
OFFSHORE WIND CLIMATE
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Overview

Wind climate

- in general
- variation in height, space and time
- offshore wind measurements
- special offshore effects
- offshore turbulence / extreme winds

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Introduction

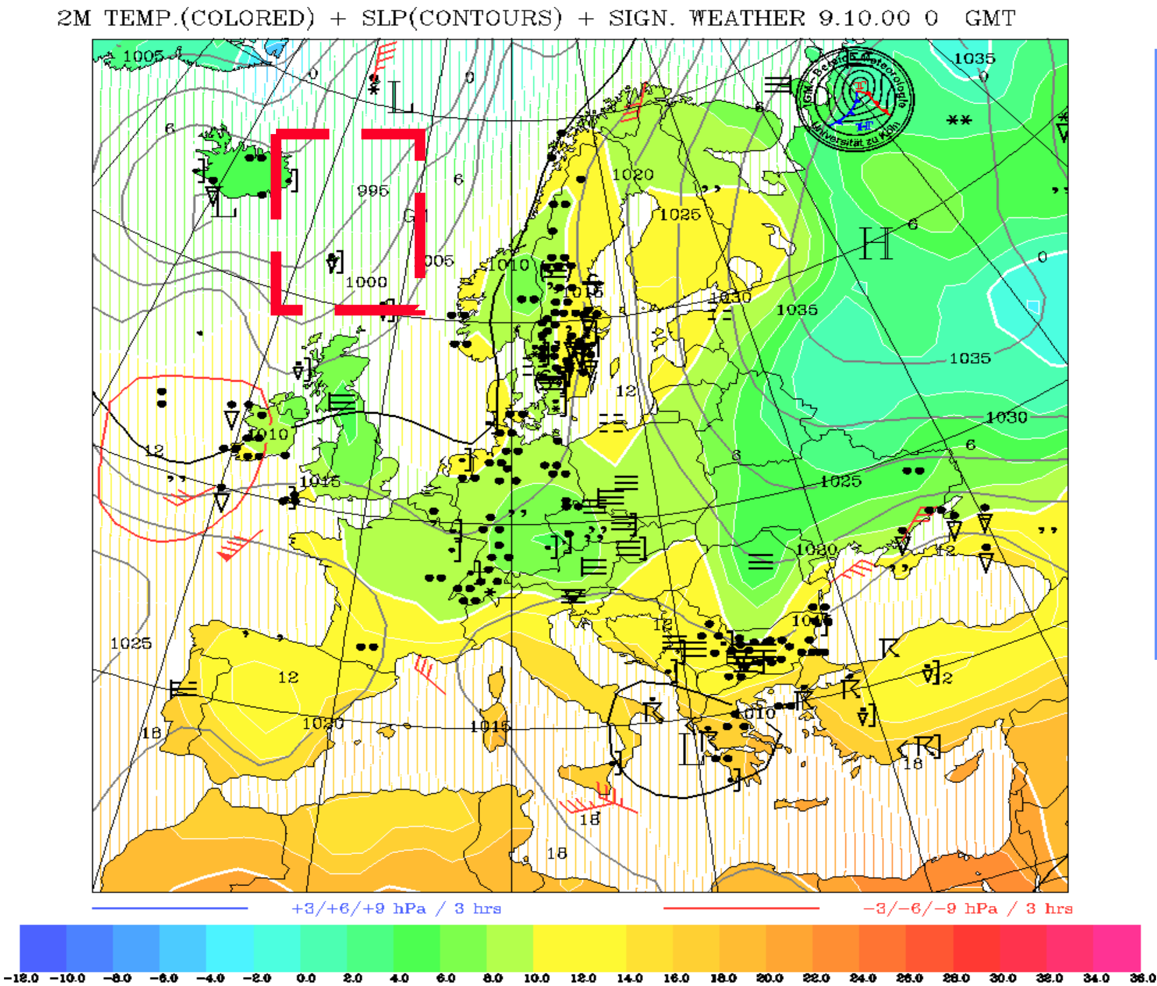
Assessment of wind climate important:

- **assessment of resources**
- **determination of gross energy yield**
- **site conditions at installation**
- **accessibility for maintenance**
- **loads on structures**

mean wind speed

turbulence
extreme wind

What is wind?



- **caused by pressure differences**
  (resulting from temperature differences)
- **influenced by earth rotation and terrain**

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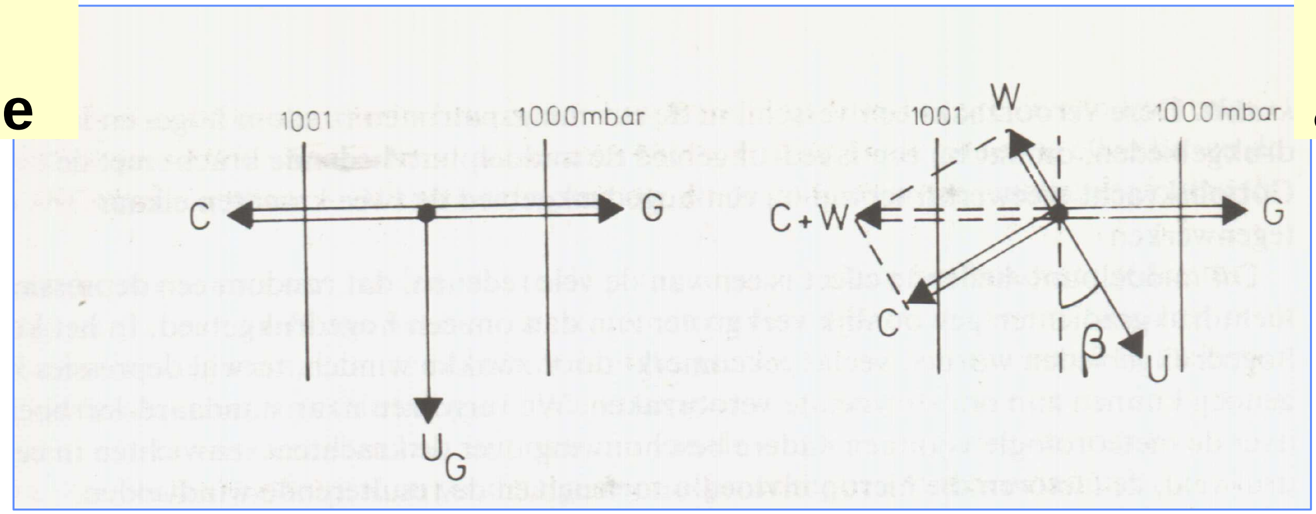
Geostrophic wind

high altitude

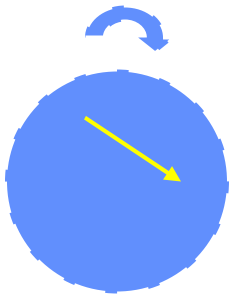
low altitude



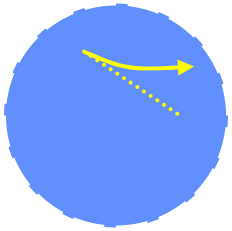
G	**:**	**pressure gradient force**
C	**:**	**Coriolis force**
W	**:**	**drag force**
U_g	**:**	**geostrophic wind**
U	**:**	**wind at the ground**

Coriolis effect

Fictitious force: just effected by rotating observer

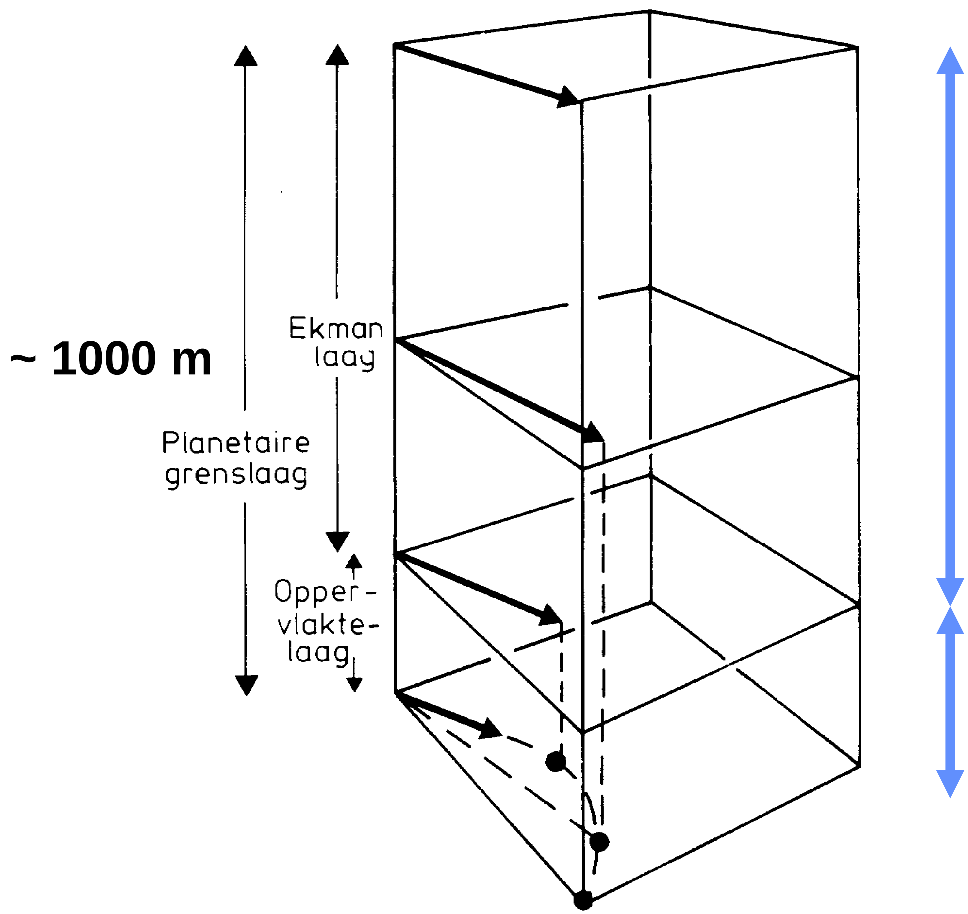


With respect to fixed frame



With respect to rotating frame

Atmospheric boundary layer



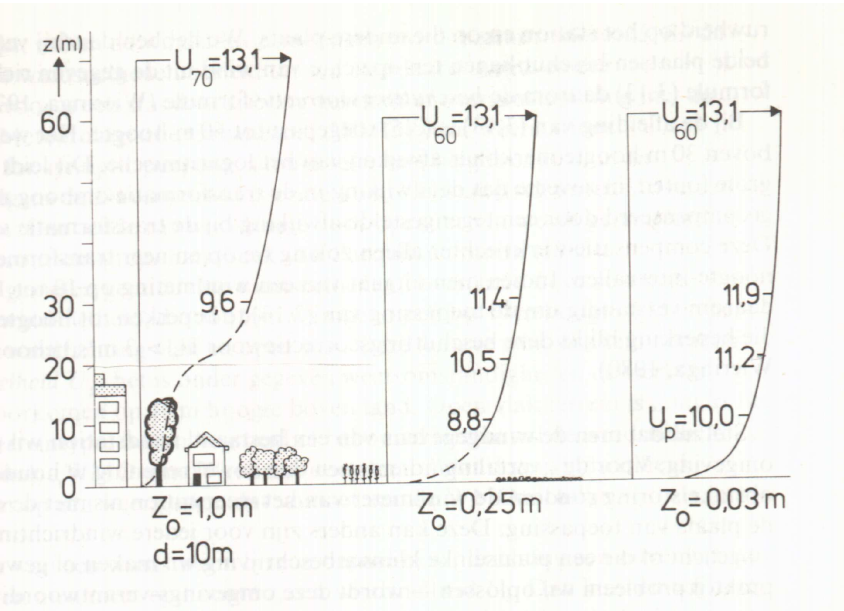
Ekman layer

variation of wind direction

Surface layer

variation of wind speed

Wind profile in surface layer (~100 m)
mechanical friction I



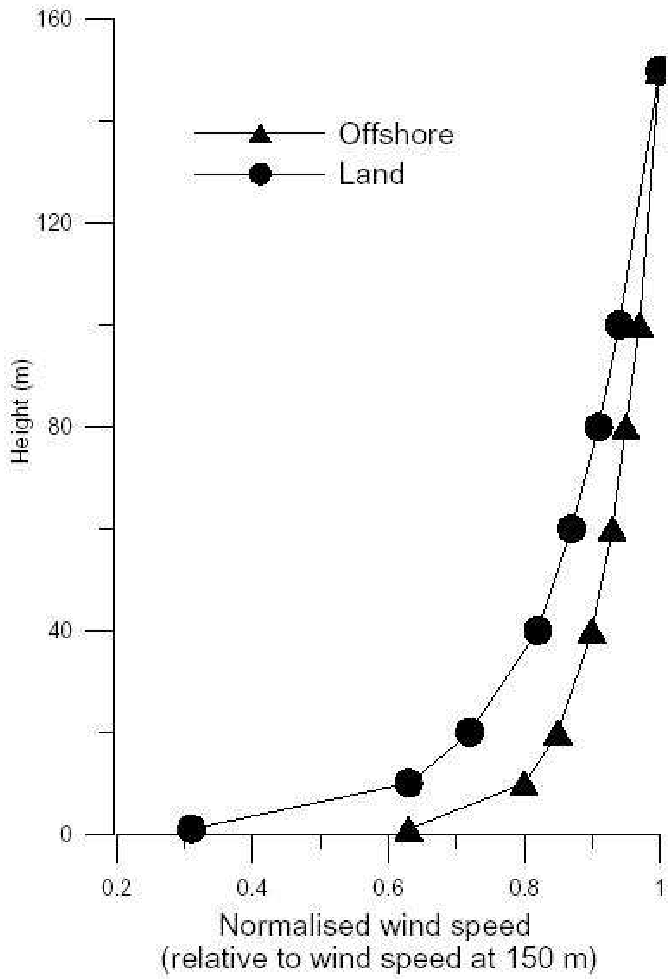
Wind profile (wind shear):

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

h_{ref} **is the reference height (10 m)**

z_0 **is the roughness length**

Wind profile in surface layer (~100 m)
mechanical friction II



At land

- z_0 **= 0.03- 0.25 m**

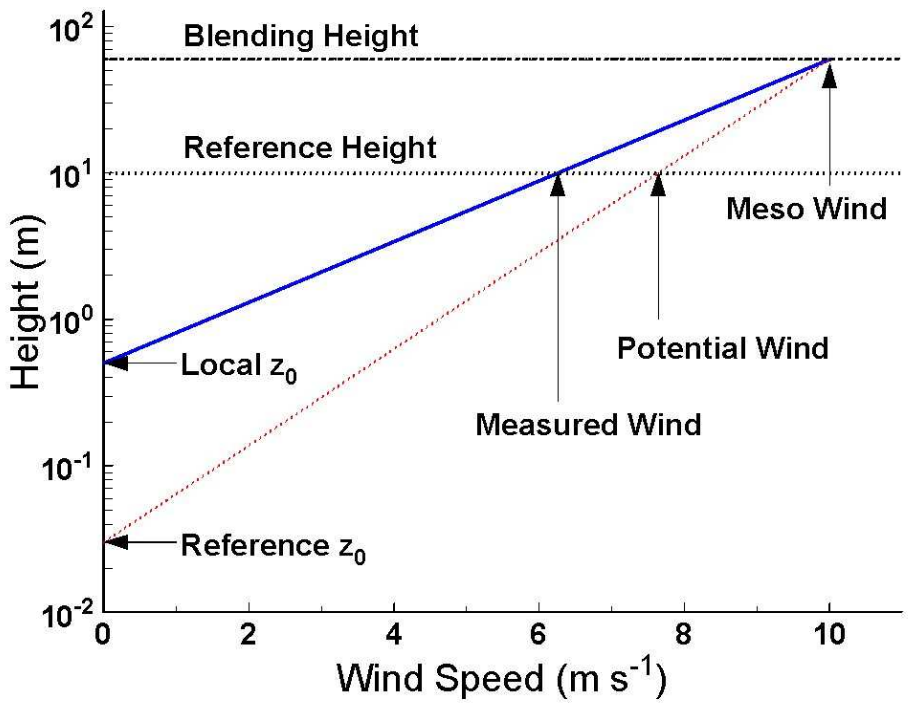
At sea:

- z_0 **~ 0.0002 m**
  but dependent upon
  - **wave height**
  - **fetch**
  - **wave age**

Charnock relation:

$$z_0 = \alpha \frac{u_*^2}{g}; \quad \alpha = 0.0185$$

Potential wind speed
correct for local roughness

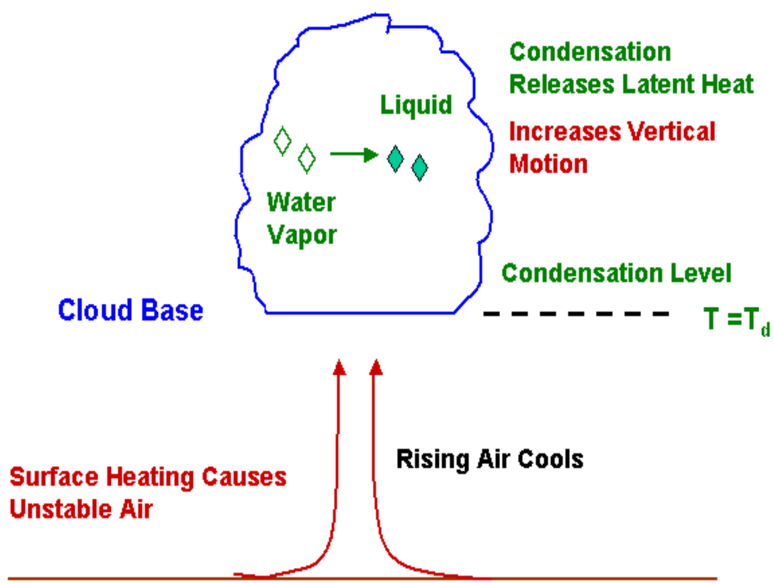


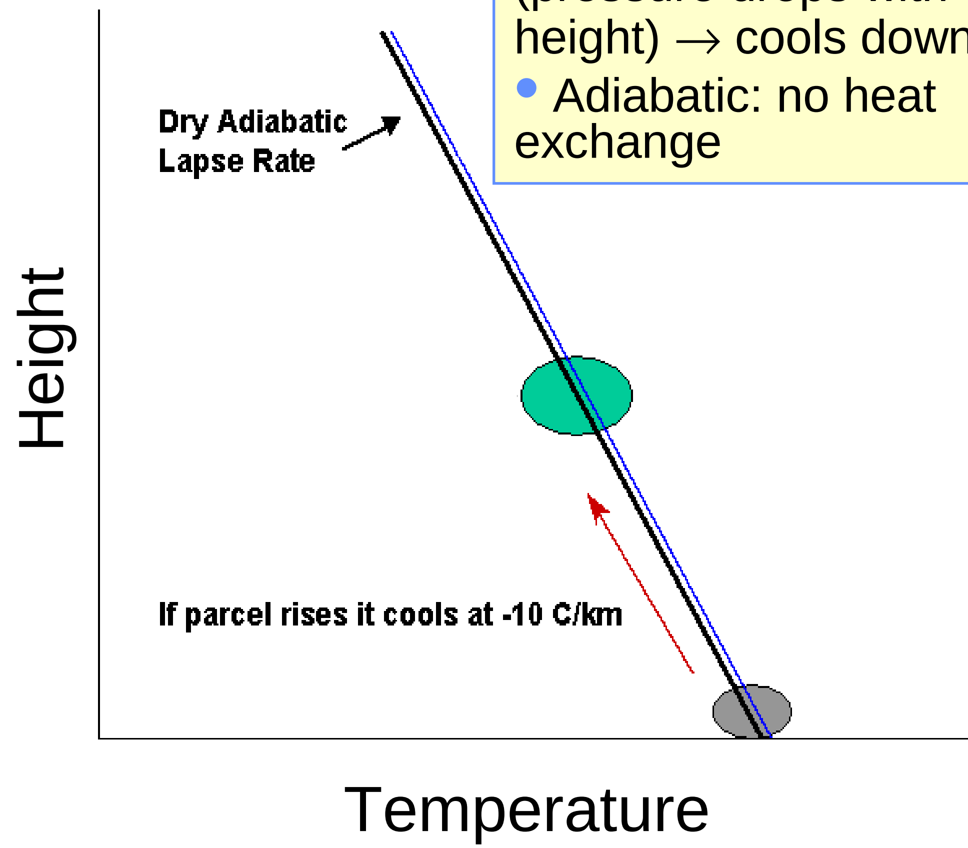
Standard height and roughness:

