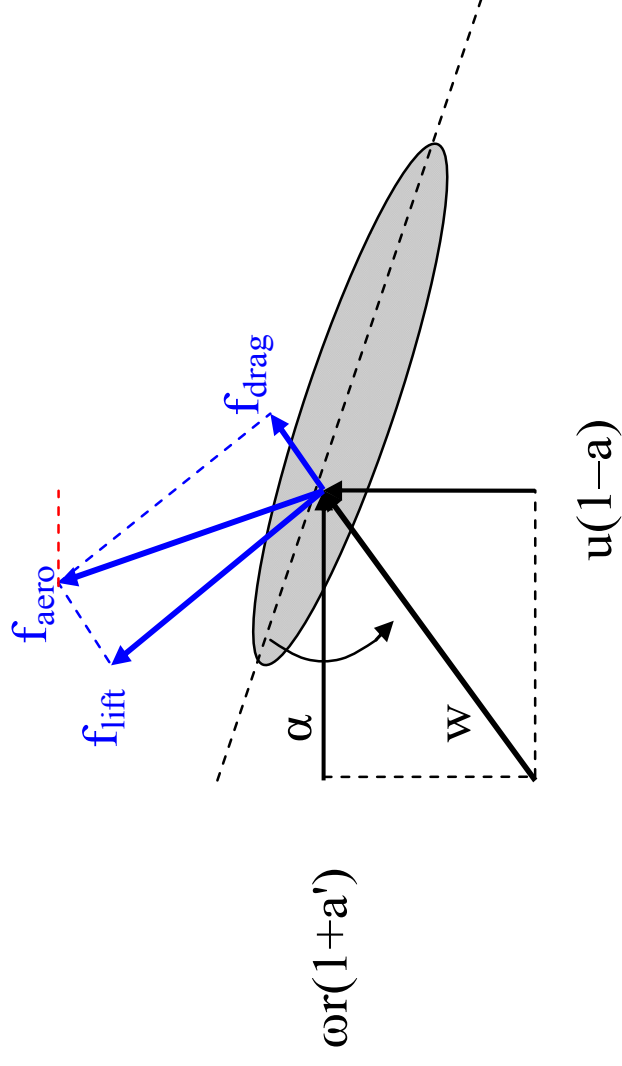


Source: Wyngaard, 1992

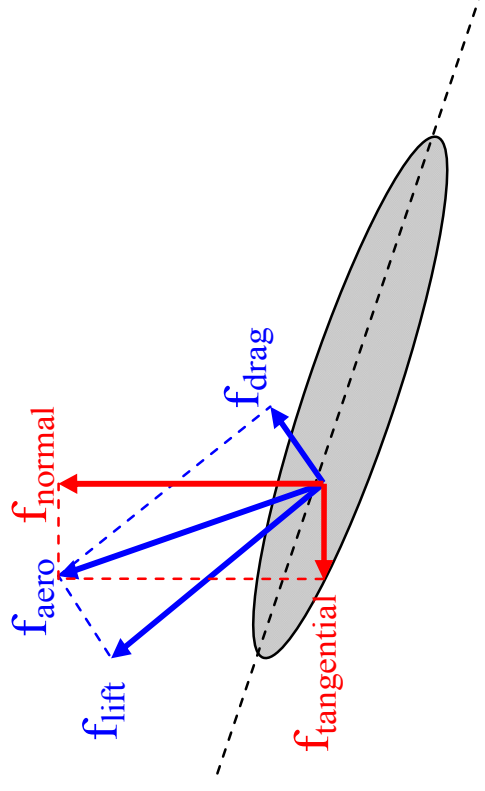
Forces on Rotor Blade Section



