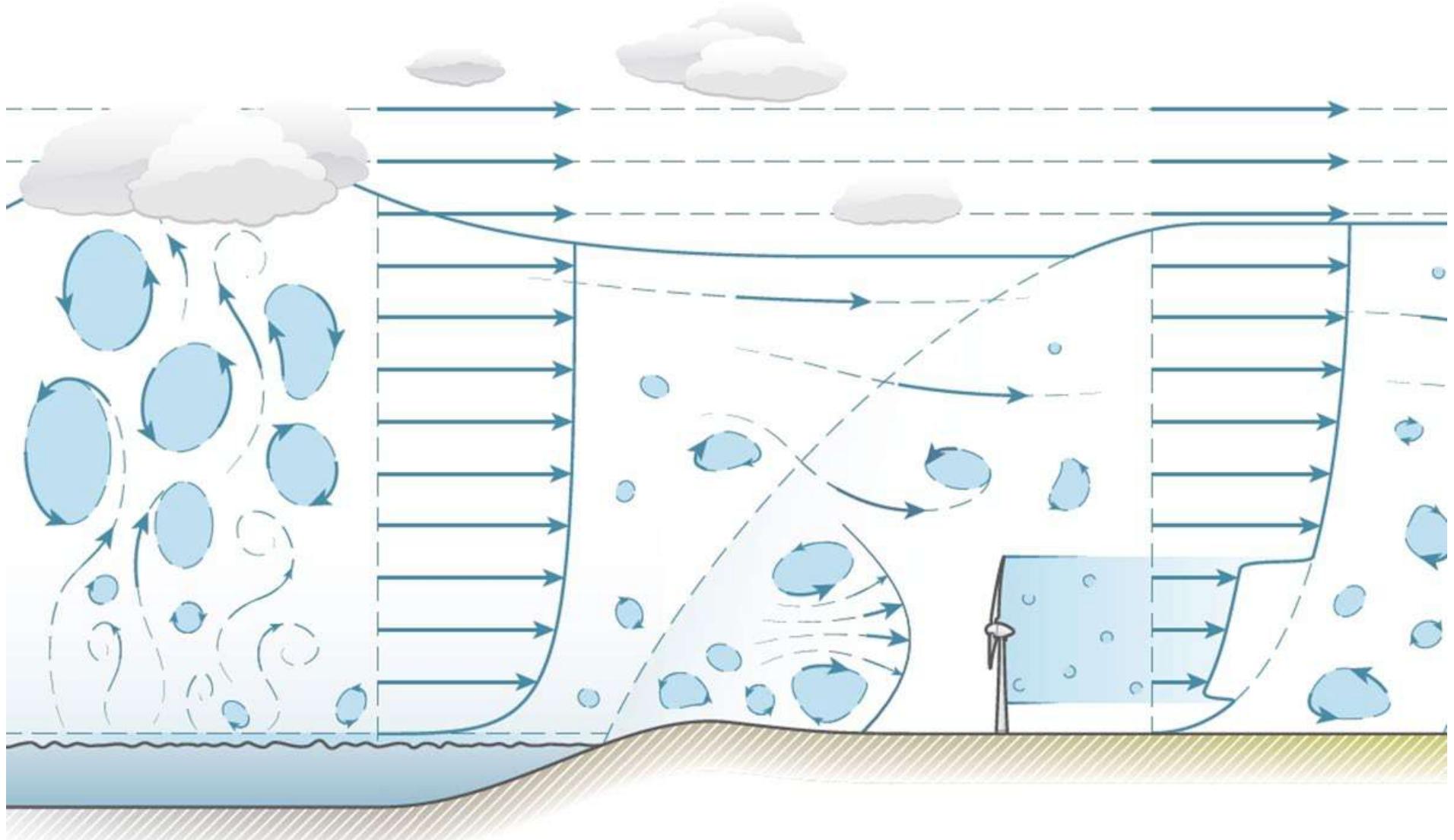


Wind loads



Wim Bierbooms

Wind loads

- Wind modelling
- Wind turbine simulation tools
- Offshore wind climate

Wind modelling

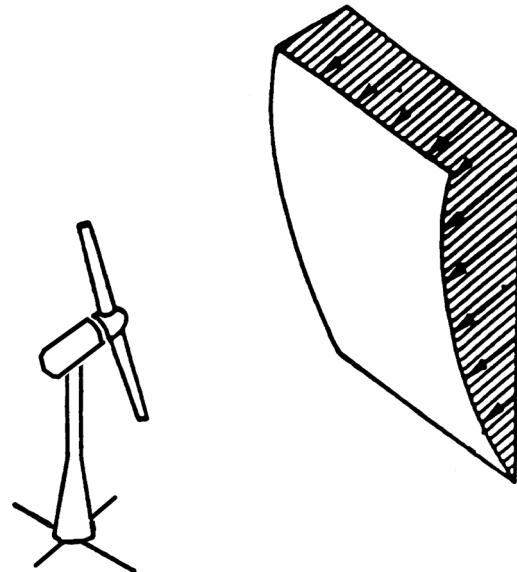
1. Deterministic wind field
2. Stochastic wind simulation
3. Extreme gusts

1) Deterministic wind field for load calculations I

Wind shear