- **10 min. (or 1 hour) average**
- **10 m. height (= h_{ref})**
- z_0 **= 0.03 m**

Wind profile in surface layer (~100 m)
thermal effects I

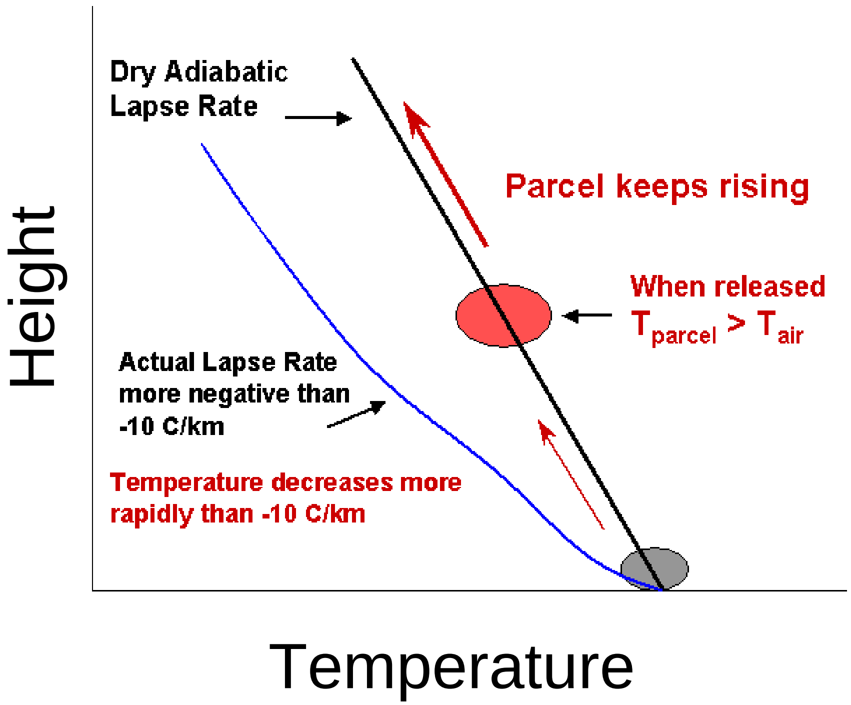
- Parcel expands (pressure drops with height) → cools down
- Adiabatic: no heat exchange





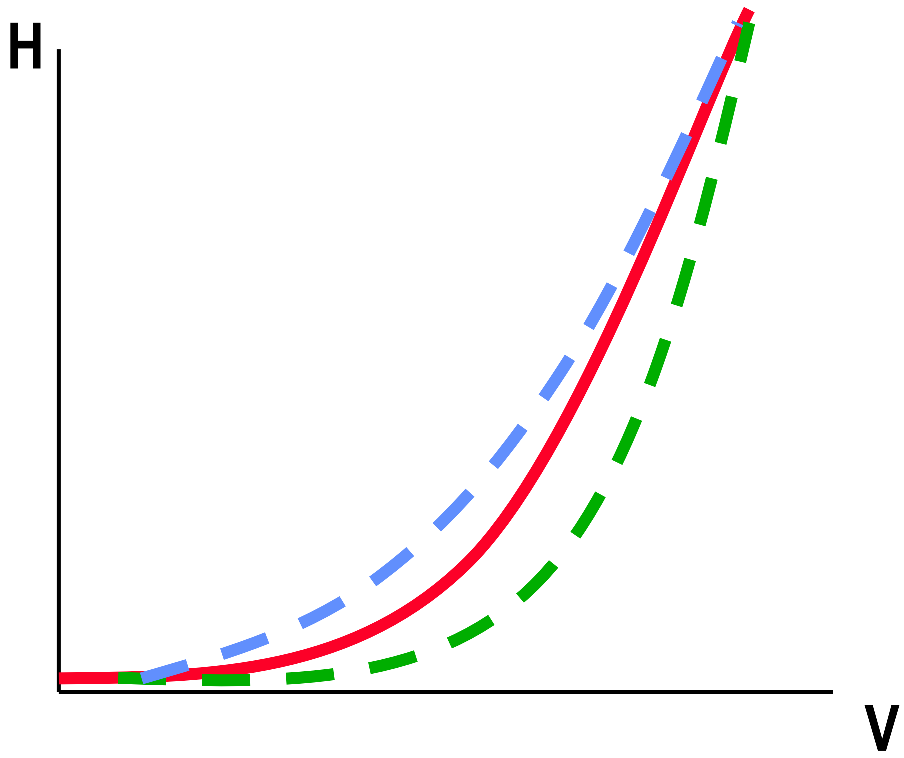
Wind profile in surface layer (~100 m)
thermal effects II

Unstable atmosphere



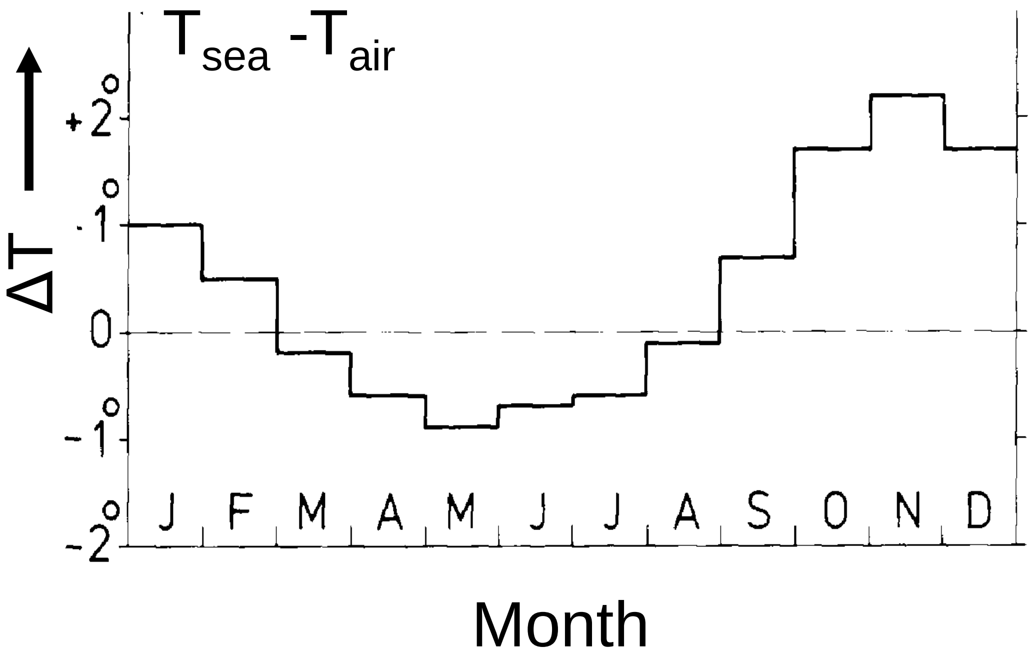
- **Vertical movements of air due to hot surface**
- **Vertical velocity exchange**
- **Steeper gradient**

Wind profile in surface layer (~100 m)
thermal effects III



- stable (cold surface)
- neutral
- unstable (hot surface)

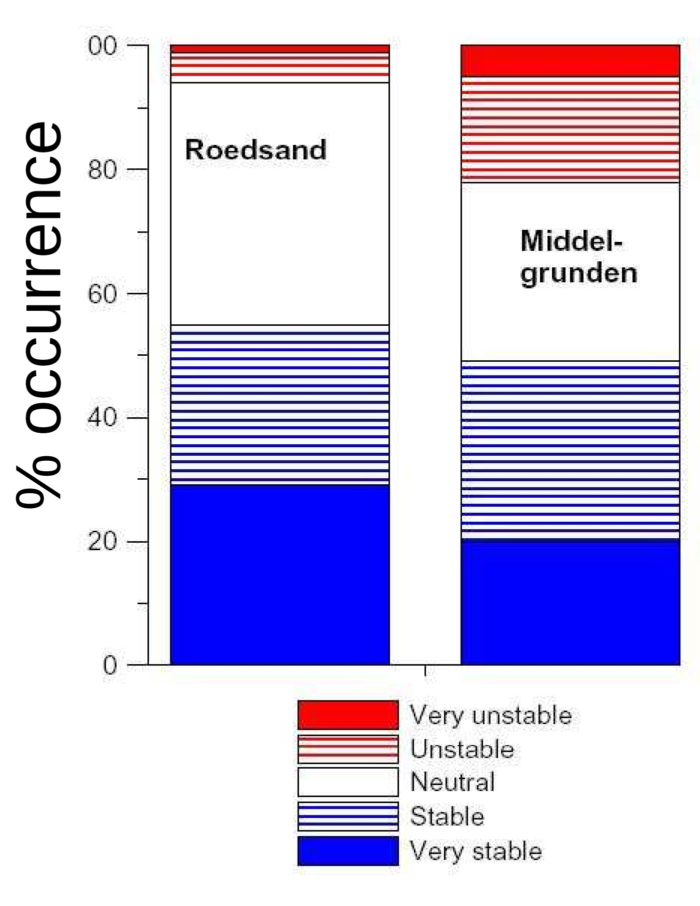
Temperature difference



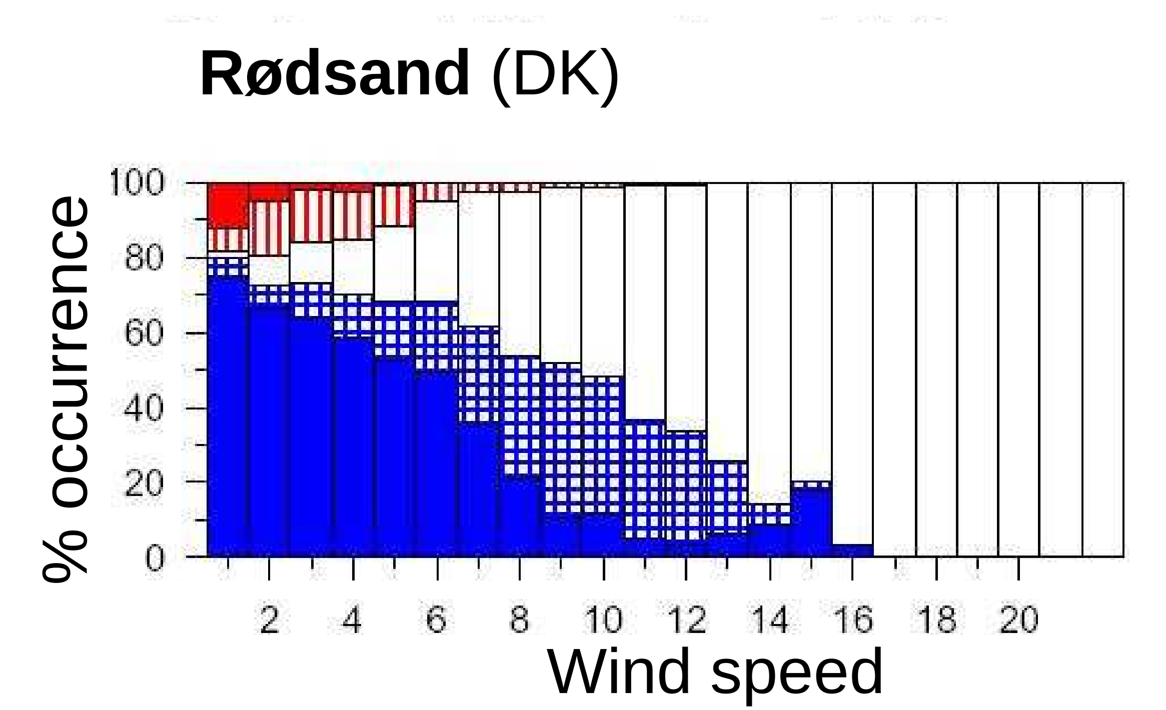
Average wind - water temperature difference at North Sea location.

- **Summer: stabilizing ΔT**
- **Winter: destabilizing ΔT**

Boundary layer stability at sea



Danish "offshore" sites



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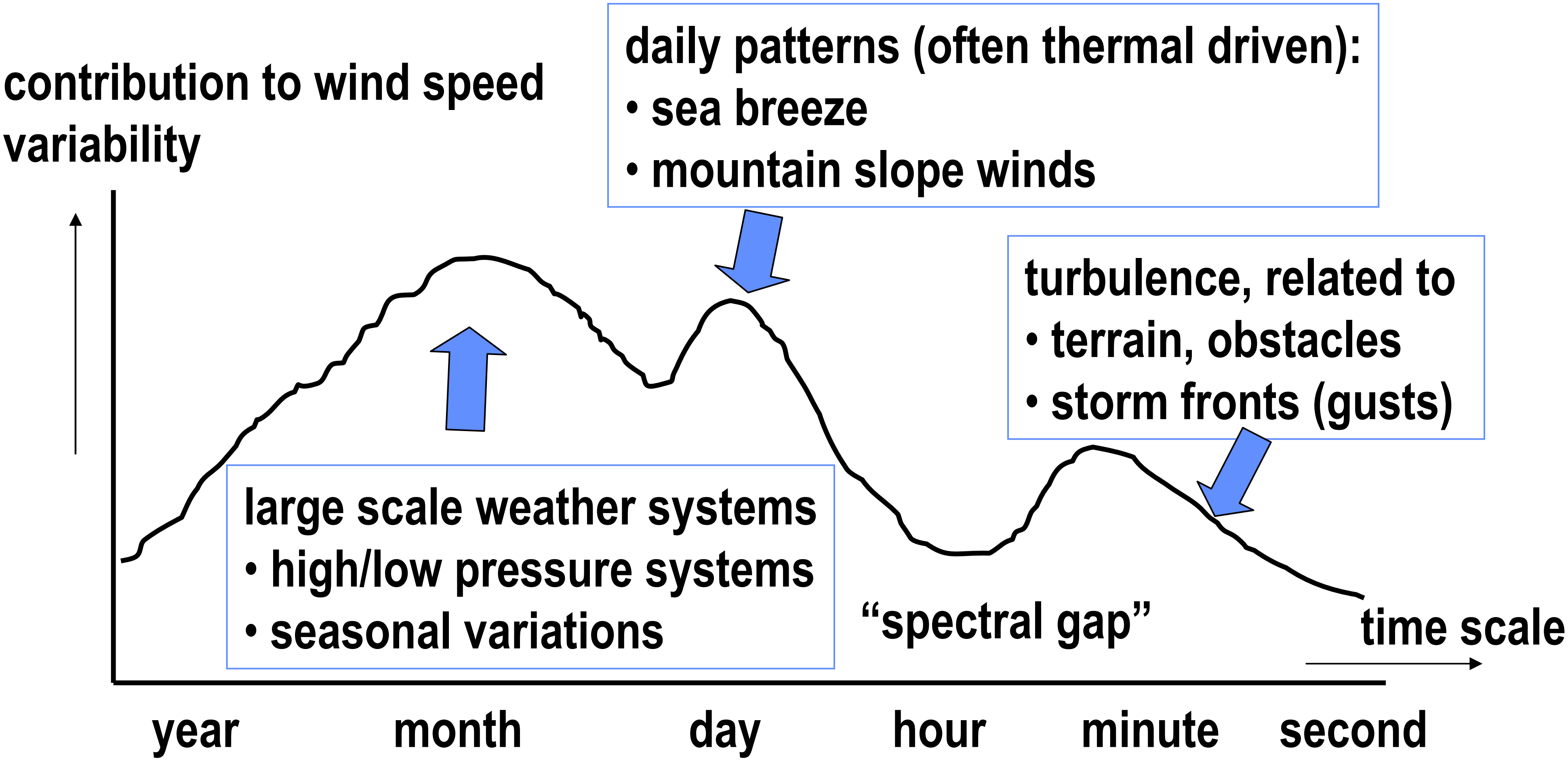
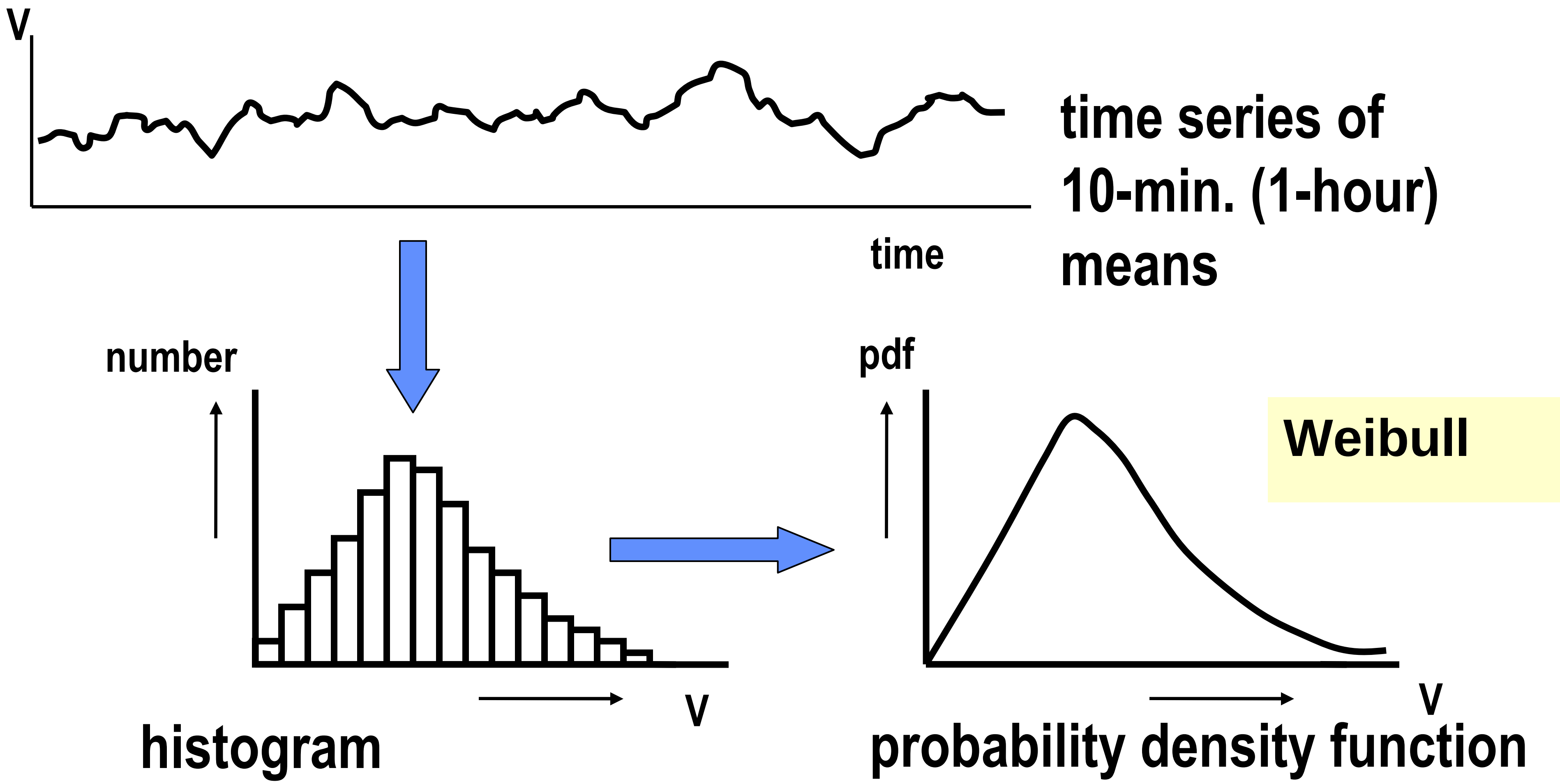
Variability of the wind in time