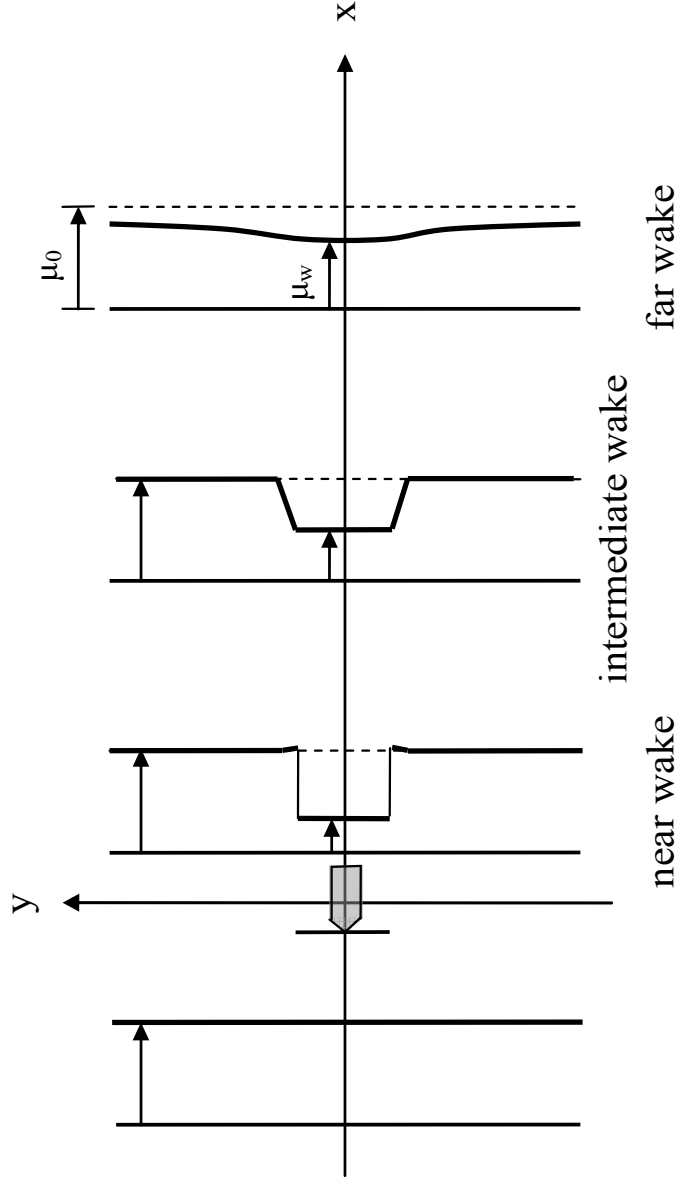
Forces on Rotor Blade Section



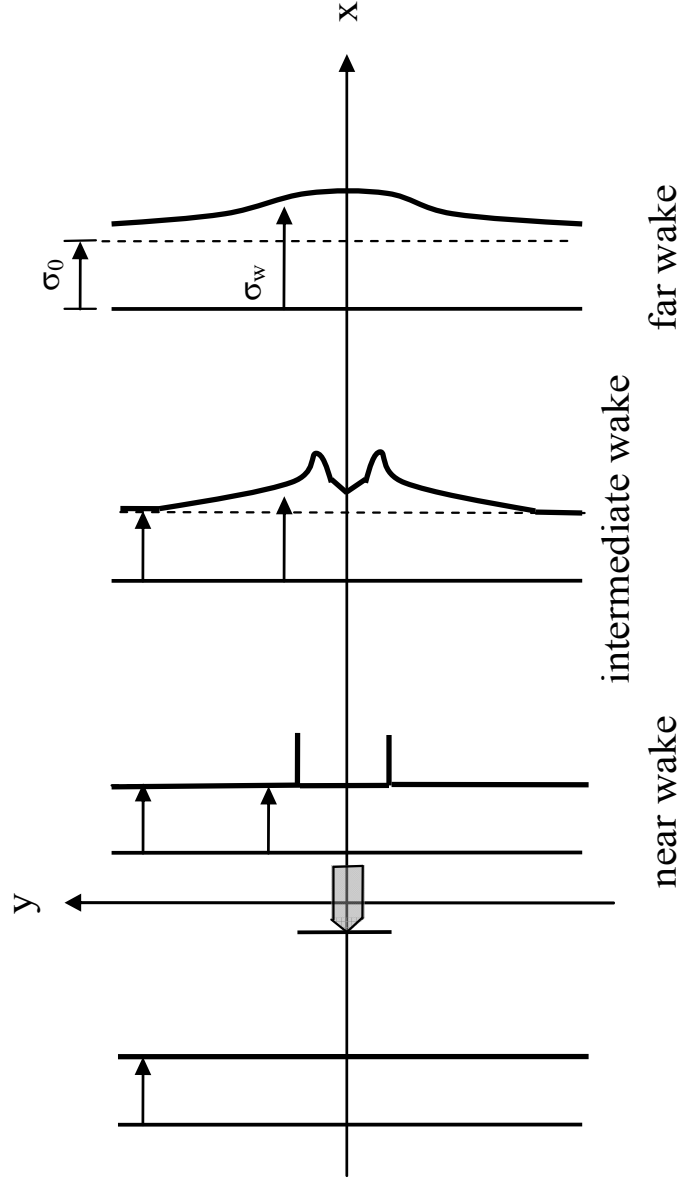
Forces on Rotor Blade Section