- theory
$$U(h_2) = U(h_1) \frac{\log(h_2 / z_0)}{\log(h_1 / z_0)}$$
 - log law (neutral)
 - z_0 : surface roughness
 - corrections for stability:
unstable (warm surface)
stable (cold)
- practice
 - power 'law' (fit)

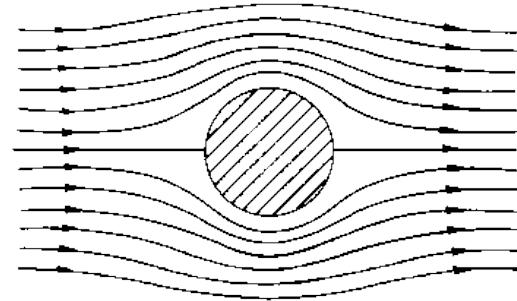
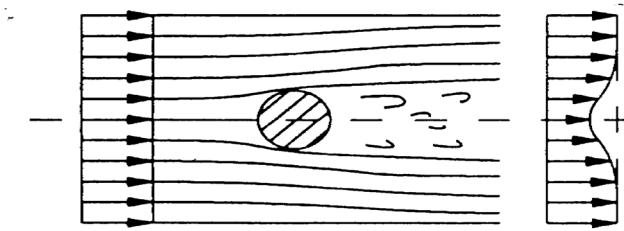
$$U(h_2) = U(h_1) \left(\frac{h_2}{h_1} \right)^\alpha$$