Space: 100-1000 km < 1 km < 10 m

Basic wind statistics



Weibull distribution

probability of wind speed < V: $1 - e^{-(\frac{V}{a})^k}$

with

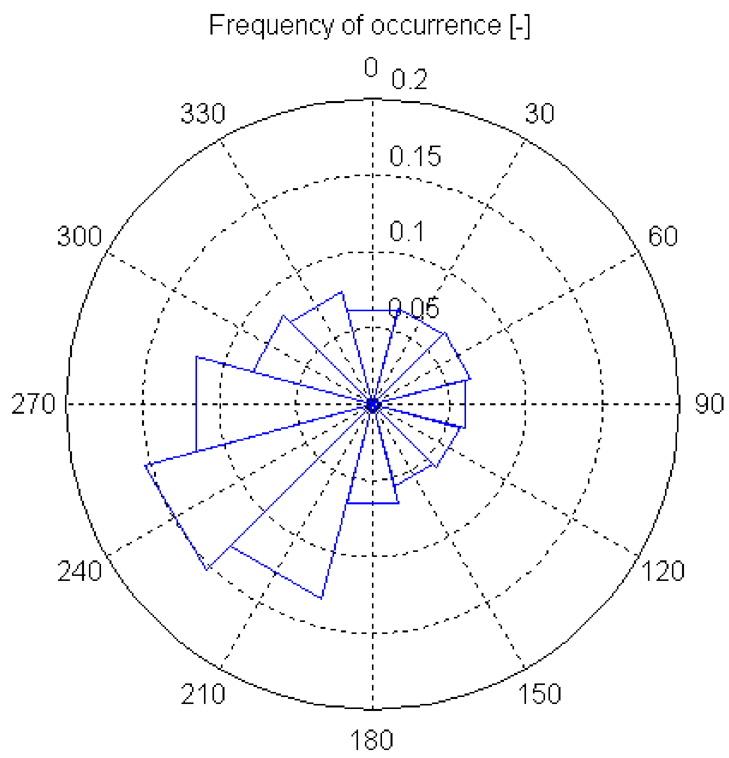
k : shape parameter (k ≈ 2 in NW Europe coast)

a : scale parameter

$$a = \frac{V_{avg(year)}}{\Gamma(1 + \frac{1}{k})}$$

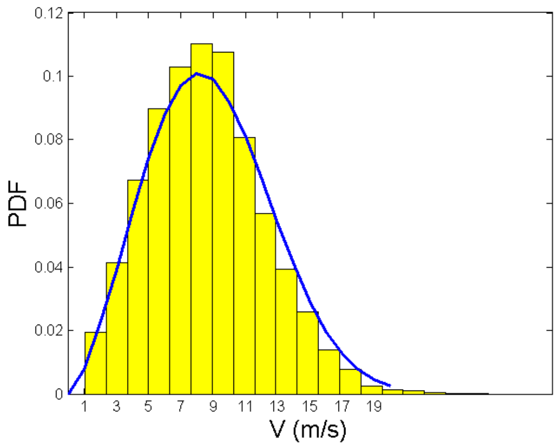
$$\Gamma(\alpha) = \int_0^\infty \beta^{\alpha-1} e^{-\beta} d\beta$$

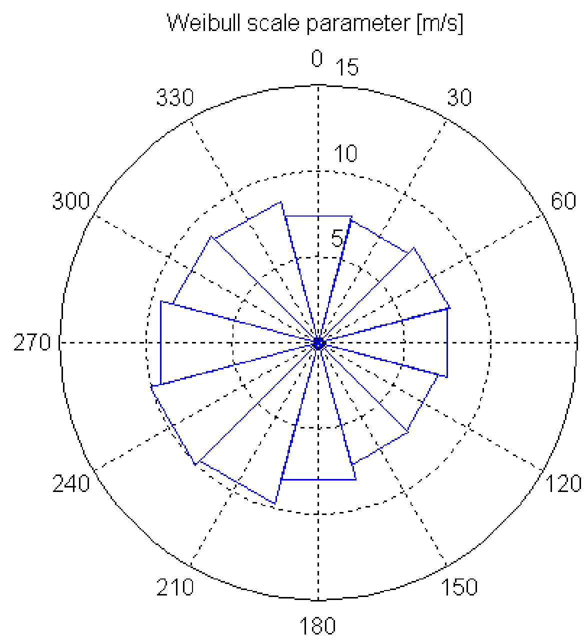
Fit of Weibull distribution – example I

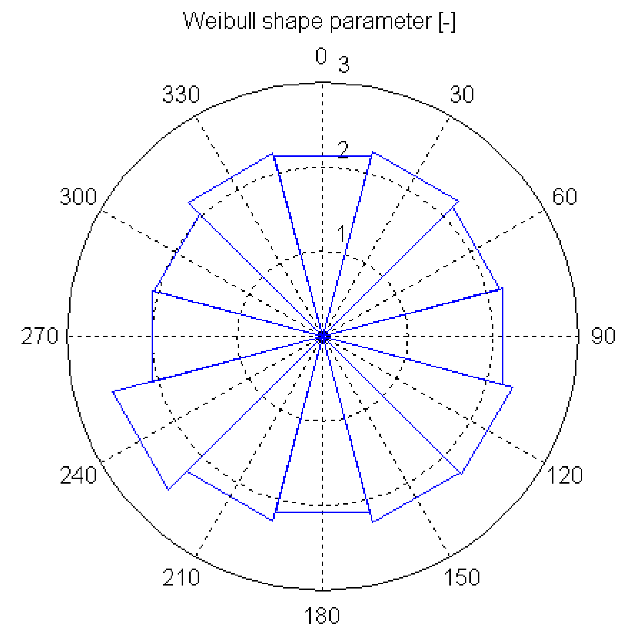


Frequency of occurrence (wind rose)

Fit of Weibull distribution – example II







Weibull scale parameter

Weibull shape parameter

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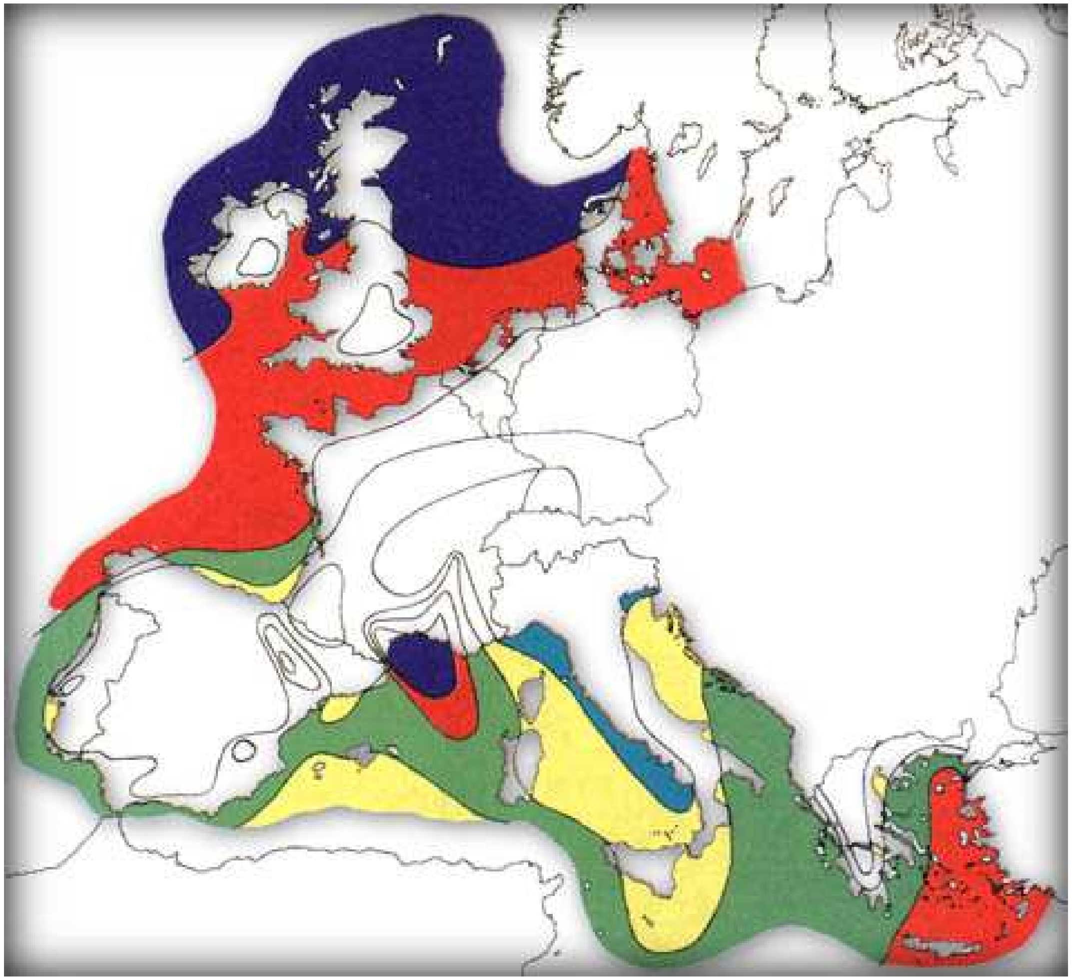
Existing offshore wind map



- **Evaluation of offshore potential**
- **Extrapolation from land measurements**
- **Not suitable for energy yield calculation**
- **Coastal effects cause main problems**

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How to obtain wind statistics for a given location ?

two basic options

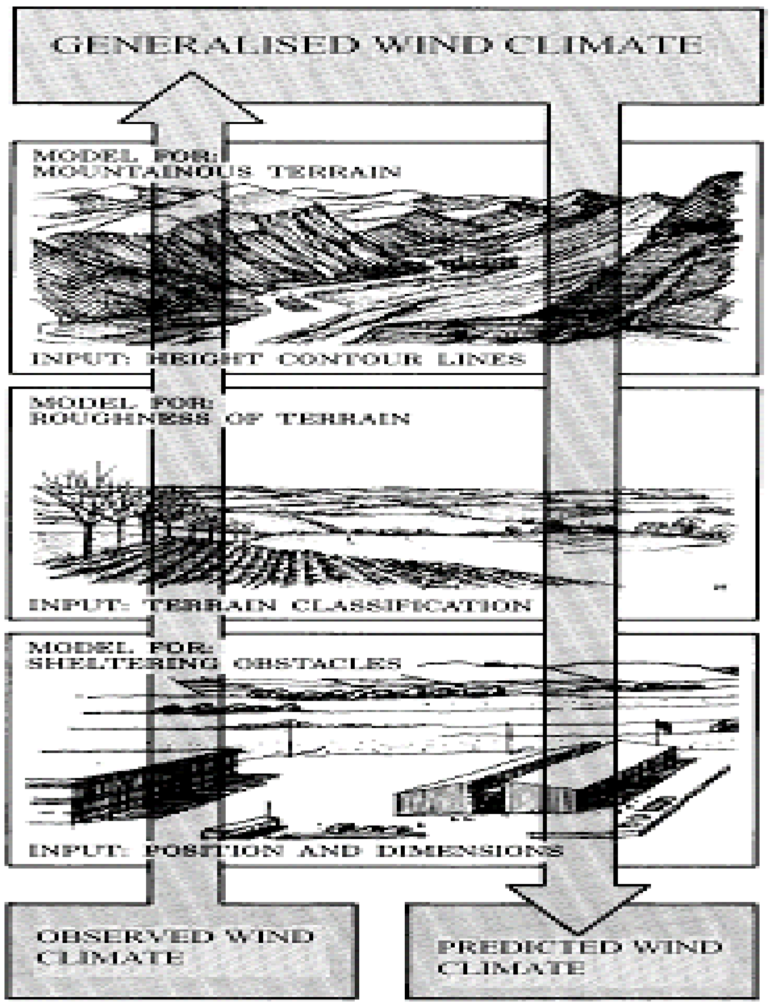
	problem:	solution:	
use existing data	data not representative	use of correction methods (fetch, obstacles on land)	Windatlas + correction methods (WA^{s}P); Other sources
perform local measurements	not possible to measure long enough to obtain good statistics	correlate with other sites which <u>have</u> reliable long term statistics	"Measure Correlate Predict" (MCP)

WA^{S}P offshore (Risø DK)

speed-up over hills

change in roughness

shelter model



Determine Offshore wind atlas at 150 m height

- **Calculate downward to hub height using local orography**
- **Account for coastal effects**
- **Not yet fully operational**

Available offshore wind data

KNMI wind network (NL)

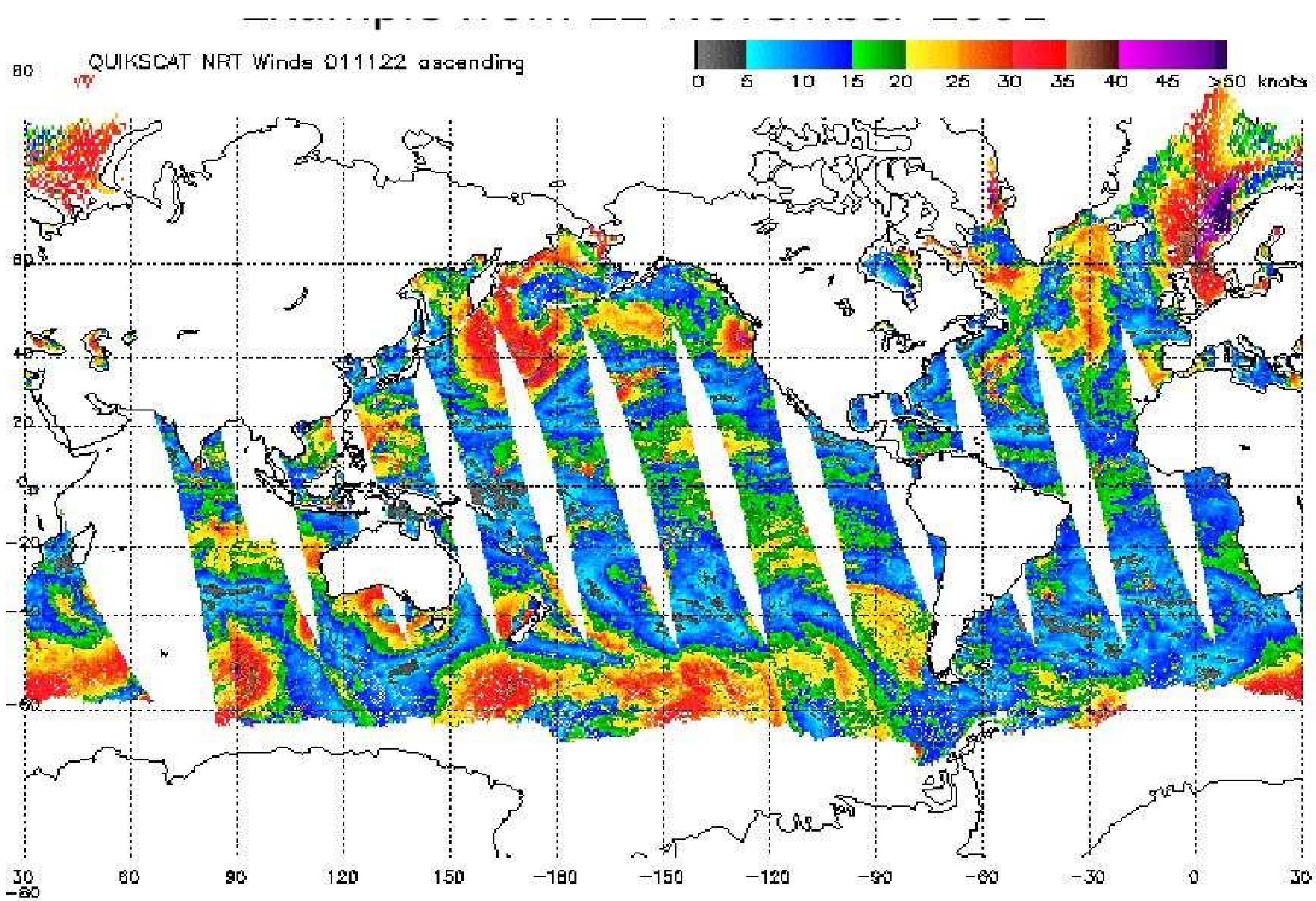
Platform data (since ’80)

- KNMI, RWS: Measuring Network North Sea (limited w.r.t. land)
- wind and wave data

Other sources

- light ships
- Voluntary Observing Ships
- databases (e.g. NESS / NEXT “hindcast” data)
- pressure data (weather forecast)
- remote sensing / satellite data