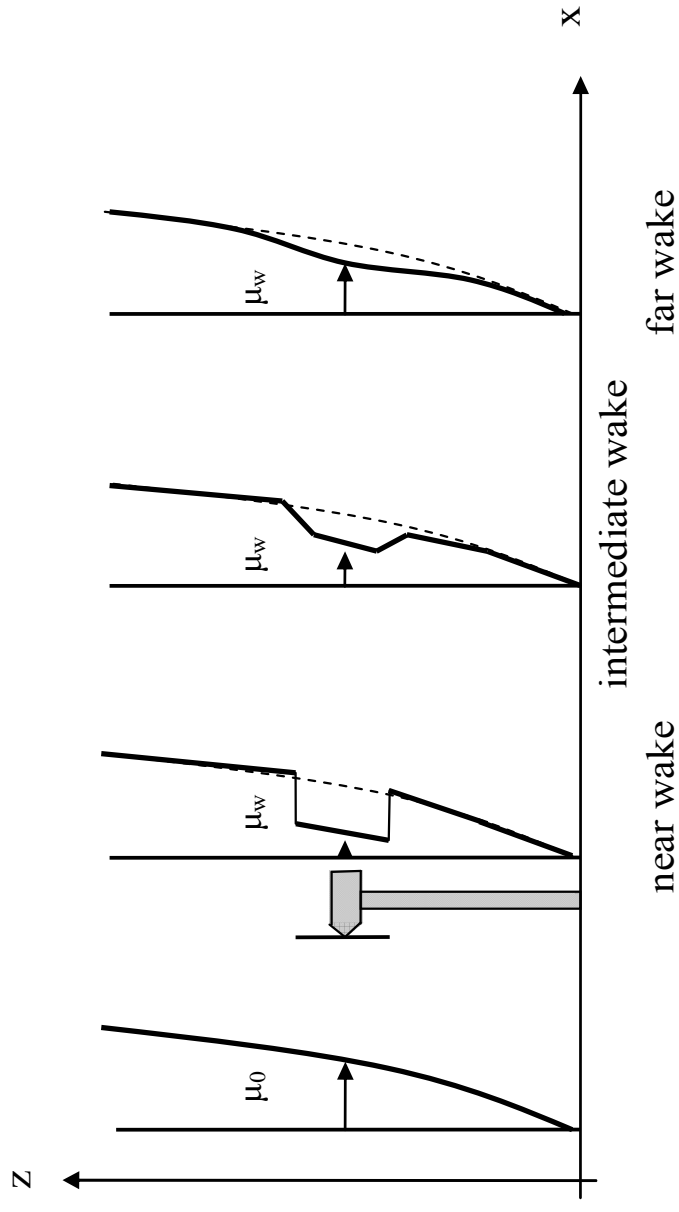
Mean Wind Speed – Top View



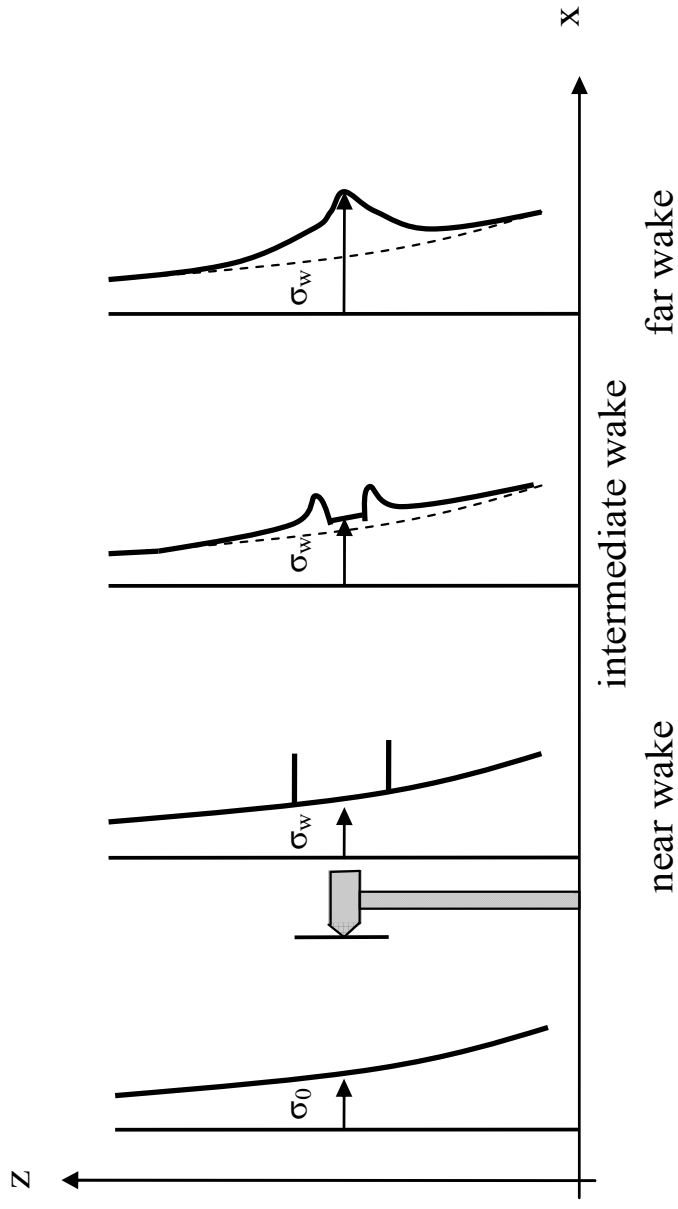
Wind Speed Standard Deviation – Top View