Deterministic wind field for load calculations II

Tower shadow

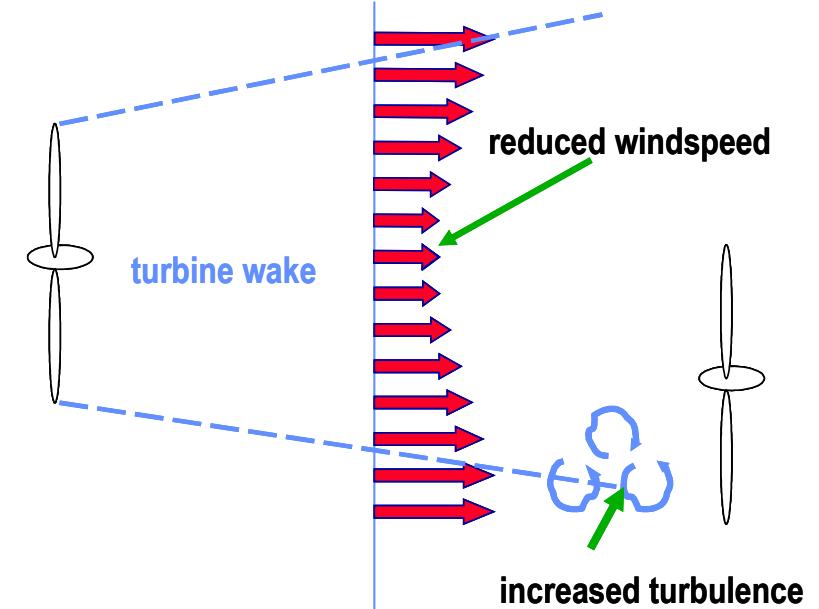
- potential flow



Deterministic wind field for load calculations III

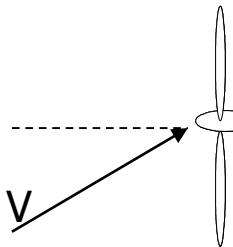
Wake

- reduced wind; increased turbulence

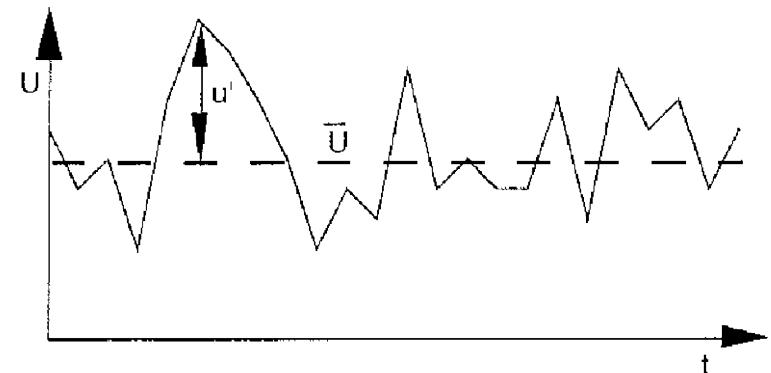


Yawed flow

- constant or harmonic

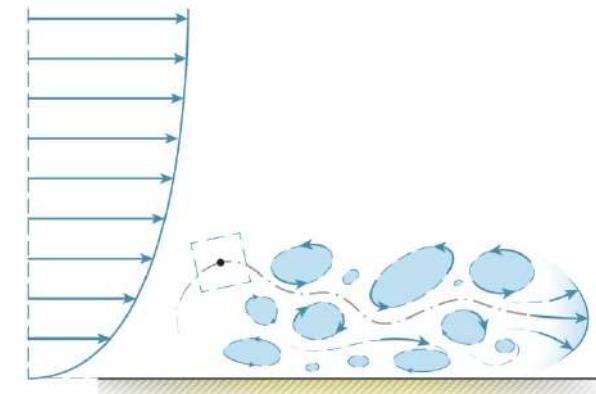
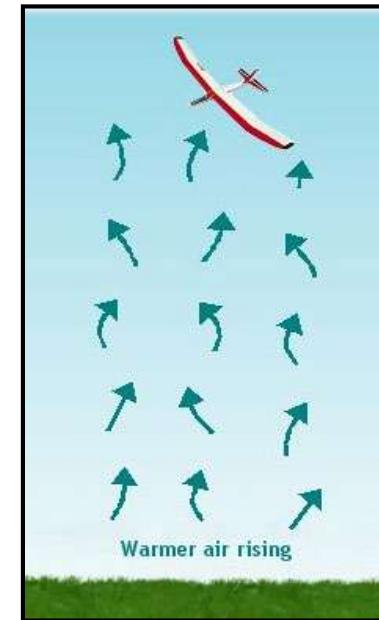