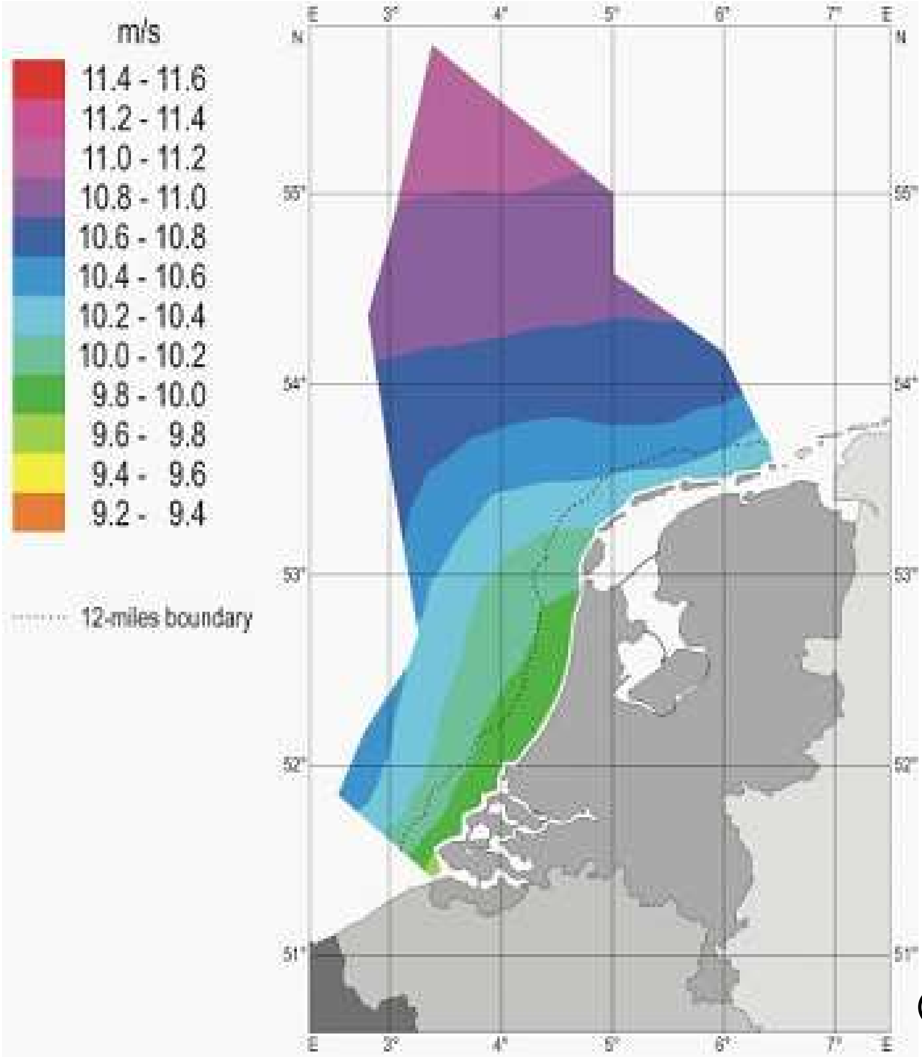
Remote sensing



Satelite sampling

- **Spatial distribution**
- **Accuracy 2 m/s**
- **Time shift**
- **Satellite passages**
- **Diurnal cycles !?**

Dutch Offshore wind map



Netherlands' Exclusive Economic Zone

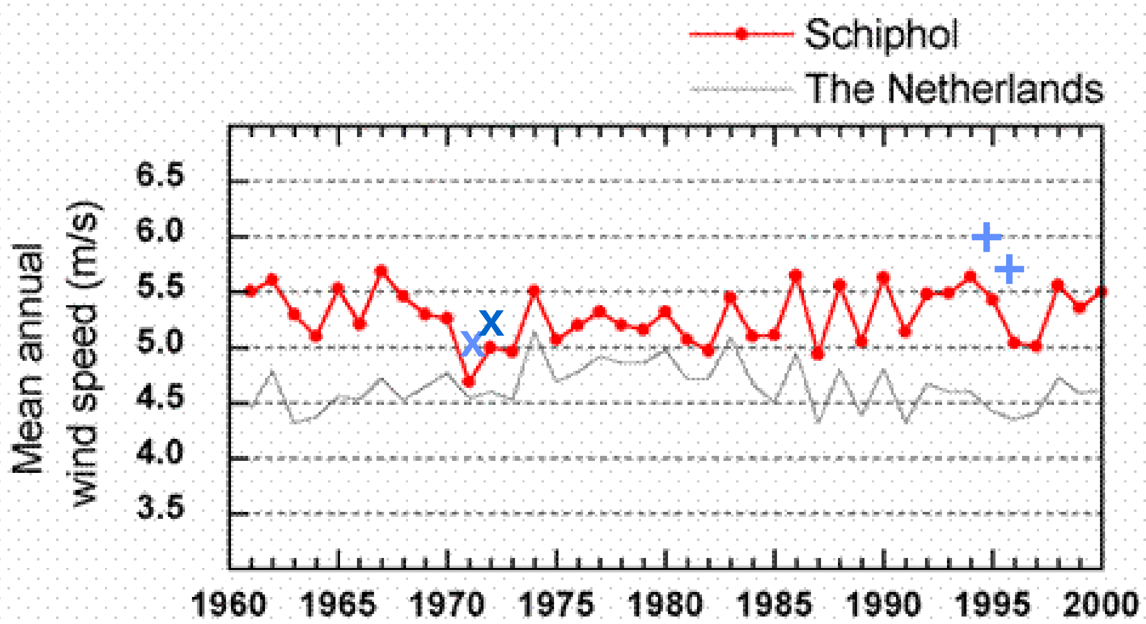
Derived from pressure data (1997-2002)

Height: 120 m

Distribution available for 5 locations

Measure Correlate Predict - example

x, +: measurements



Background MCP:

time series annual wind speeds look similar; high and low values occur at the same years

Long term correction factors

2 years of measurements of a site near Schiphol

+: 0.95

x: 1.05

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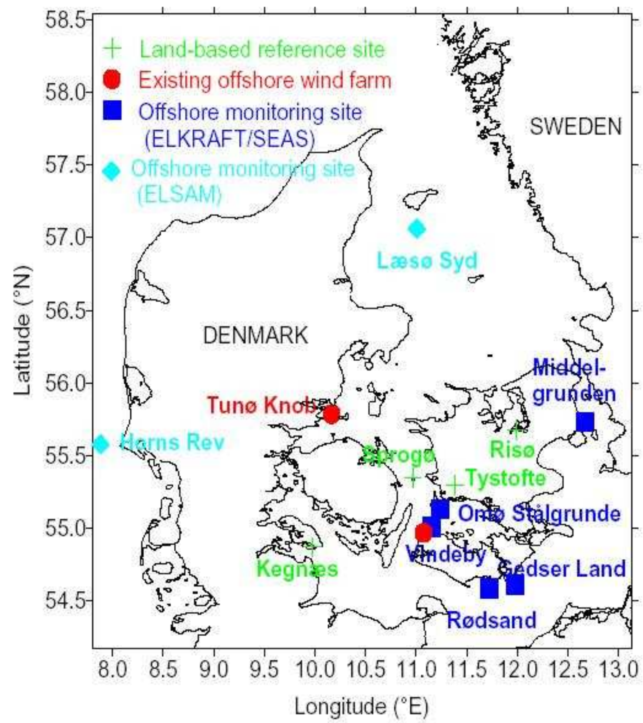
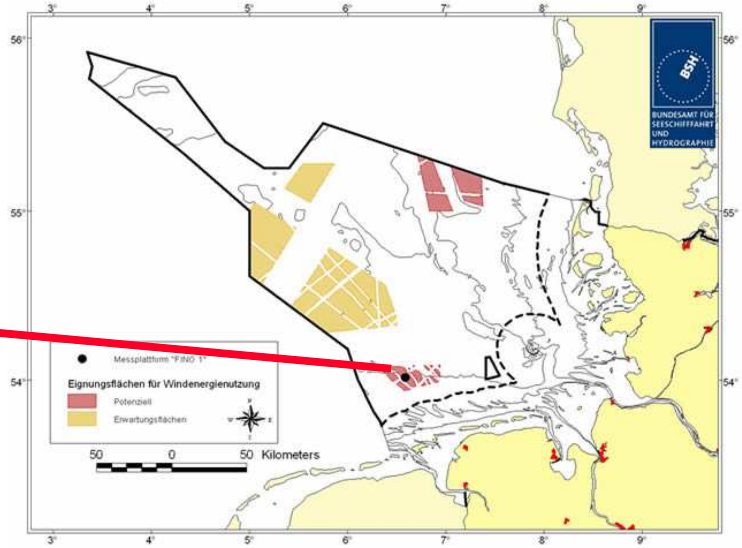
MCP: dedicated measurements I



Risø/SEAS meteo masts at sea

5 locations 50 m height in Danish seas

MCP: dedicated measurements II

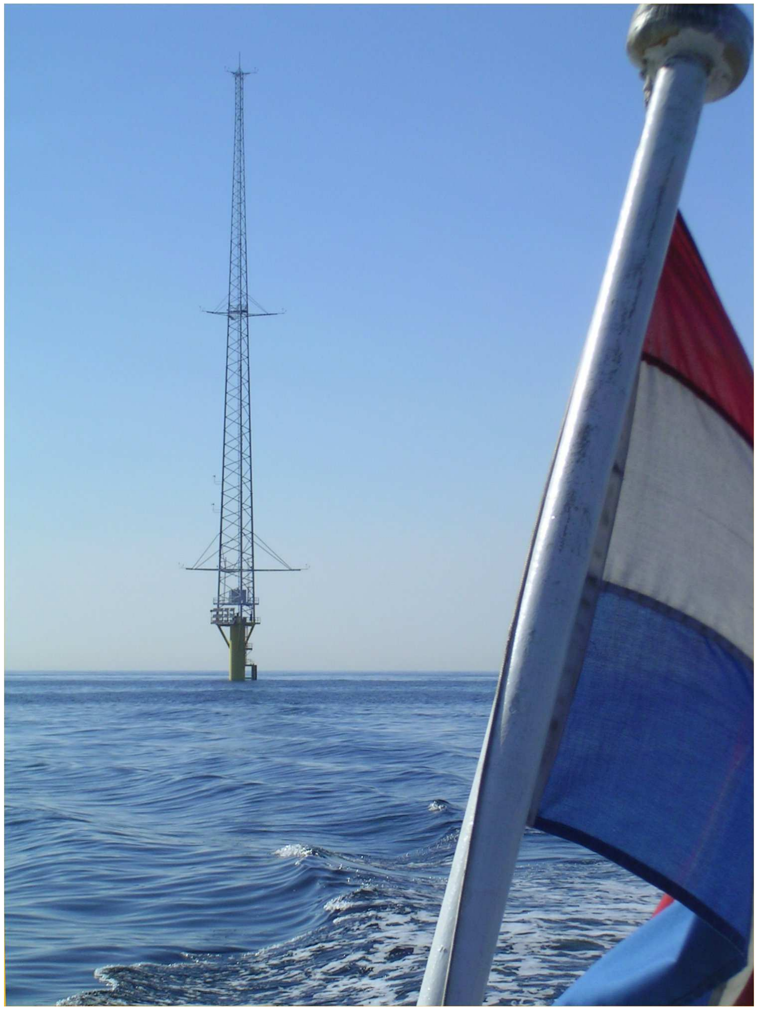


www.fino-offshore.de

"Fino" platform in German part of the North Sea

105 m height; full site assessment: Hydro, meteo and biological surveys

MCP: dedicated measurements III



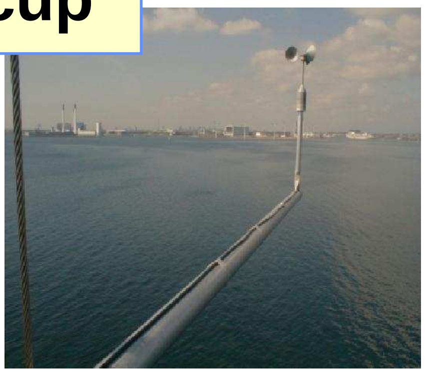
Platform OWEZ (116 m)

- **WEOM**
- **3 levels; 3 sides; booms of 12m**
- **2003**
- **also metocean data**

- **“Monitoring- en evaluatie programma Near Shore Windpark” by the Dutch Government**

MCP: dedicated measurements IV

cup



sonic

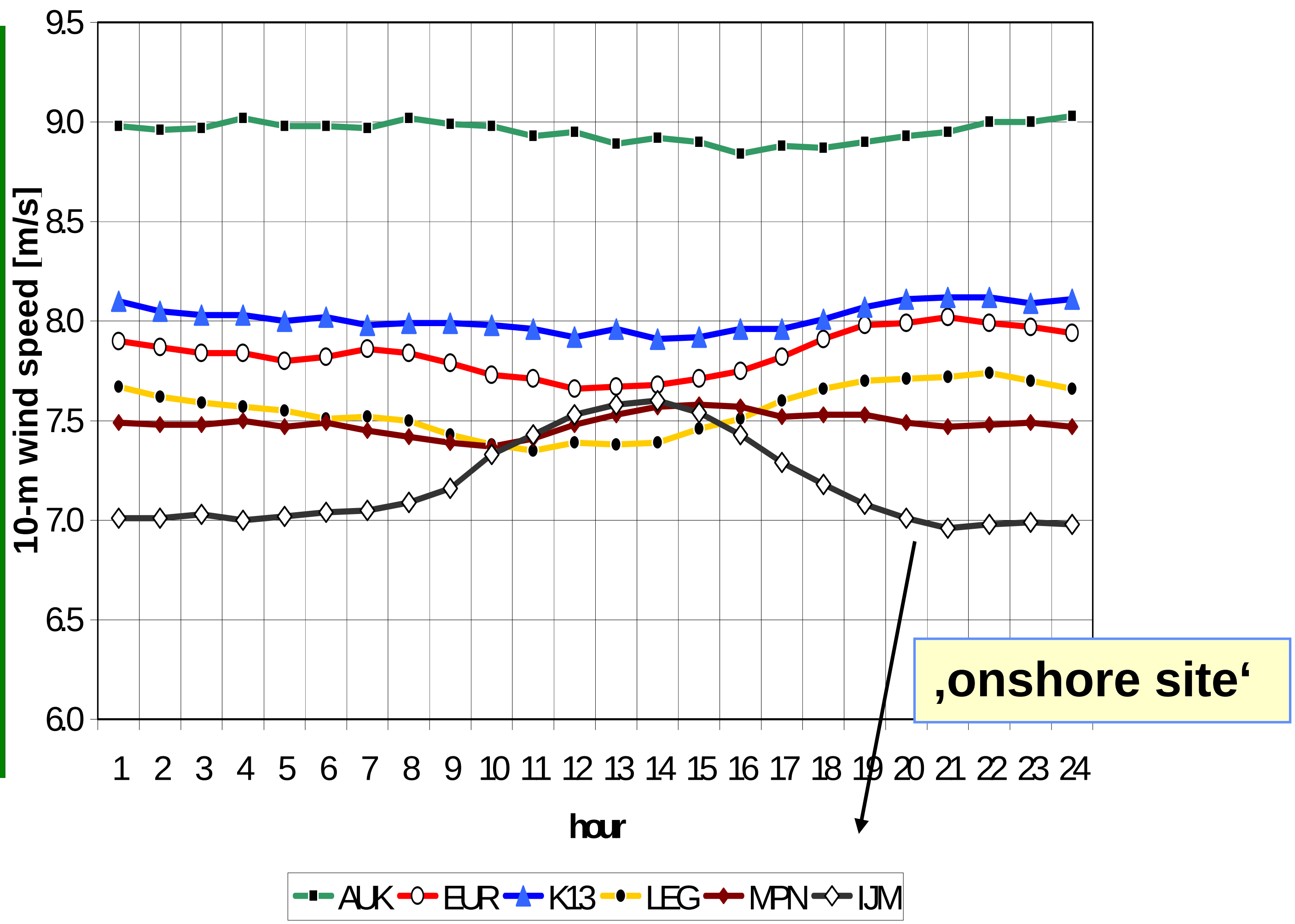
Meteo masts at sea:

- **Corrections for mast shadow**
- **Well proven but expensive**

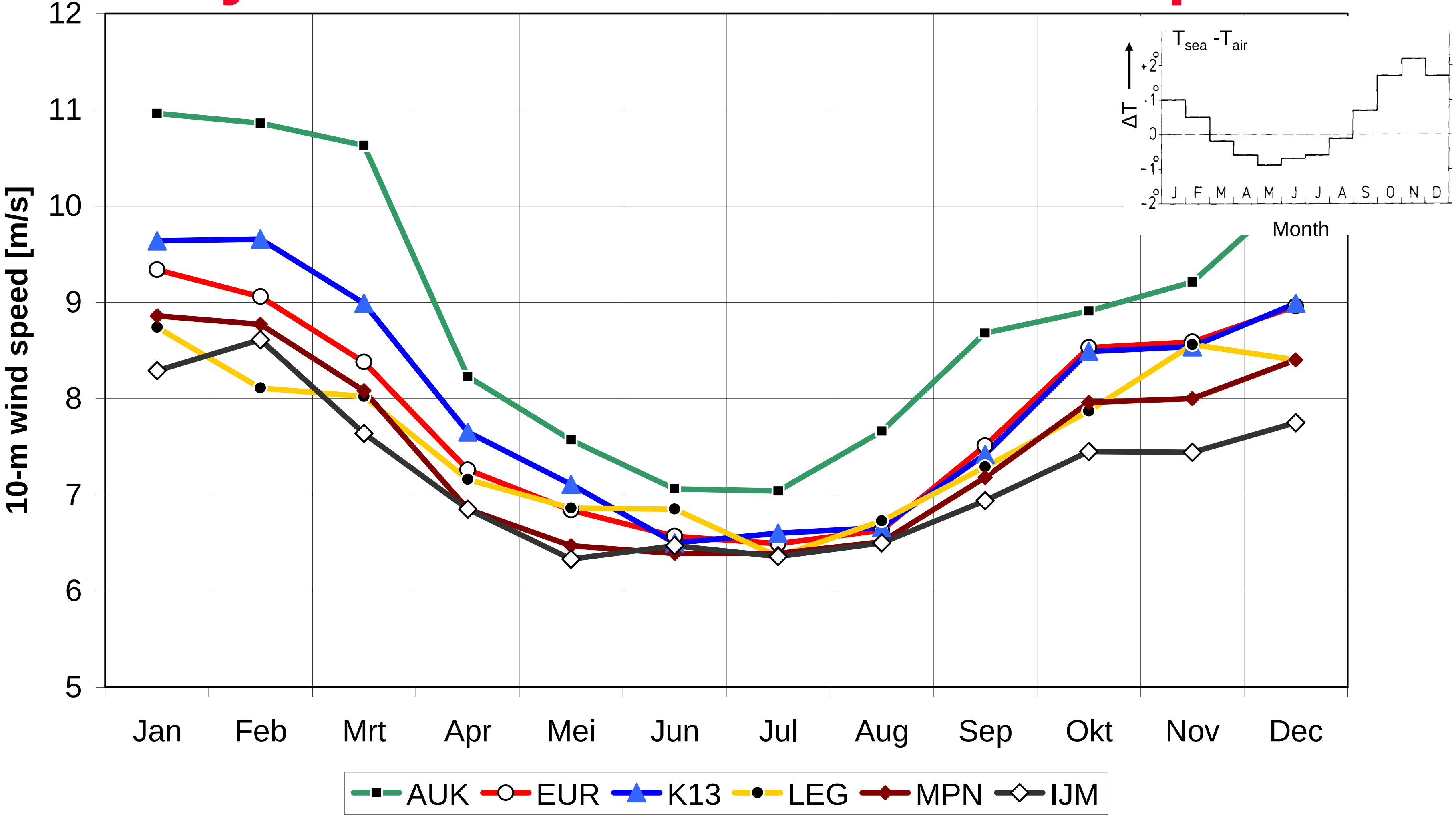
Sodar / Lidar anemometers

- **Doppler shift of an acoustic pulse / laser**
- **Promising but expertise required**