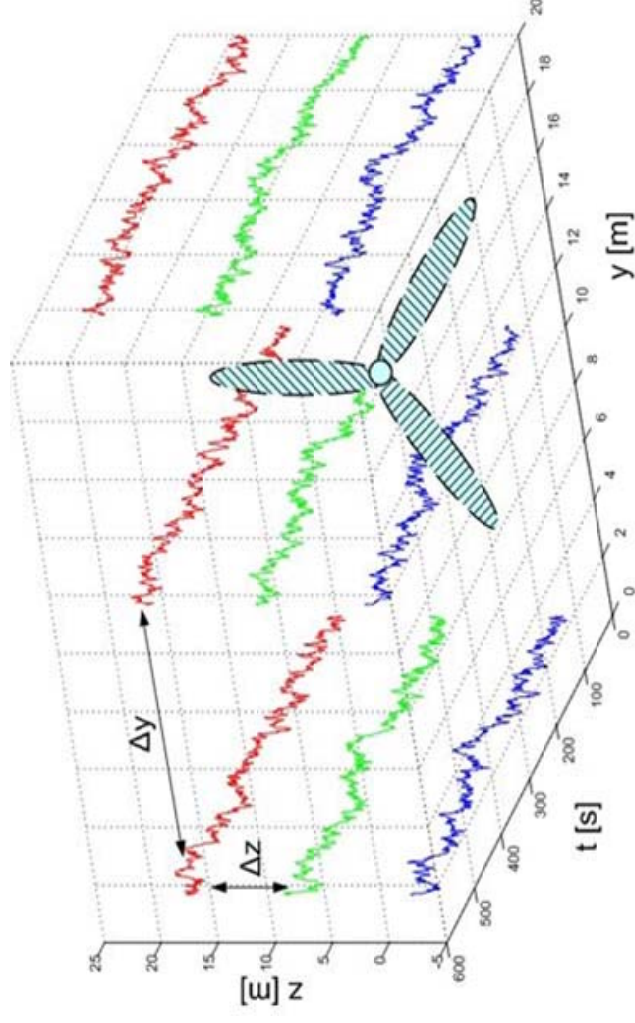
Mean Wind Speed – Side View



Wind Speed Standard Deviation – Side View

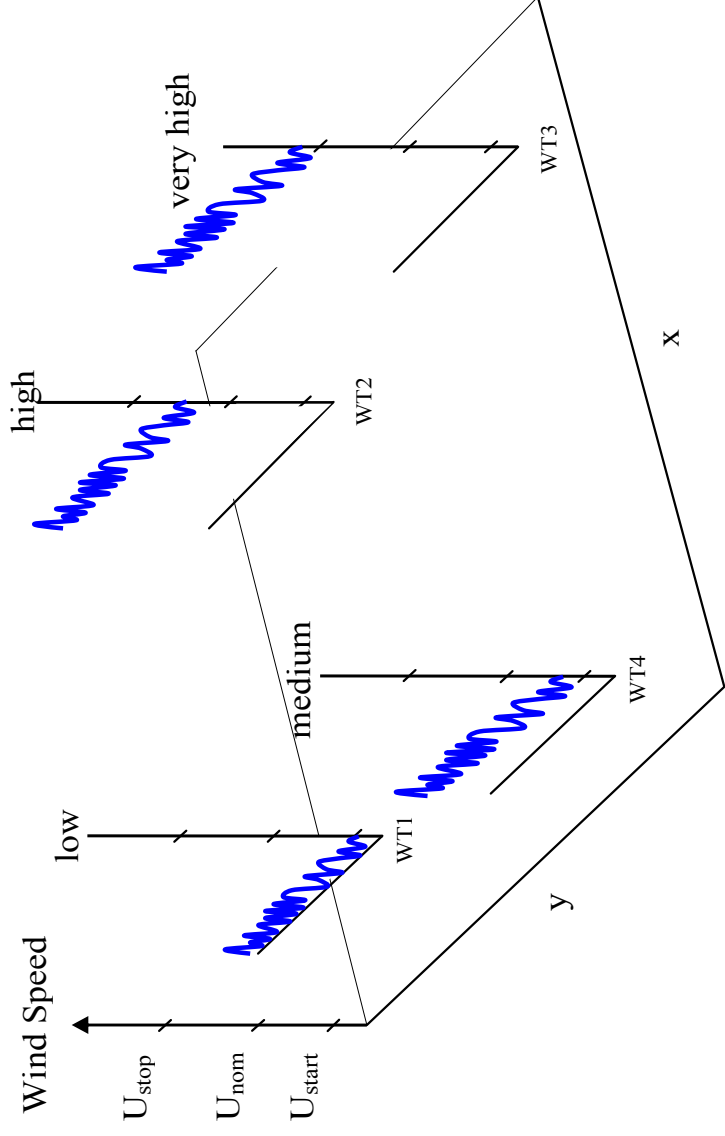