Hourly variation of offshore wind speed



Monthly variation of offshore wind speed



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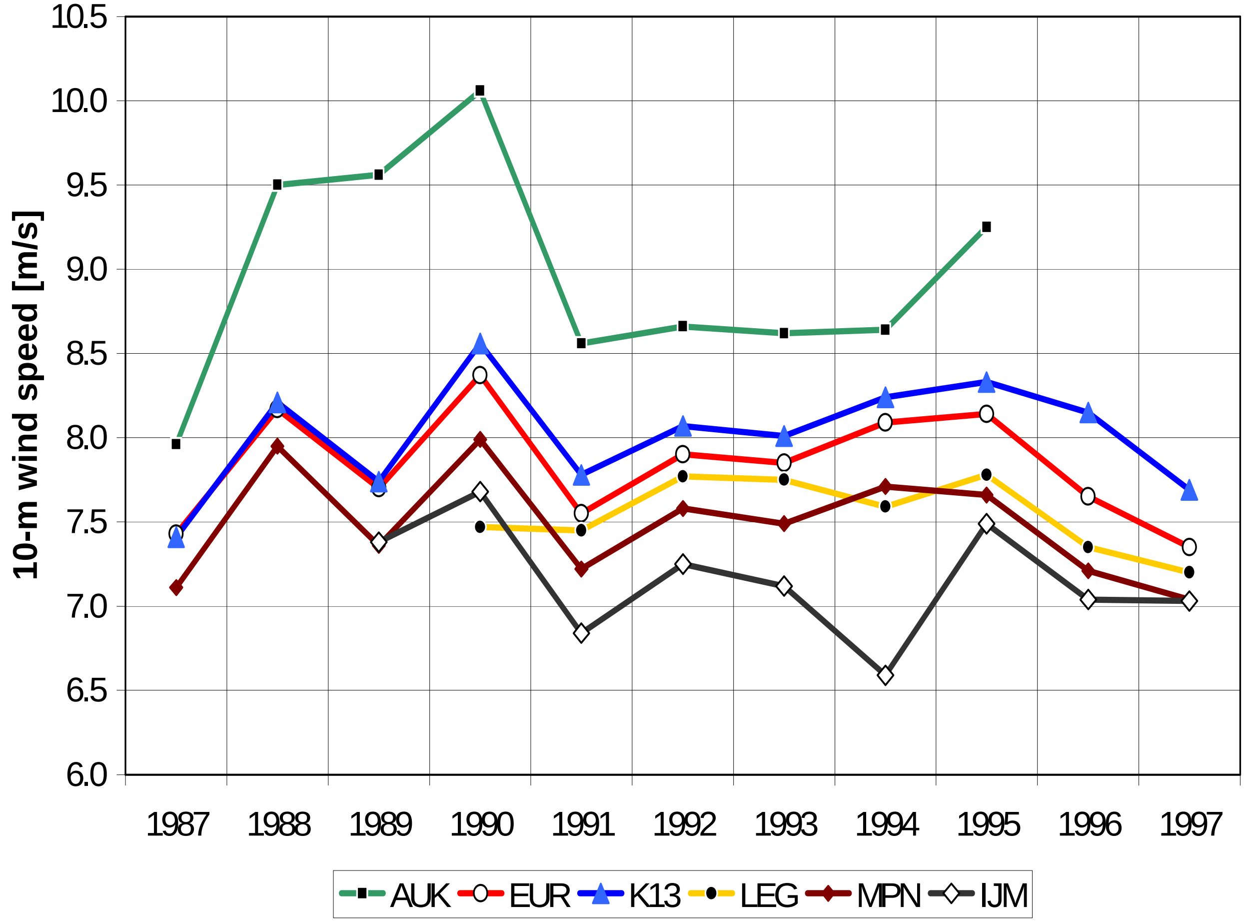
Annual variation of offshore wind speed

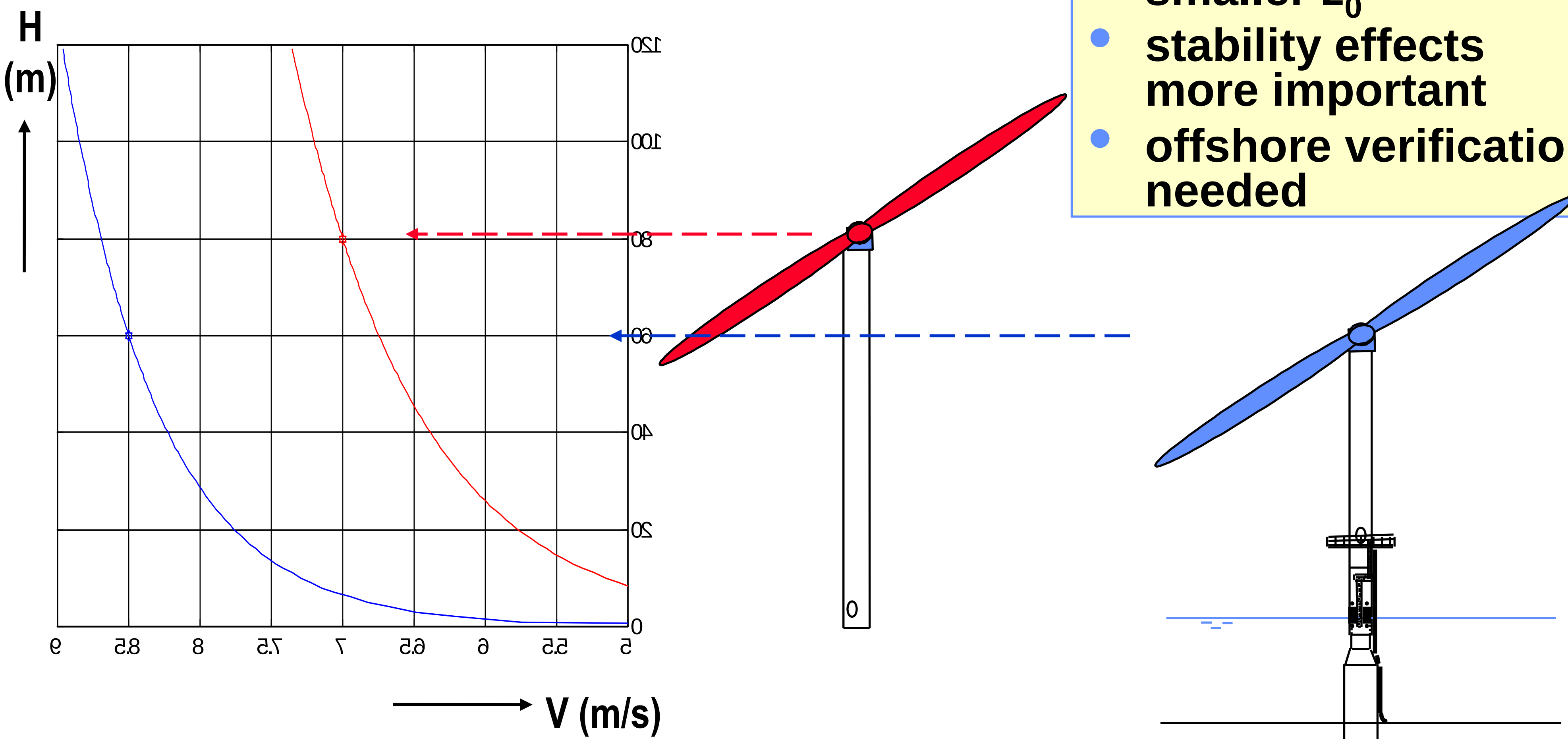


Consequences:

- **Annual energy yield / income will vary from year to year !!**
- **Base energy yield estimation on long period (20-30y)**

Offshore versus onshore: wind shear

- larger V
- smaller z_0
- stability effects more important
- offshore verification needed



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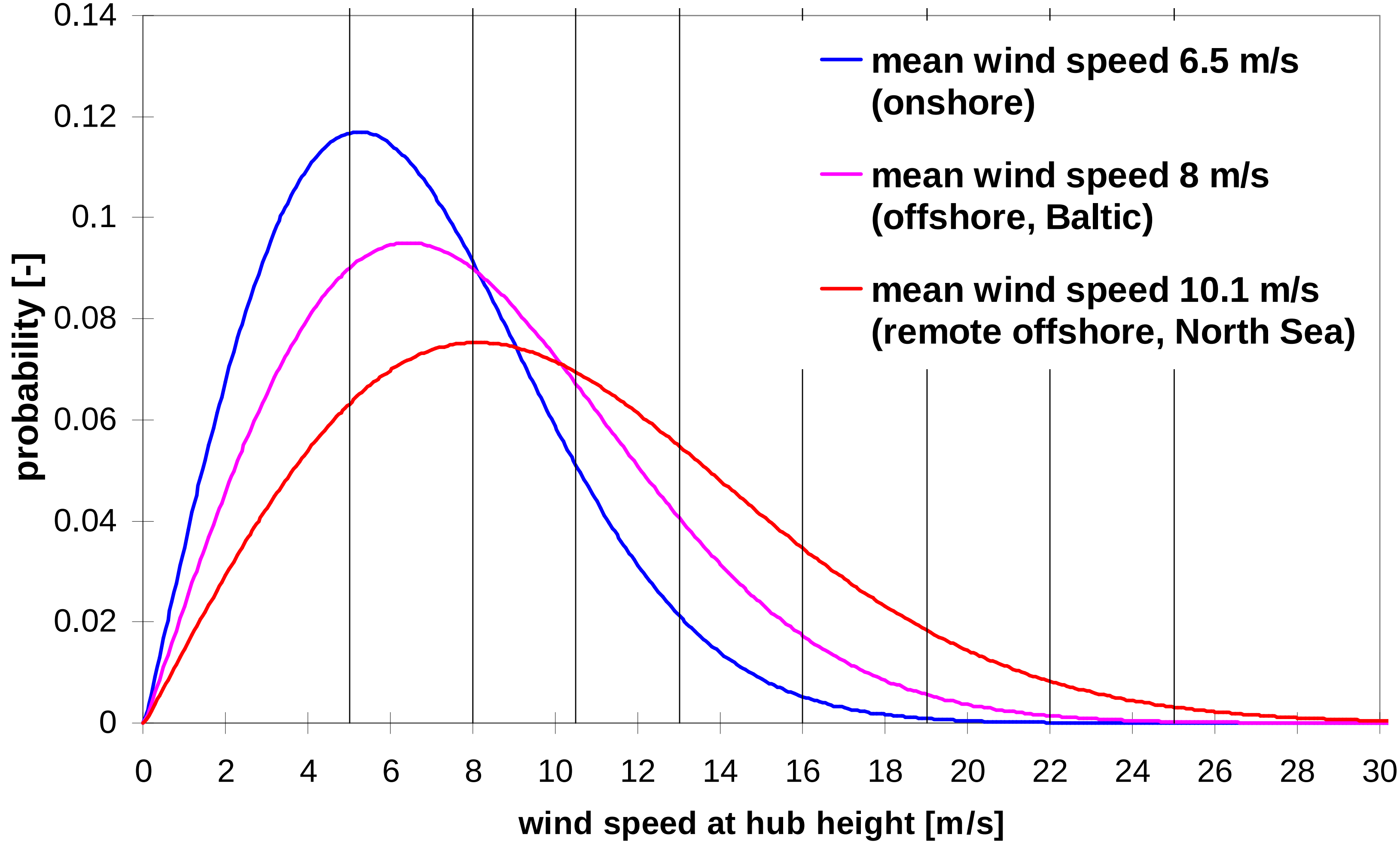
Offshore versus onshore: Weibull distribution



Wind climate offshore versus onshore

	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

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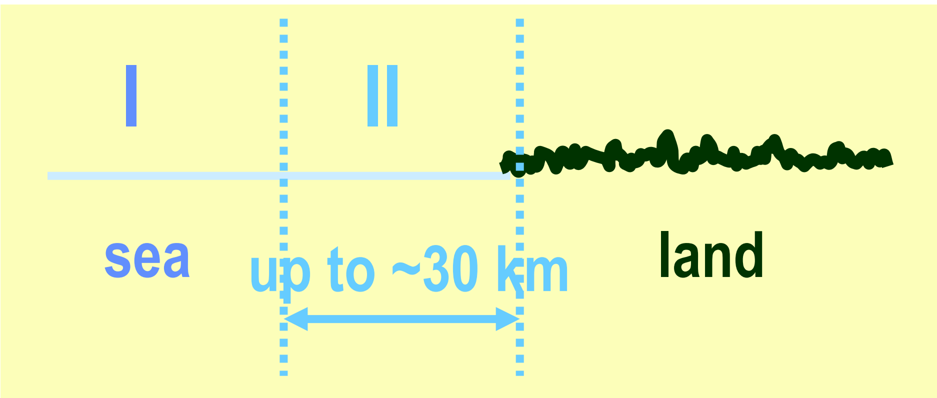
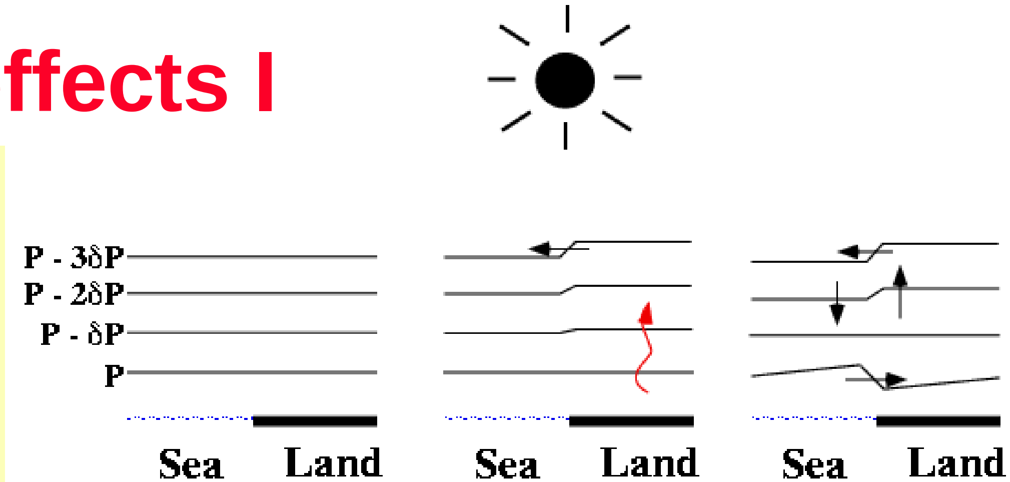
Coastal effects I





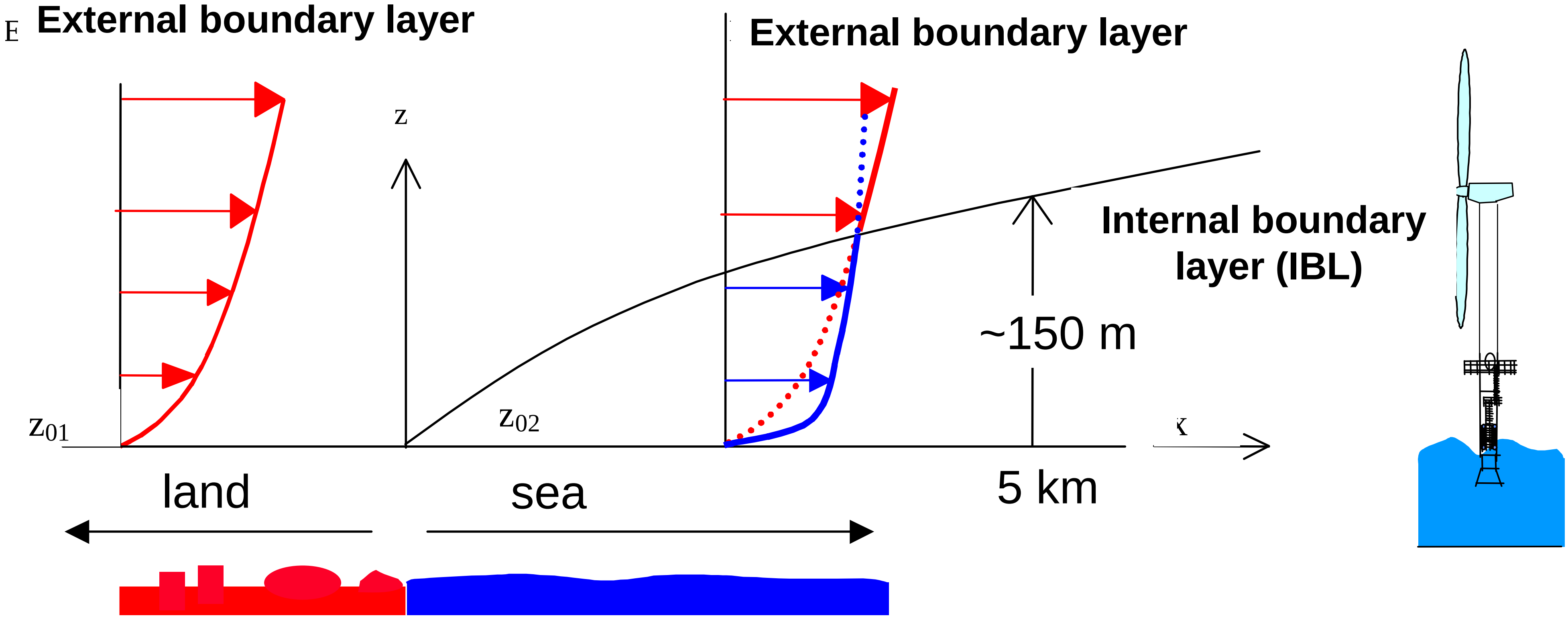
I ⇨ "windatlas" methods (z_o depends on waves fetch age)

II ⇨ coastal discontinuity zone:

- strong variations in air/sea temperature gradient (winter ~ summer   onshore ~ offshore wind)
- resulting strong effect upon stability
- further complicated by internal boundary layer effects

➡ model improvement still underway

Coastal effects II
change in surface roughness



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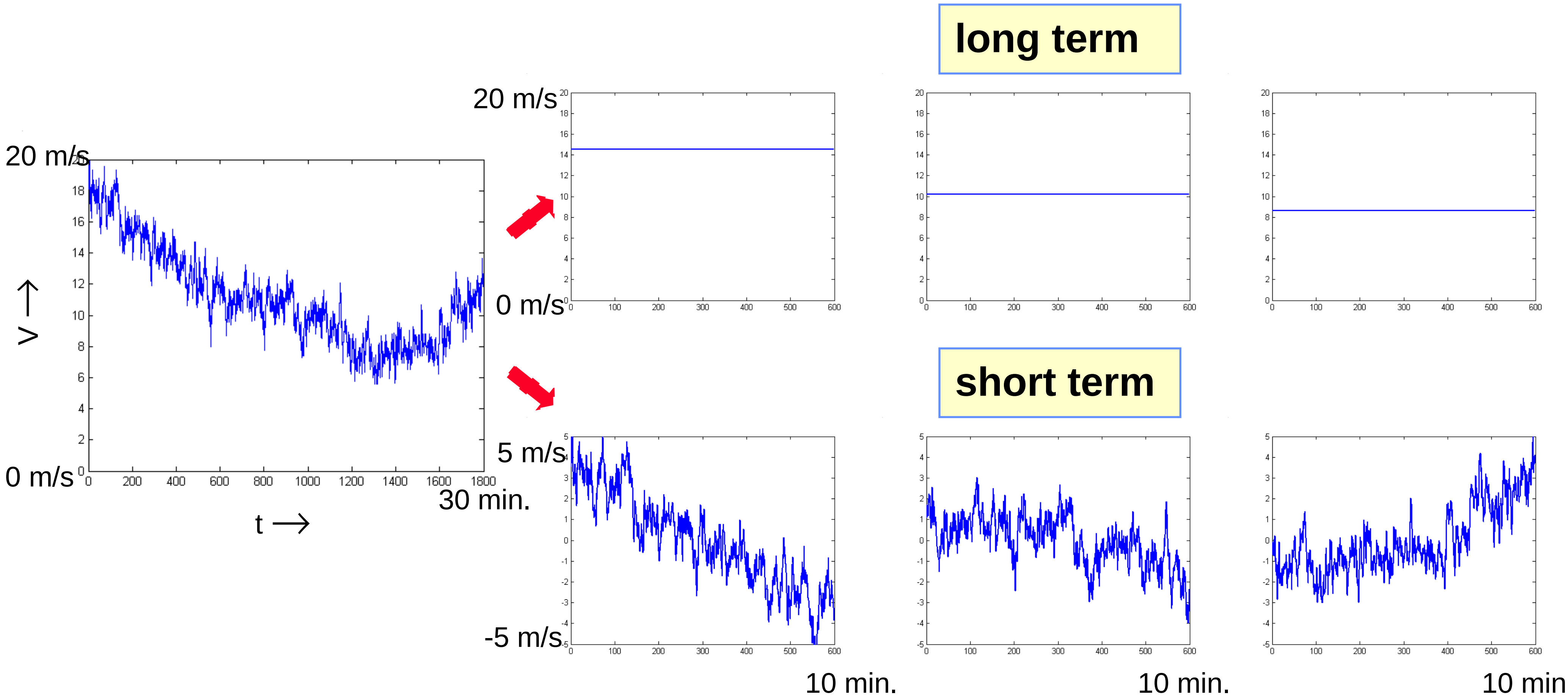
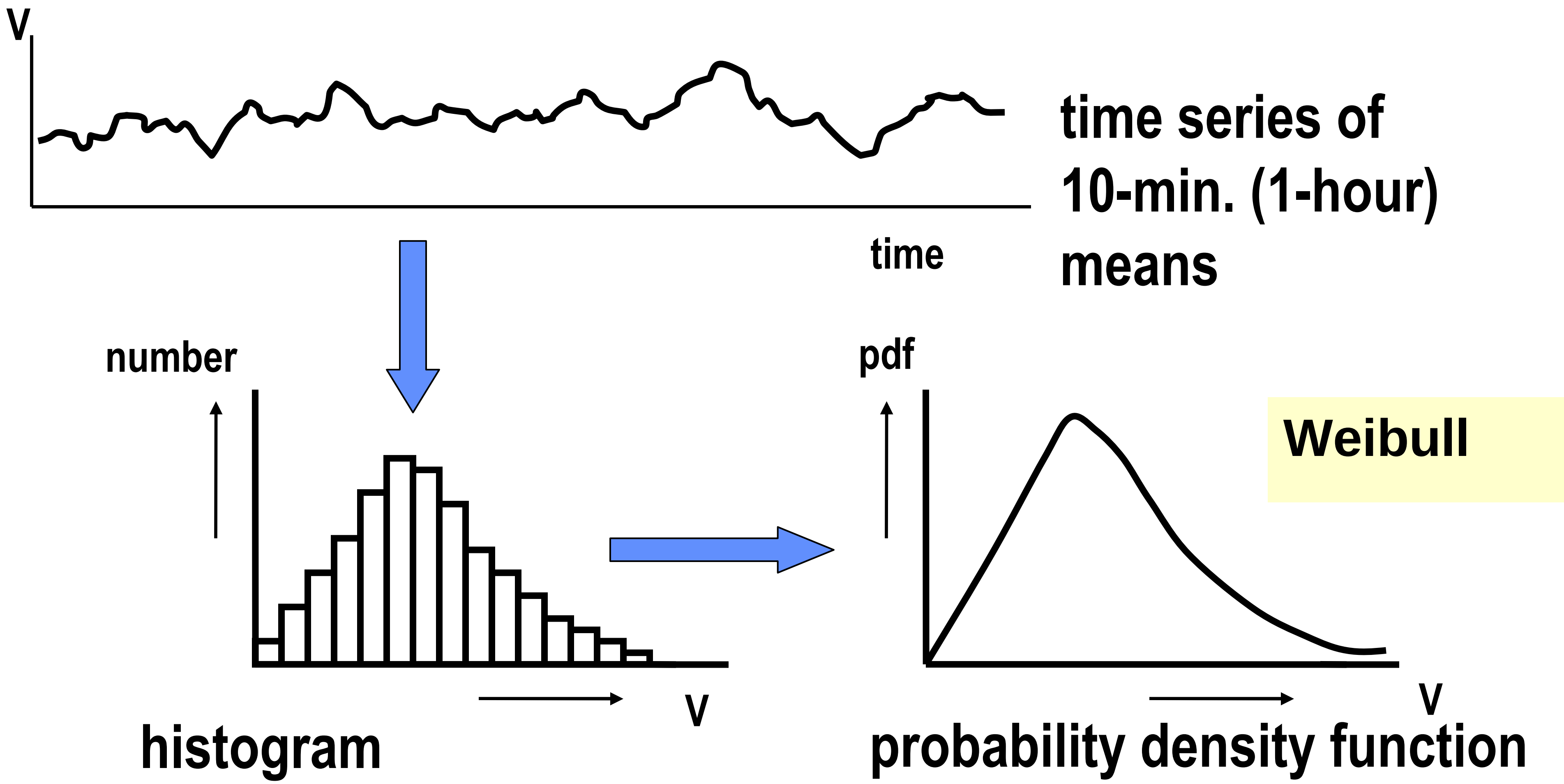
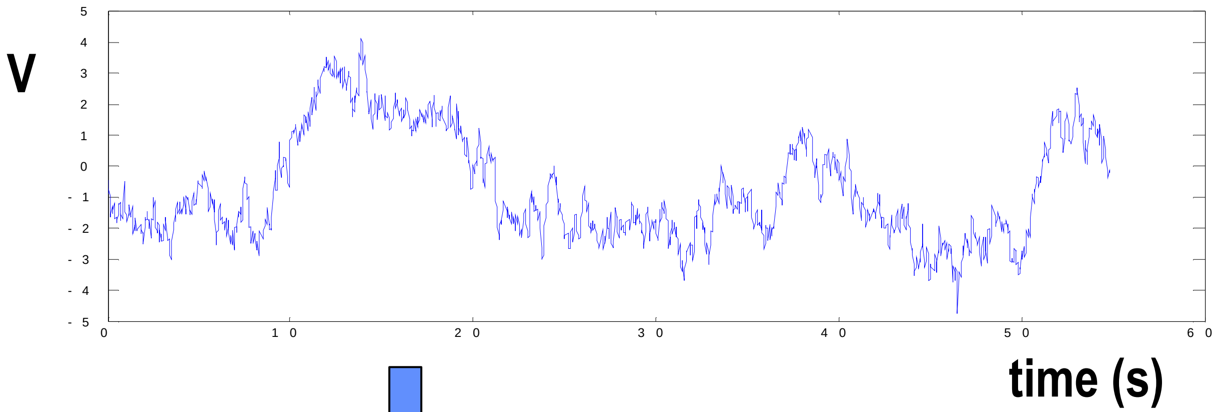
Basic wind statistics
distinction between long and short term



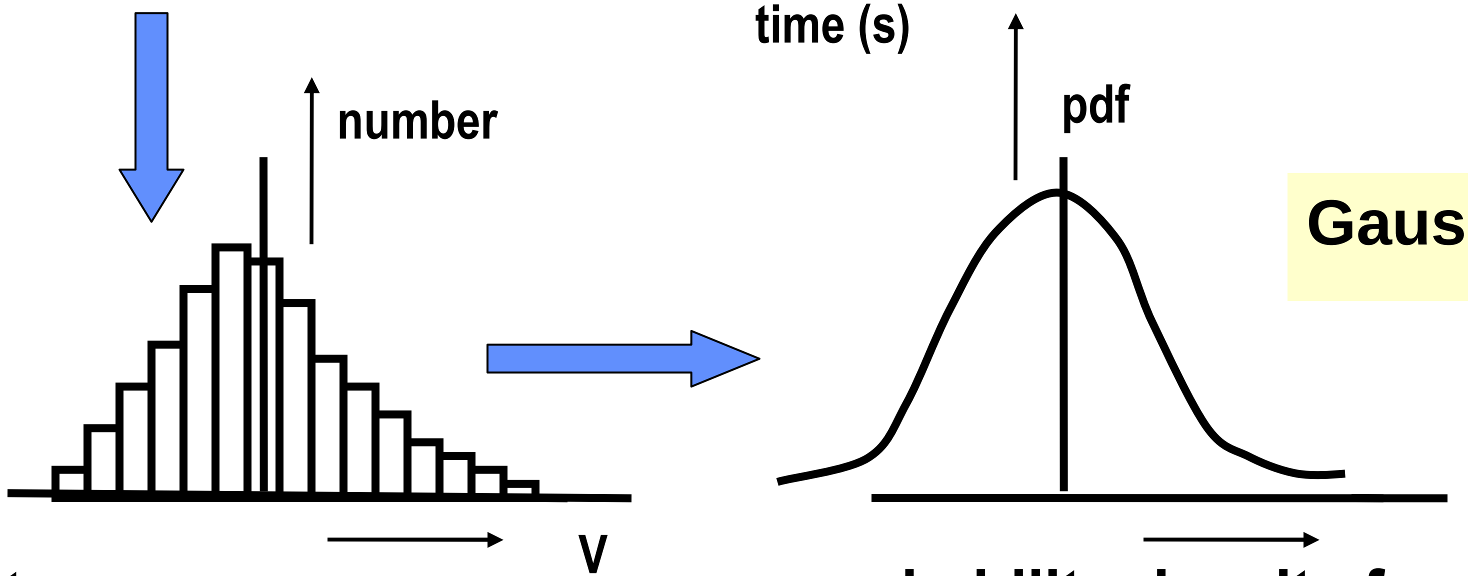
RECAP: Basic wind statistics – long term



Basic wind statistics - short term



time series of wind (turbulence)

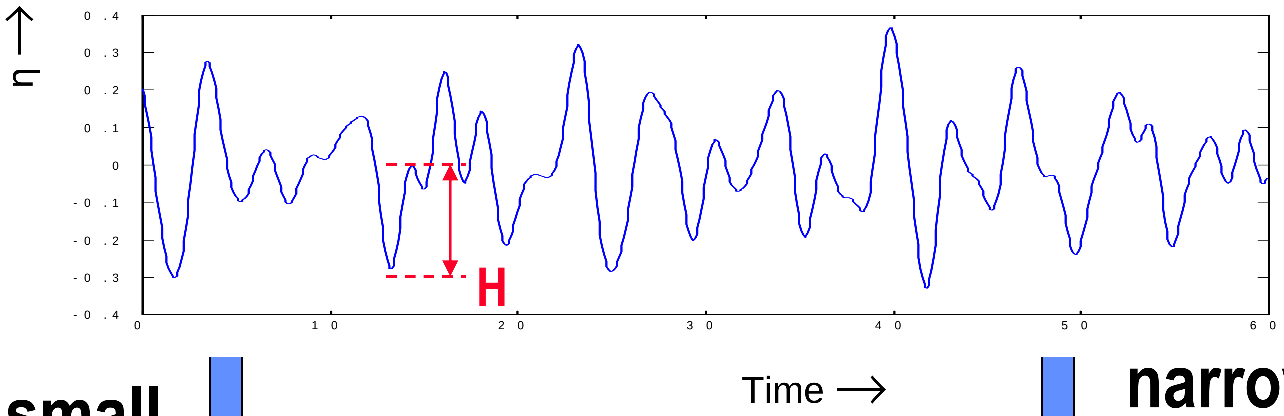


Gauss

histogram

probability density function

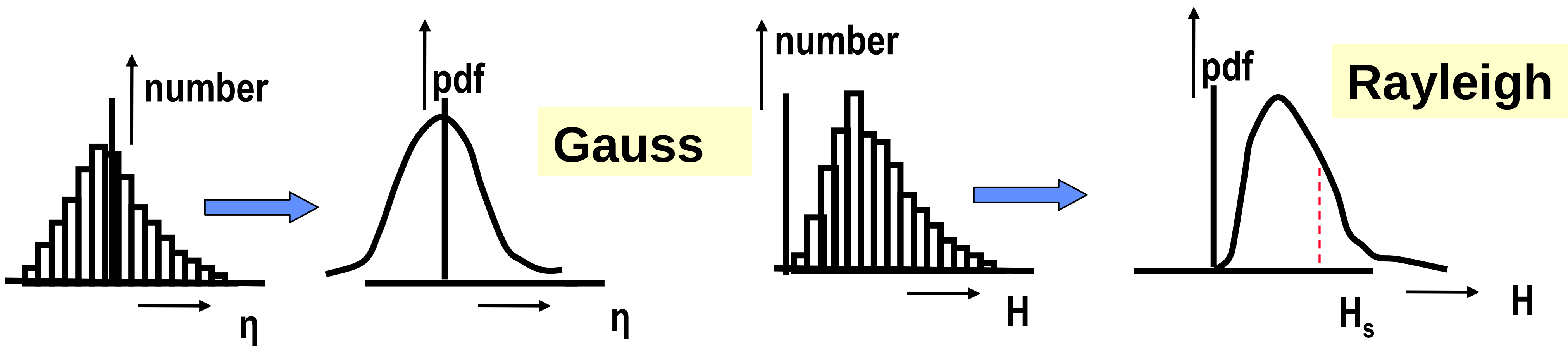
Basic wave statistics - short term



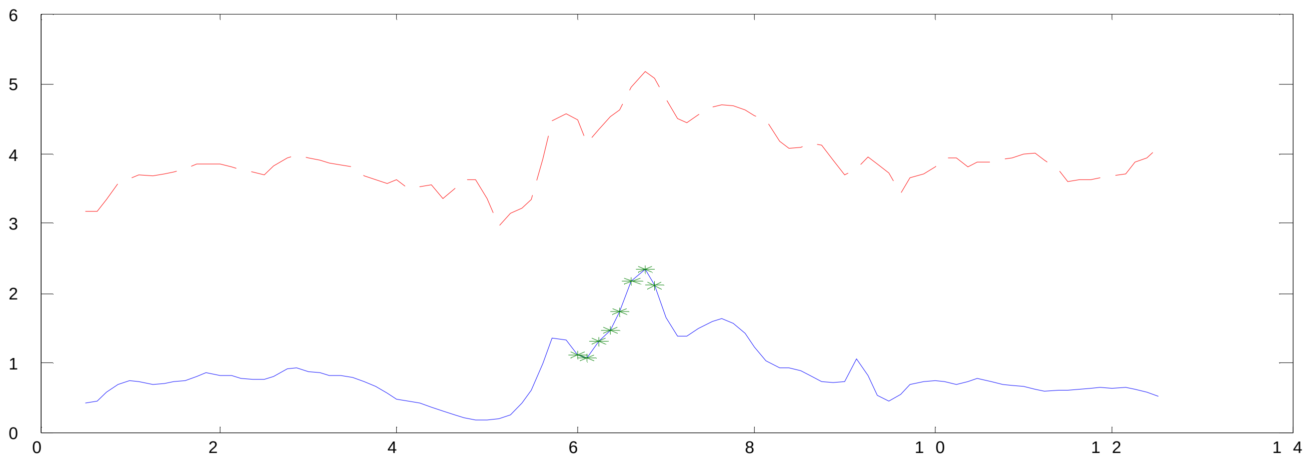
time series of water elevation

small waves

narrow banded



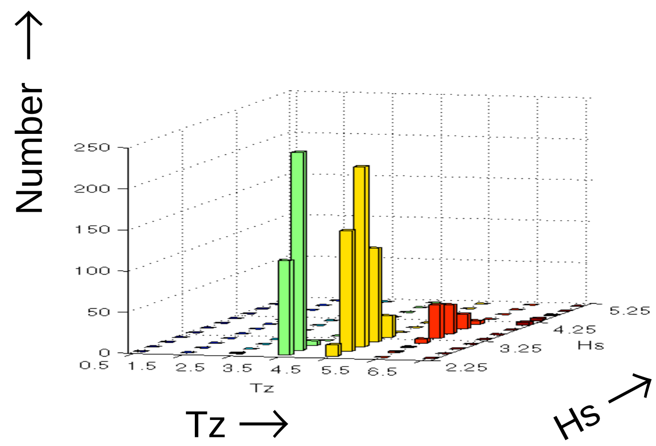
Basic wave statistics - long term



time series of Hs and Tz (each 3-hour)