Wind Turbine Rotor

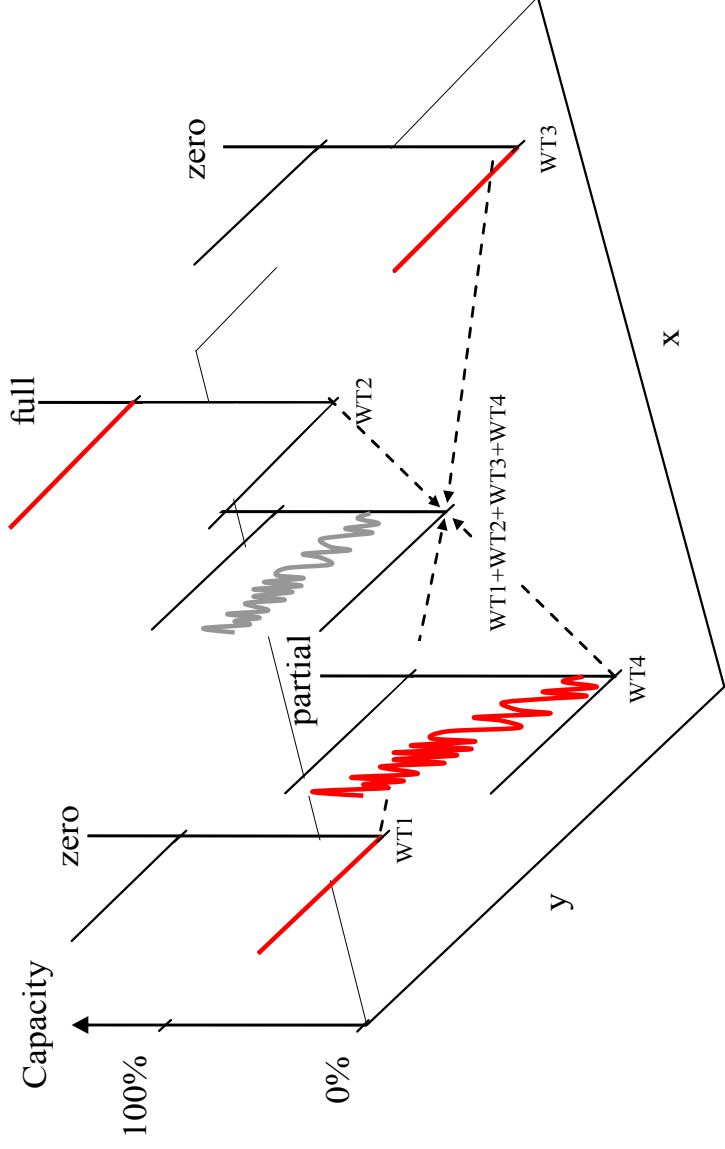


Source: Tom Obdam

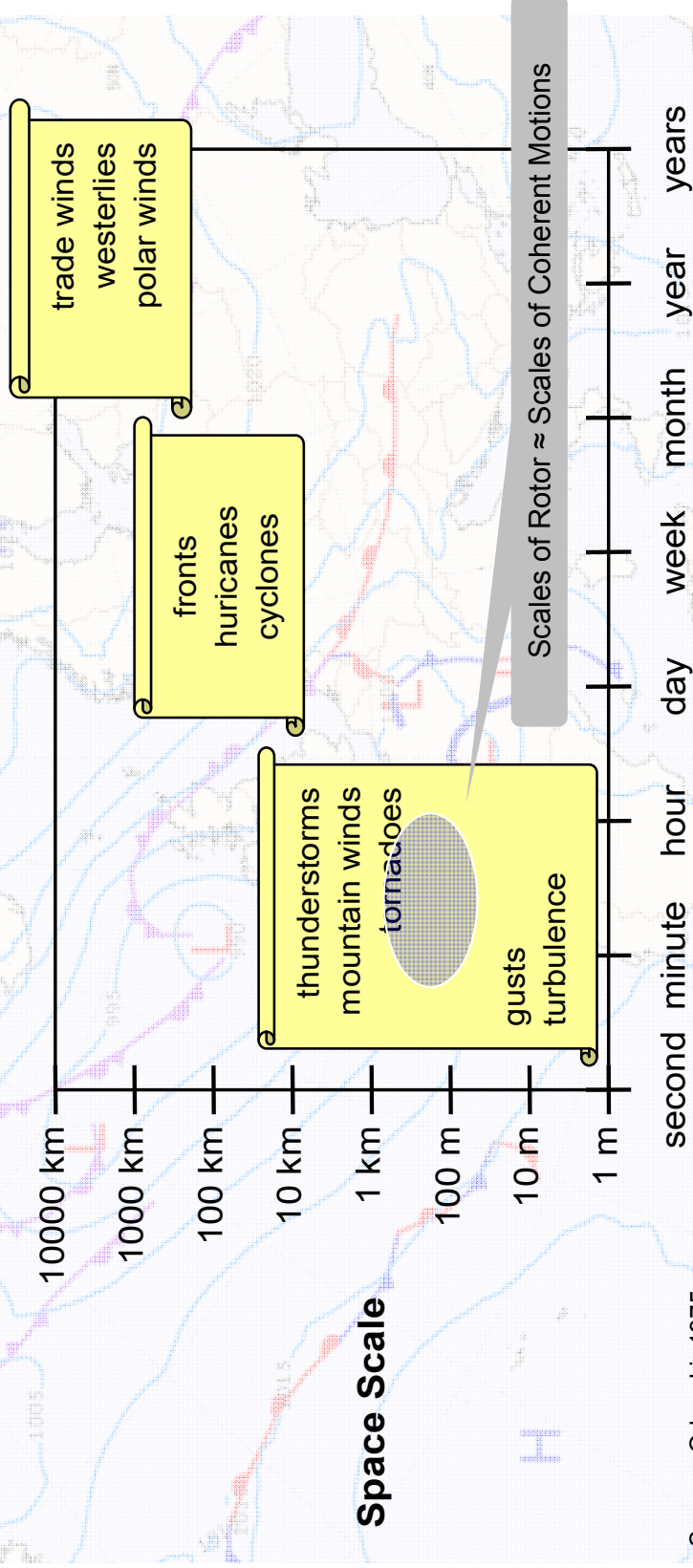
Cluster of Wind Turbines