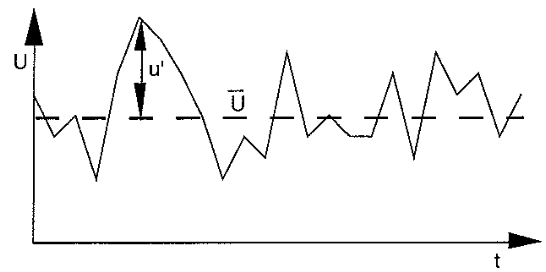
time (days)

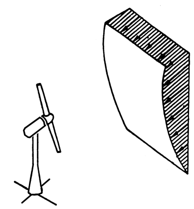
scatter diagram ('2d histogram')

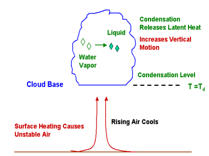


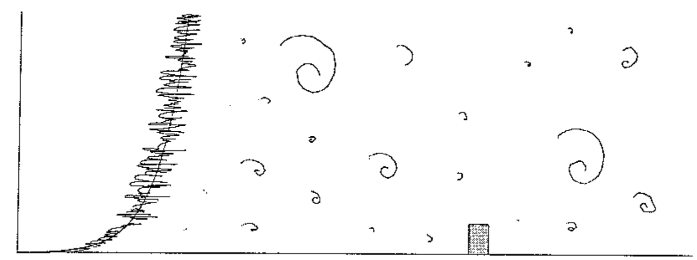
Turbulence - characteristics

- **random variations around mean U**
- **turbulence intensity TI=σ/U**
- **production:**
  - **wind shear (mechanical)**
  - **buoyant (convective / thermal)**
- **loss:**
  - **dissipation (into heat)**
- **superposition of eddies, swirls (size from 2 km to 1 mm)**









Intermezzo: spectrum

Power spectral density function

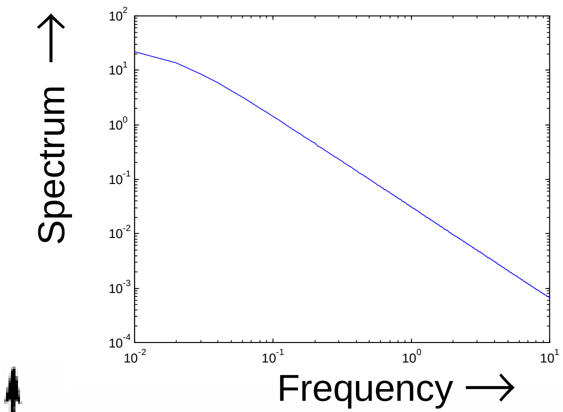
- **'distribution of energy content over frequencies'**
- **area below curve = σ^2 (variance)**
- **largest eddies have most energy**

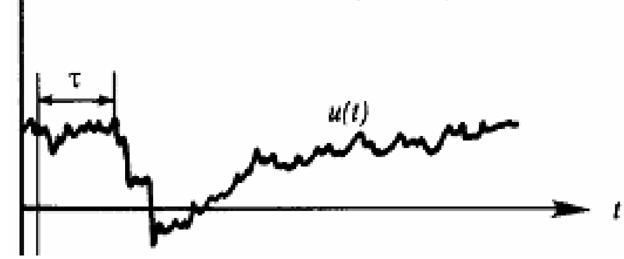
(Integral) time scale

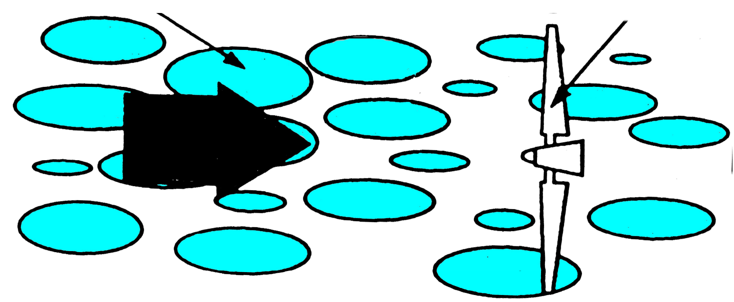
- **measure of time over which wind speed is correlated**

(Integral) length scales

- **characteristic size of eddy**







DUWIND
DELFT UNIVERSITY WIND ENERGY RESEARCH INSTITUTE

Stochastic wind simulation; one-point I

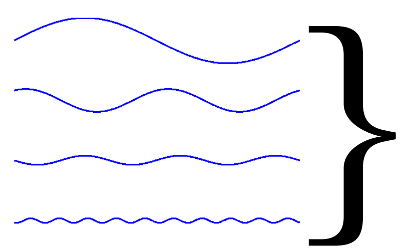
Generation of a 10-min time series

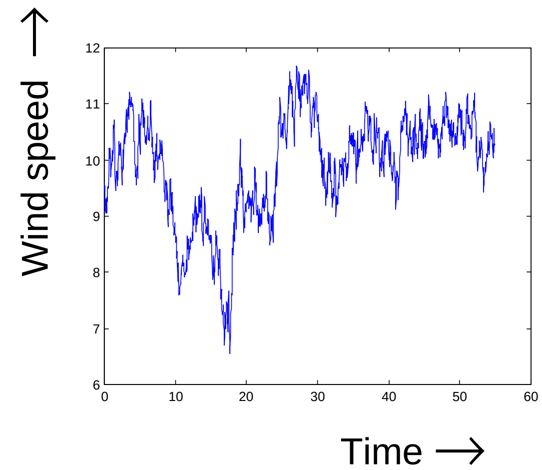
Summation of harmonics:

$$u(t) = \sum_{k=1}^{K} \sqrt{S_k \, \Delta f} \, \cos(\omega_k t + \phi_k)$$

S_k: spectrum value

ϕ_k: random (uniform 0-2π)





Stochastic wind simulation; one-point II

Choice of spectrum:

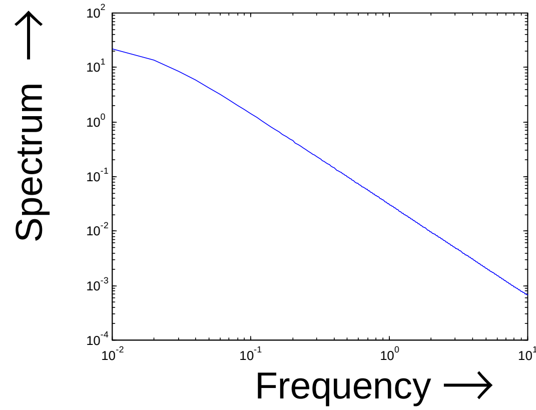
- **von Karman (isotropic)**
- **Kaimal**

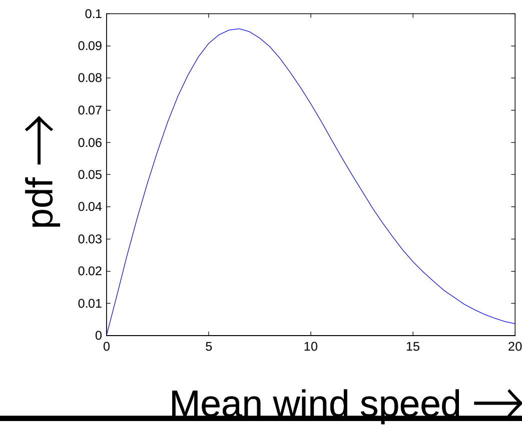
Spectrum depends on:

- **mean wind speed**
- **length scales**
- **turbulence intensity (offshore ~ 8%)**

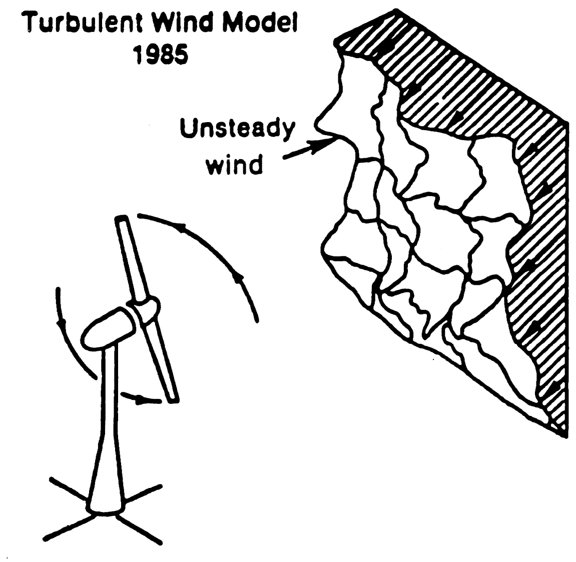
Generate wind field for several mean wind speeds

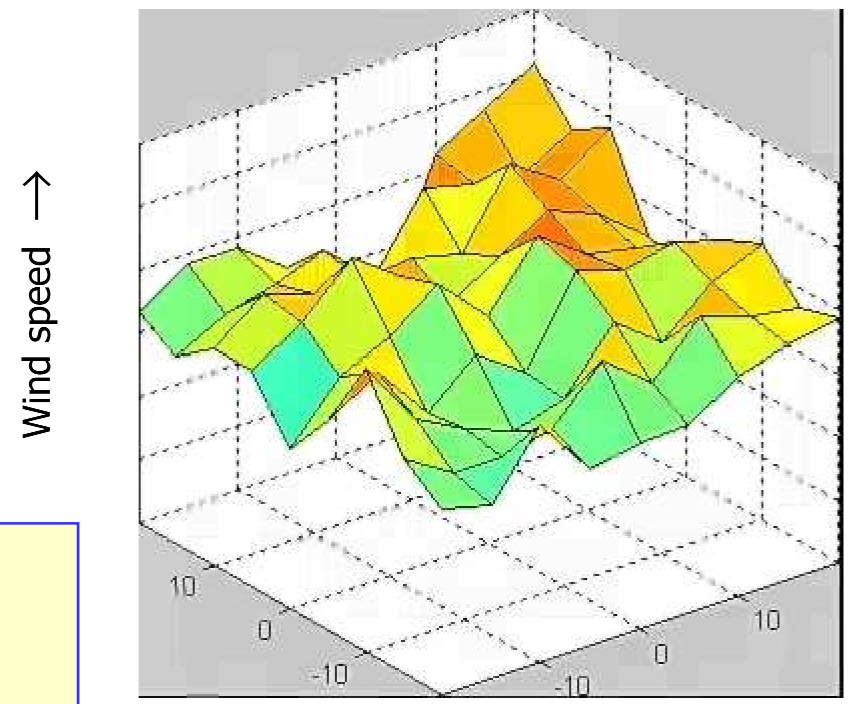
- **distribution: Weibull**





Stochastic wind field simulation - example

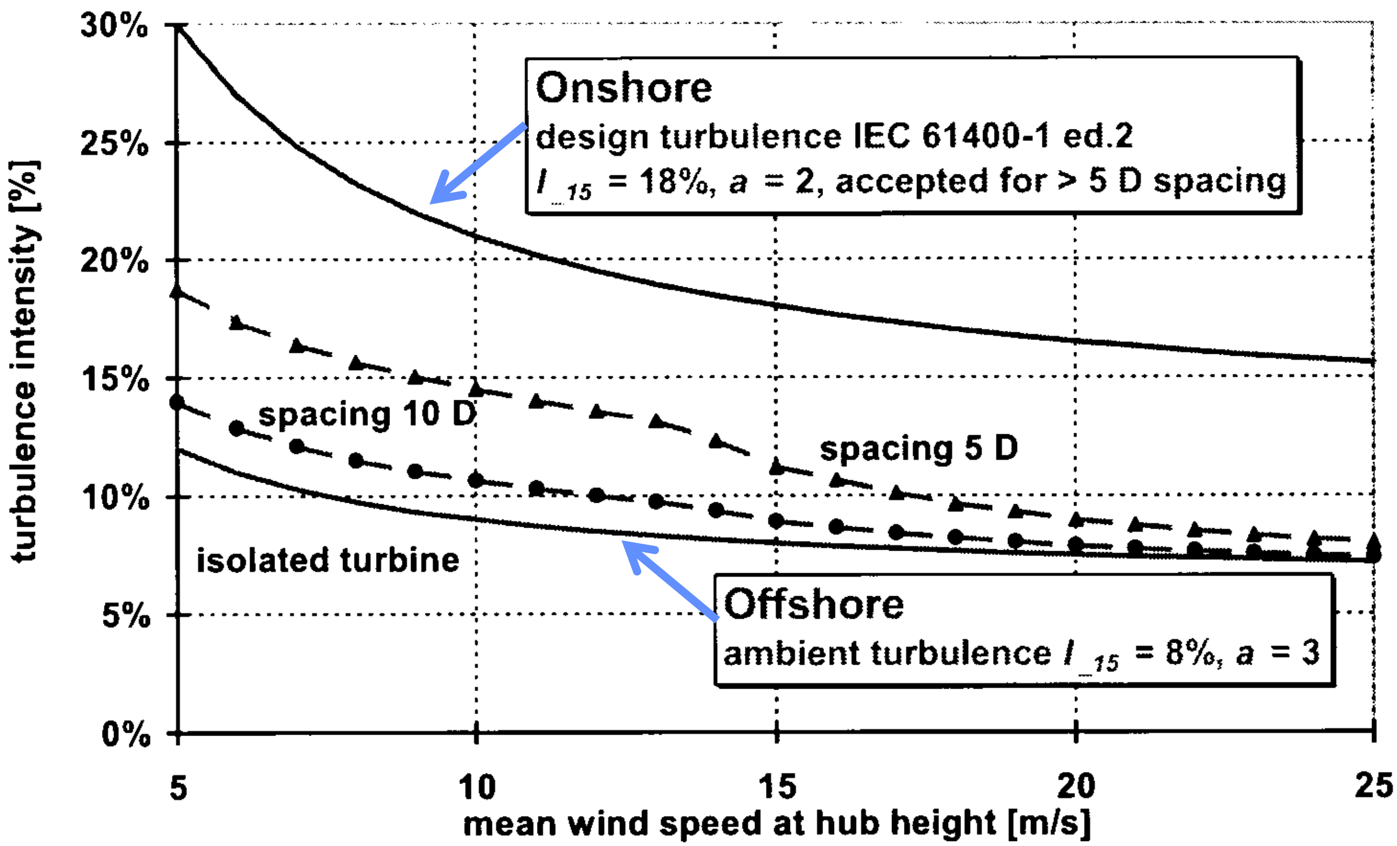




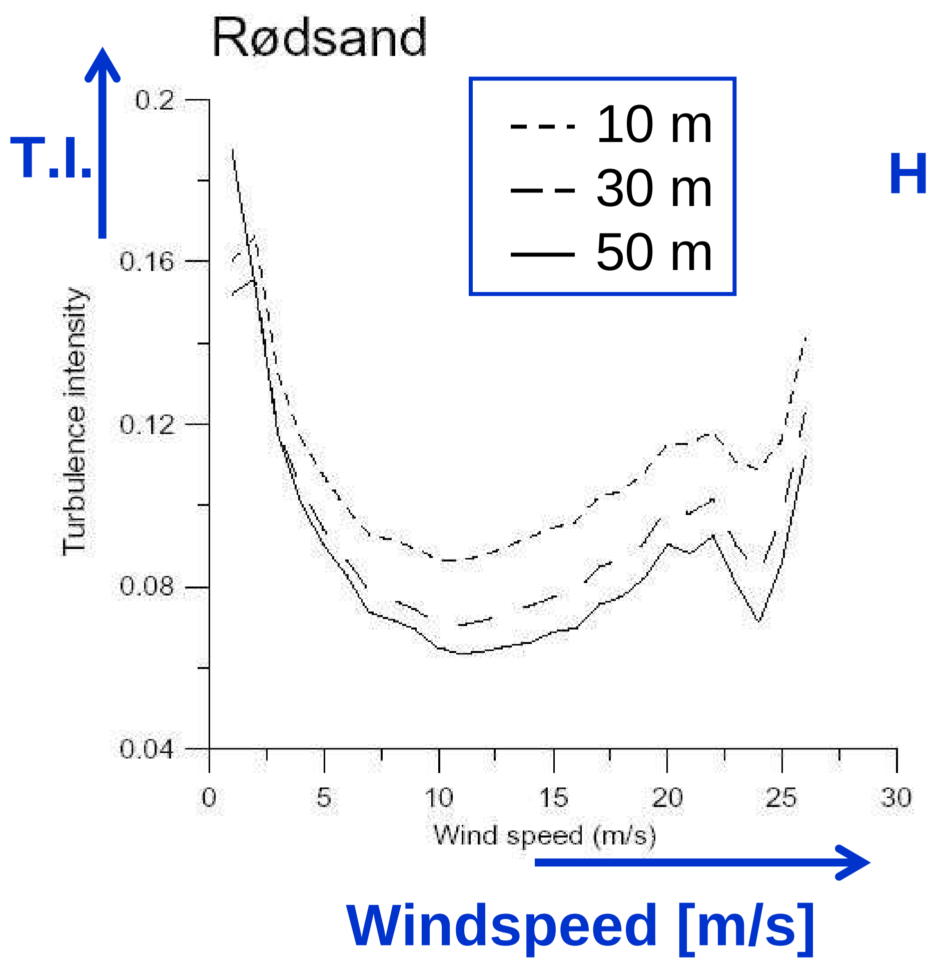
Bladed; 3 velocity components:

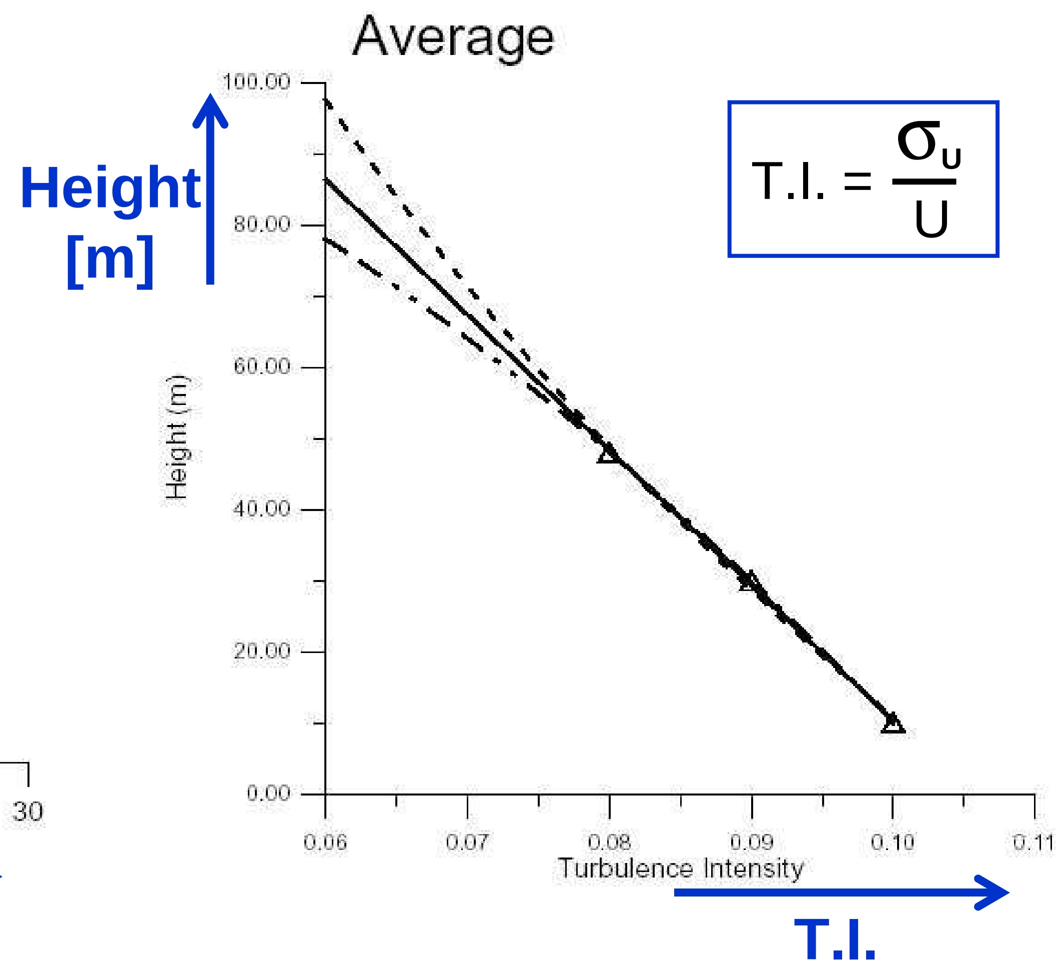
- **u; longitudinal**
- **v; lateral**
- **w; vertical**