Cluster of Wind Turbines



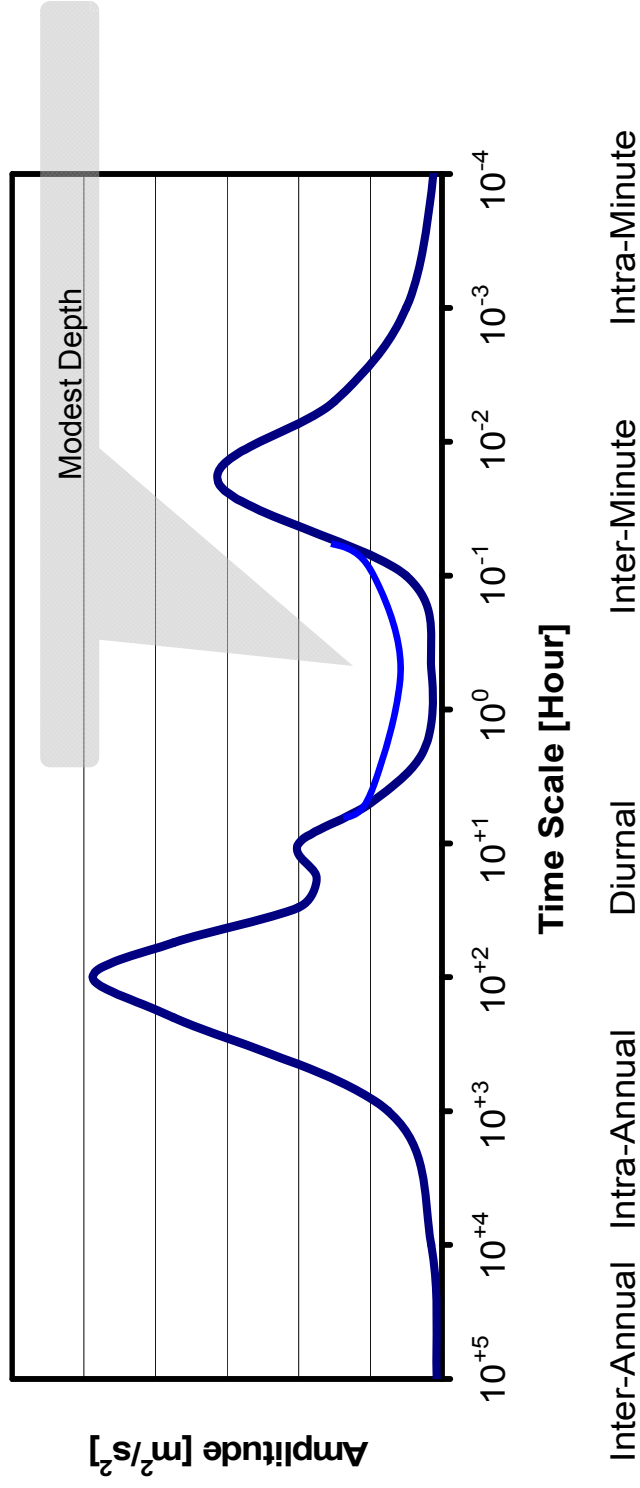
Rotor and Wind Scales



Source: Orlandi, 1975

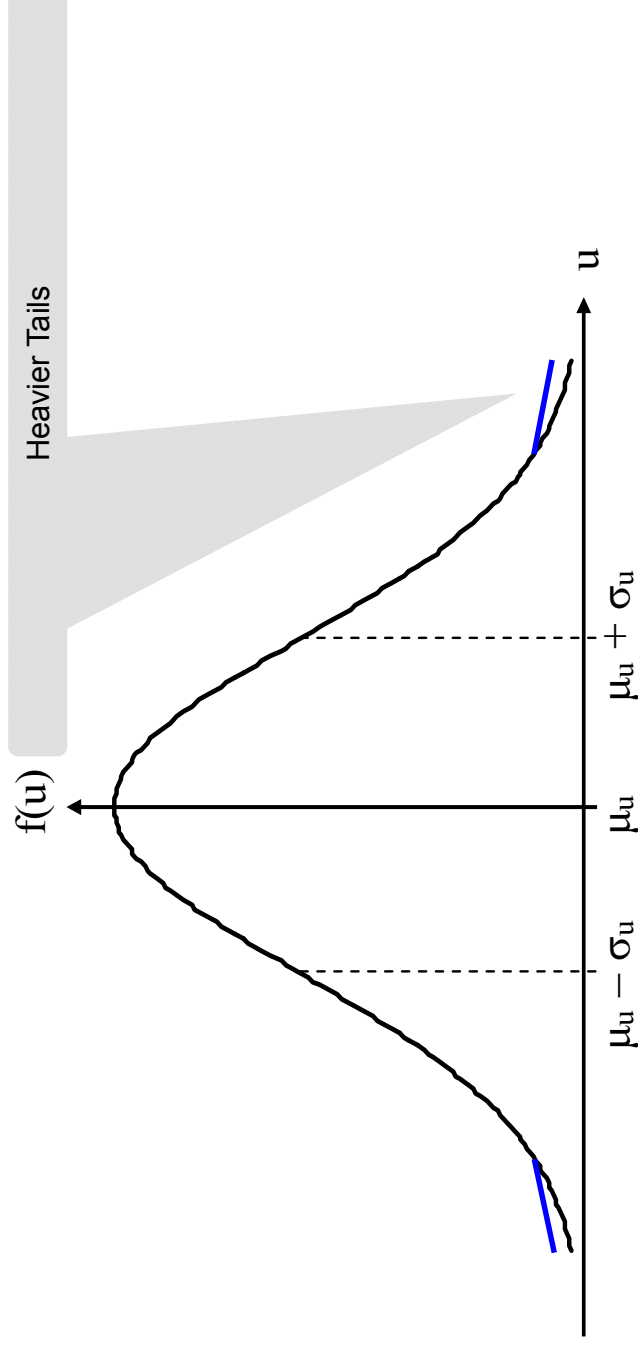