Onshore vs. offshore turbulence



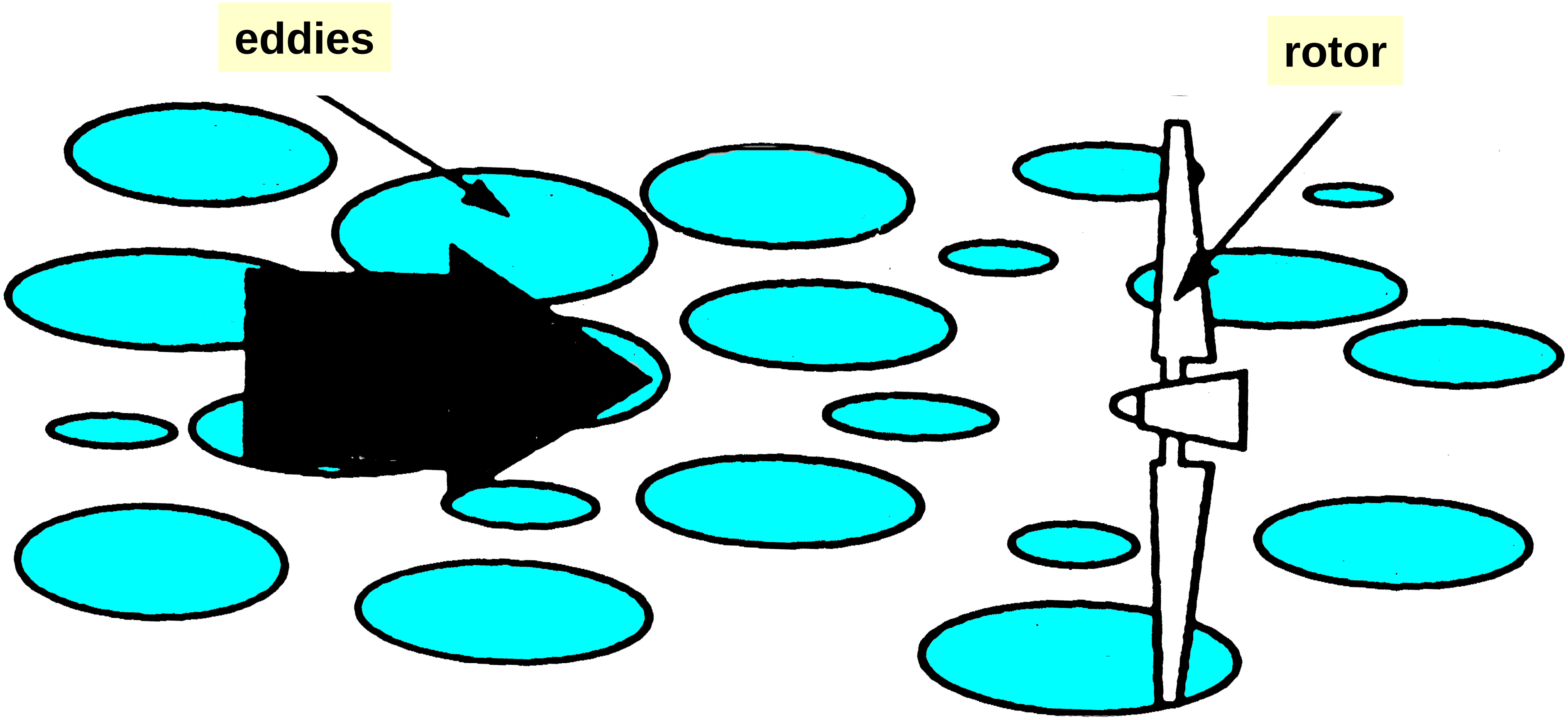
Measured offshore turbulence intensity T.I.





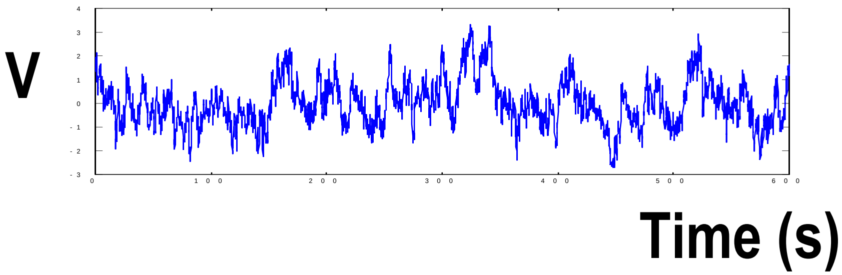
$$T.I. = \frac{\sigma_u}{U}$$

Rotational sampling of turbulence

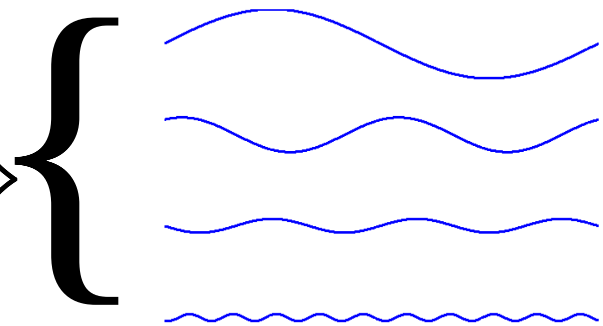


Rotational turbulence spectrum

turbulence



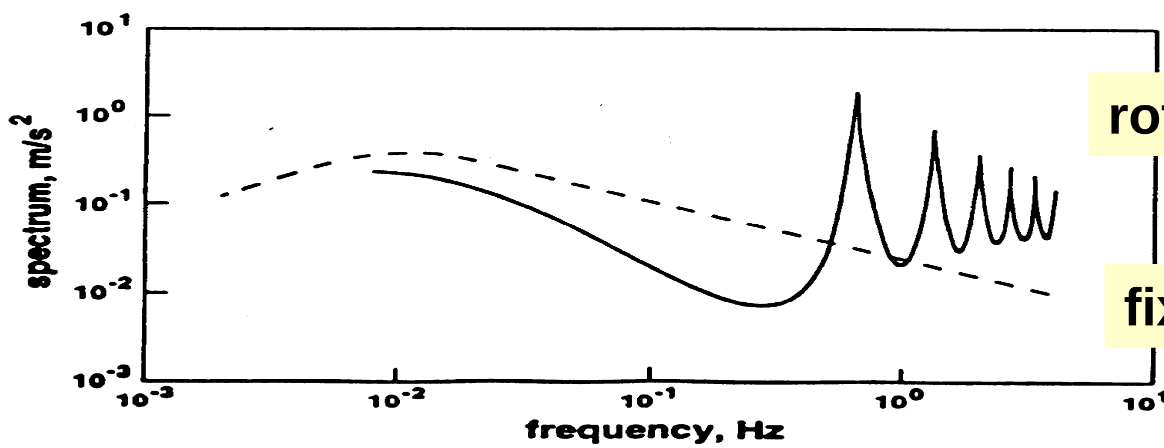
⇒



summation of harmonics (random phases)

⇓

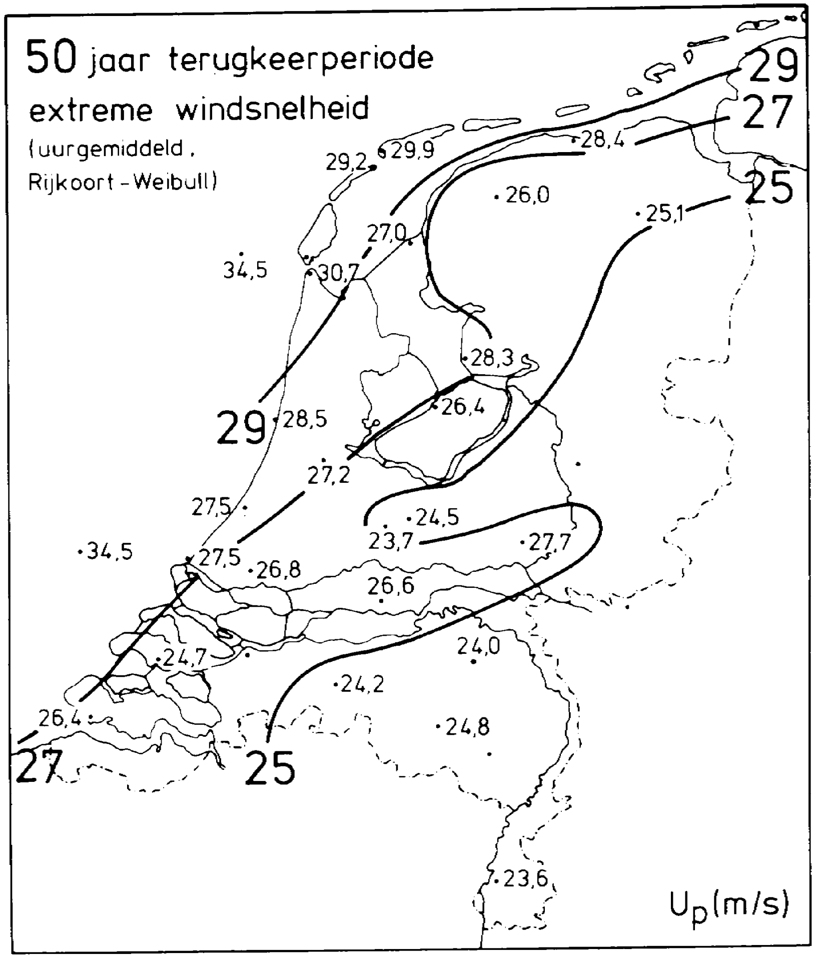
spectrum



rotating observer

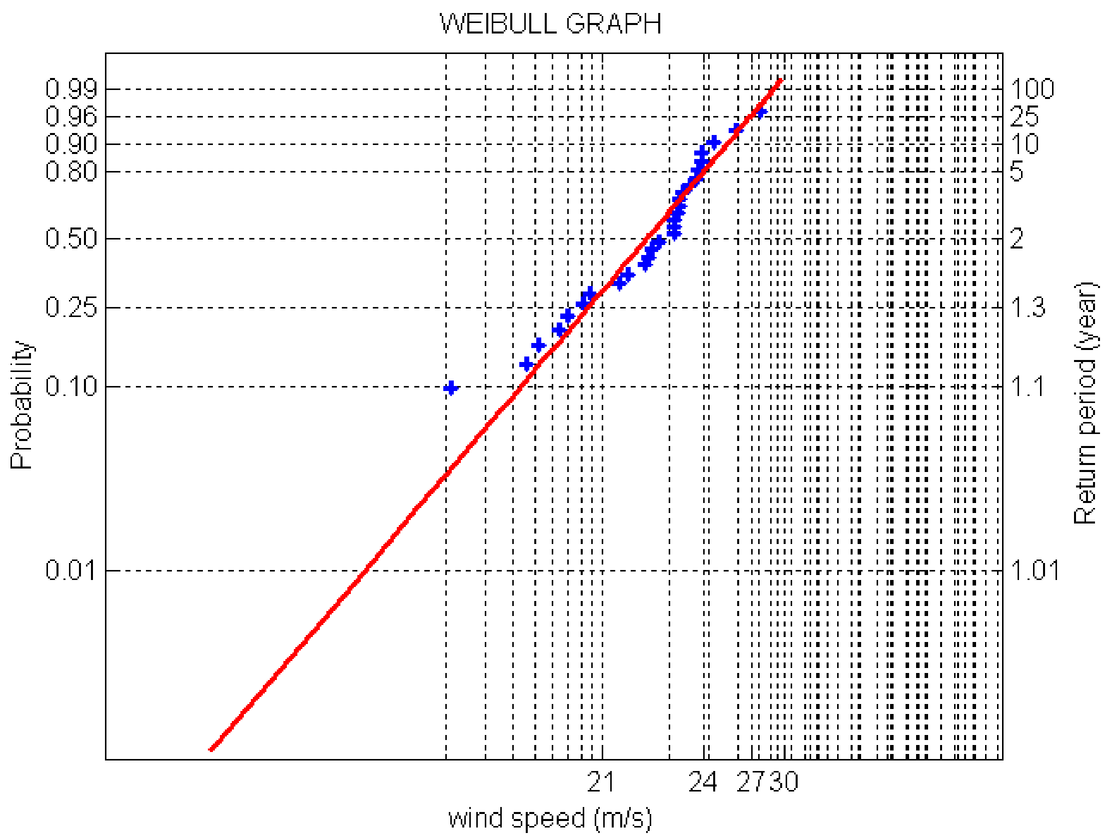
fixed observer

Extreme winds



- **No offshore map (yet)**
- **Extrapolation of data covering several years (extreme value theory)**

Extreme value analysis - example

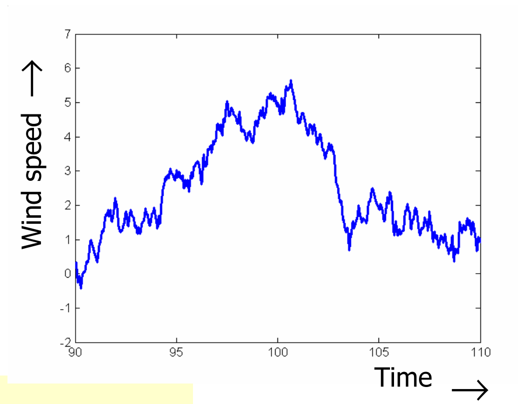


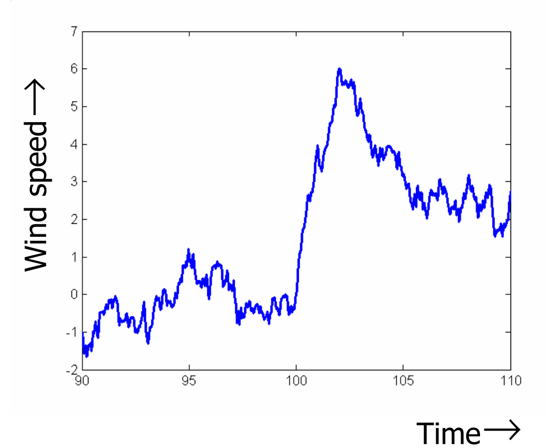
- **determine yearly maxima U_i**
- **order them to magnitude:**
  19.8, 20.7, …. 27.2, 27.5 m/s
- **fit to extreme value distribution (different functions / methods available)**
- **read from graph: 50-years value**

Extreme gusts

'Real'

- **maximum amplitude**
- **maximum rise time**





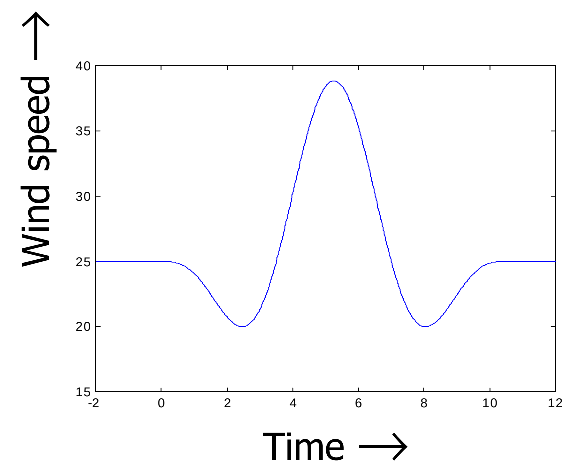
IEC (included in Bladed):

deterministic gust

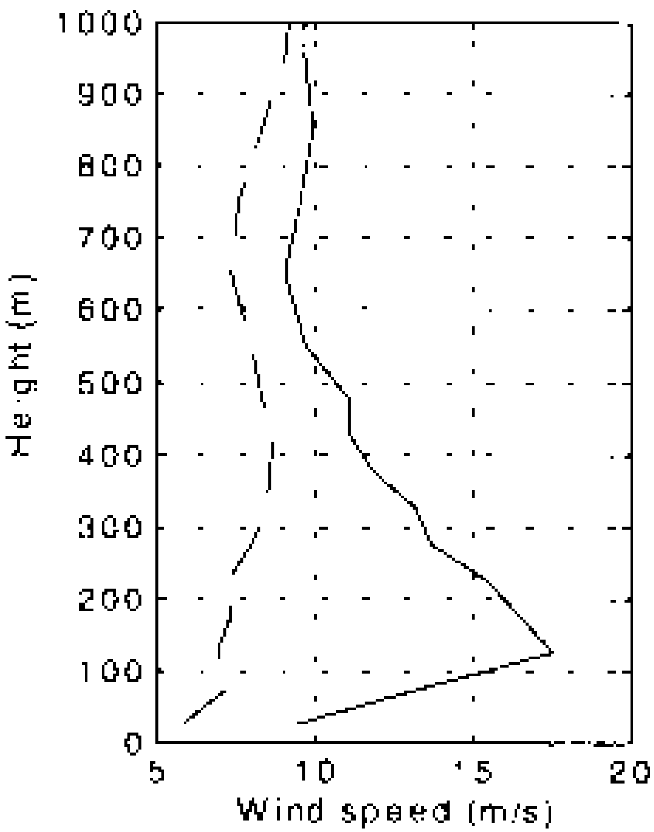
uniform over rotor plane

also:

- **extreme direction change**
- **combination**
- **extreme wind shear (vertical and horizontal)**



Low Level Jet



Wind maximum at relative low levels (~150 m); larger then geostrophic wind

Stable night time conditions

Common in Baltic Sea;
Also in North Sea?

➡ **Sodar measurements**