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Wind Speed Spectrum



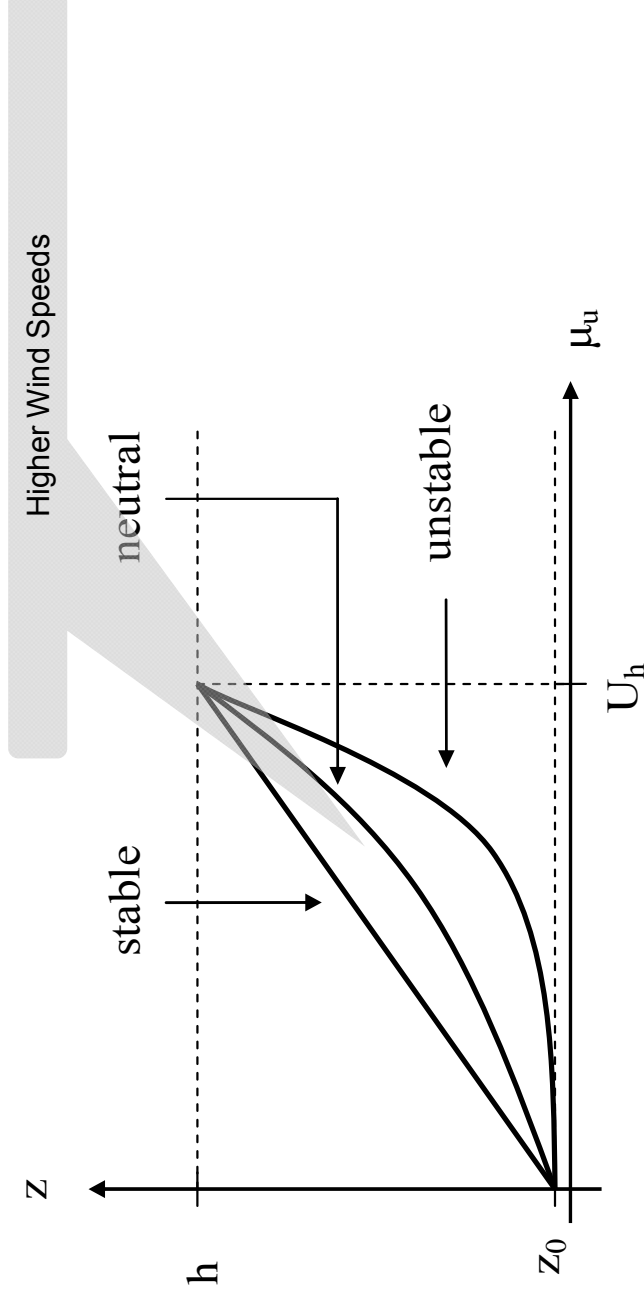
Source: Courtney and Troen, 1990; Gjerstad et al., 1994

Distribution of Wind Speed Variation



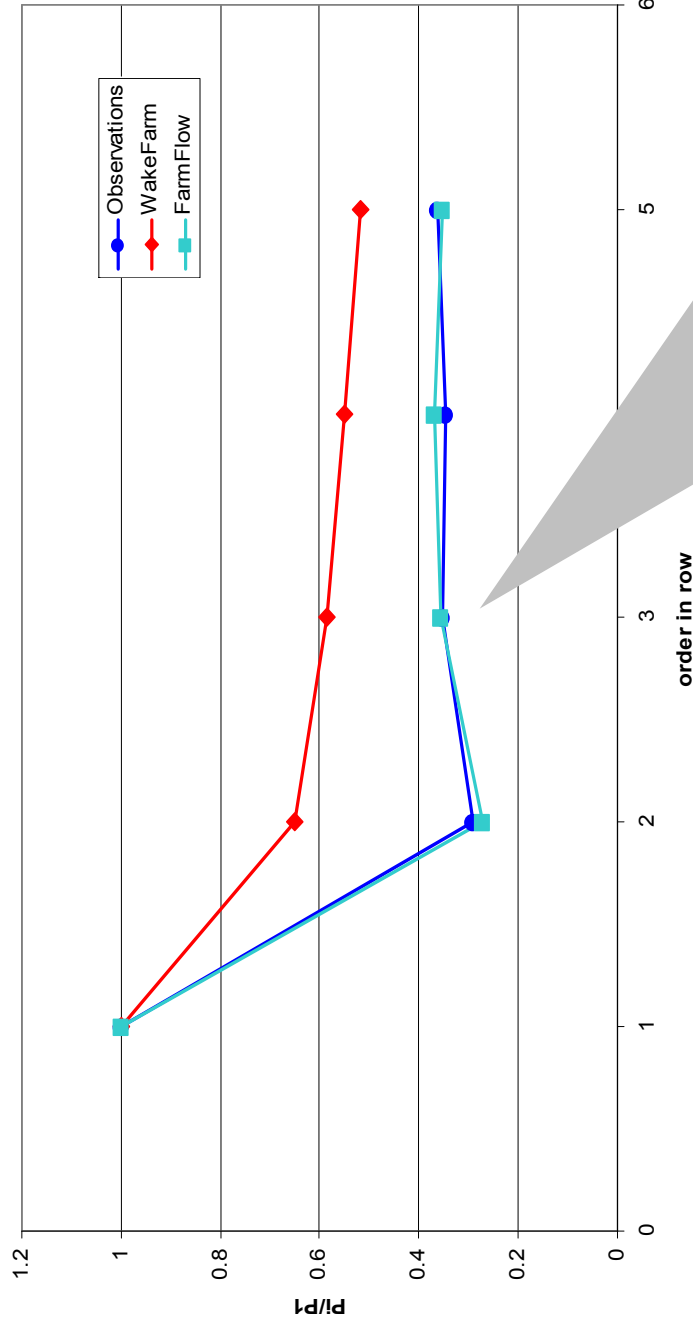
Source: Böttcher et al., 2006

Wind Speed Profile



Source: Gryning et al., 2007

$k\varepsilon$ -models versus measurements



Source: Edwin Bot

Near Wake: Reduced turbulent mixing
 Intermediate Wake: Turbulent mixing concentrated
 in annular shear layer

- Wind energy conversion
- Flow towards, near and behind a wind turbine
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Wind turbine rotor and Wind farm Aerodynamics

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