Turbulence



Turbulence

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



Intermezzo I: spectrum

Power spectral density function

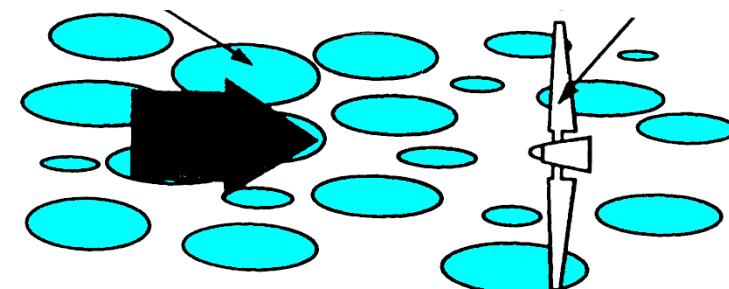
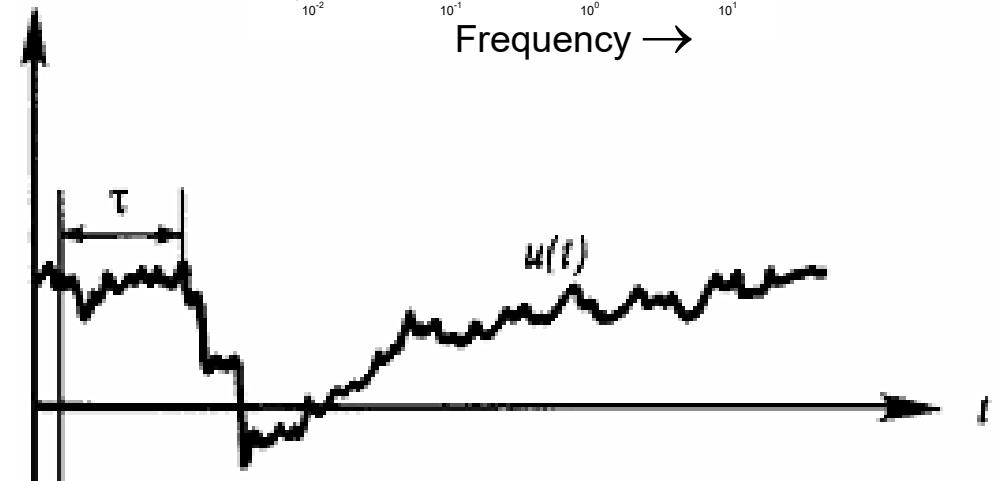
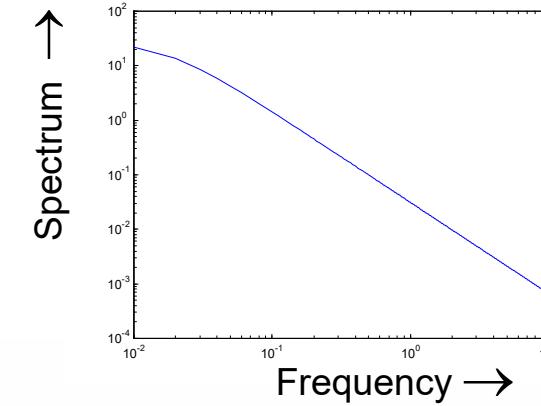
- 'distribution of energy content over frequencies'
- area below curve = σ^2 (variance)
- largest eddies have most energy

(Integral) time scale

- measure of time over which wind speed is correlated

(Integral) length scales

- characteristic size of eddy



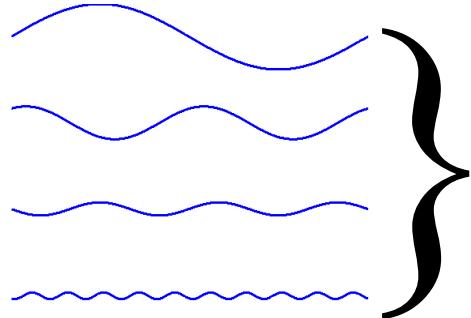
2) Stochastic wind simulation; one-point I

Generation of a 10-min time series:
summation of harmonics:

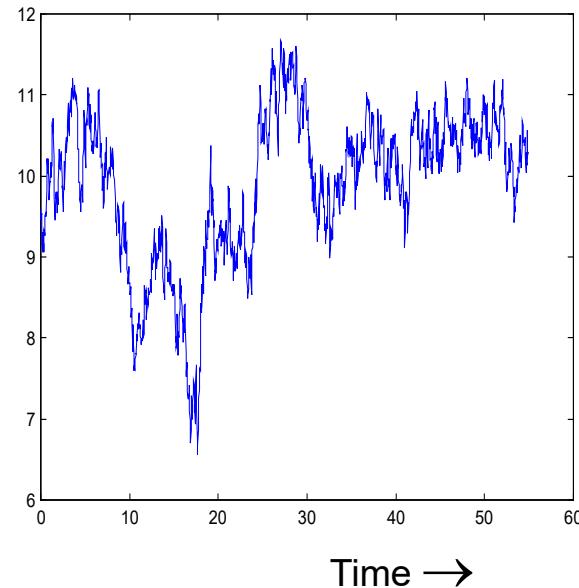
S_k : spectrum value

ϕ_k : random (uniform 0- 2π)

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



Wind speed →



Stochastic wind simulation; one-point II

Choice of spectrum:

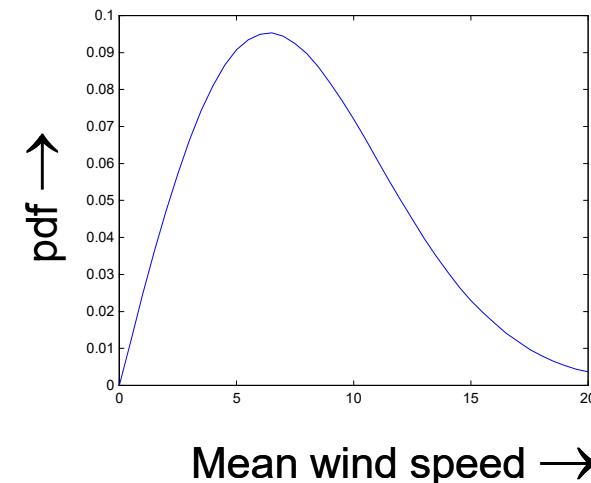
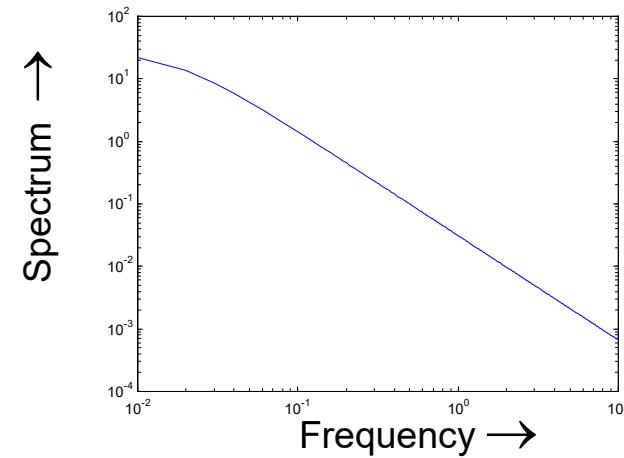
- von Karman (isotropic)
- Kaimal

Spectrum depends on:

- mean wind speed
- length scales
- turbulence intensity

Generate wind field for several mean wind speeds

- distribution: Weibull

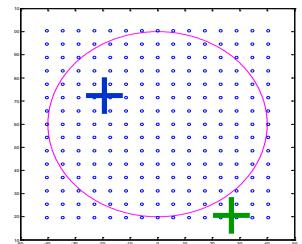
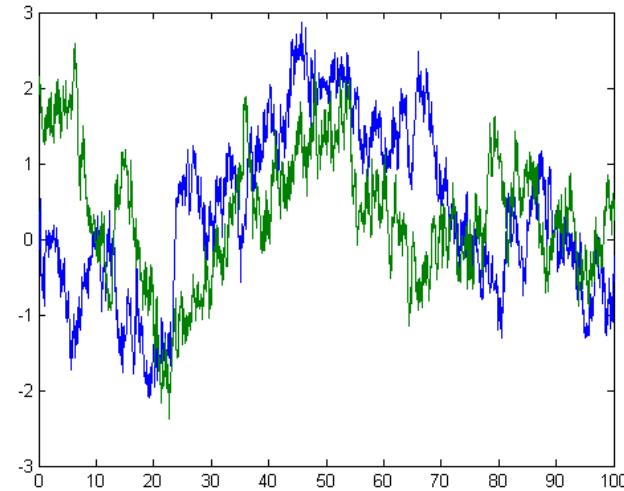
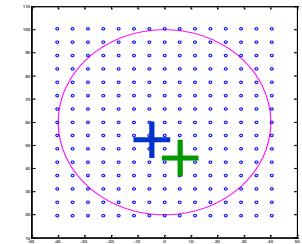
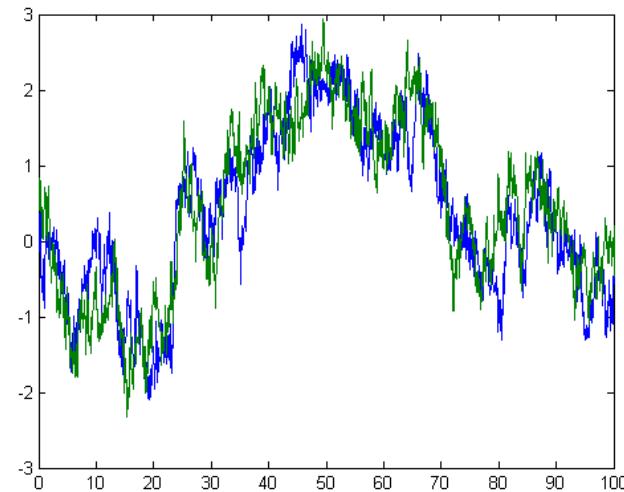


Stochastic wind simulation; field I

Generalisation of:

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

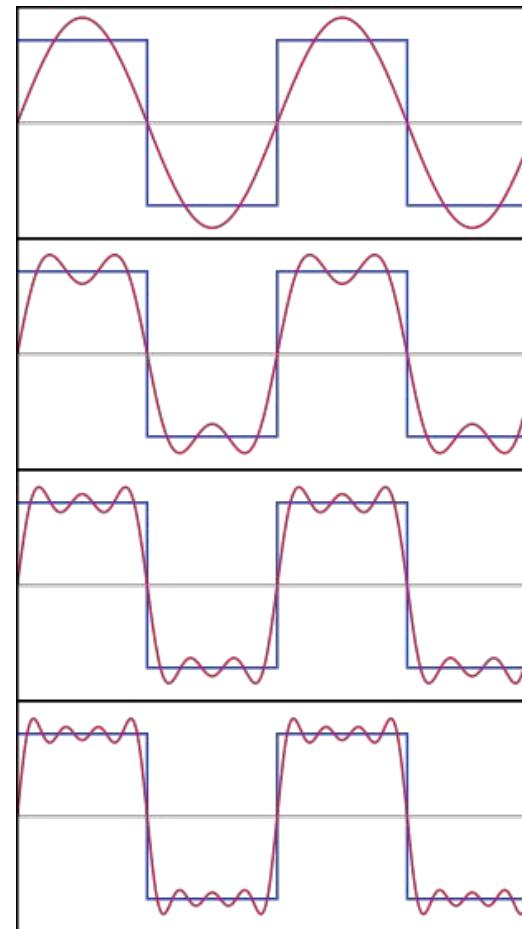
Example: consider 2 points in rotor plane



Intermezzo II: Fourier series

a Fourier series decomposes periodic signals into the sum of sines and cosines functions

Example:
square wave



1st harmonic

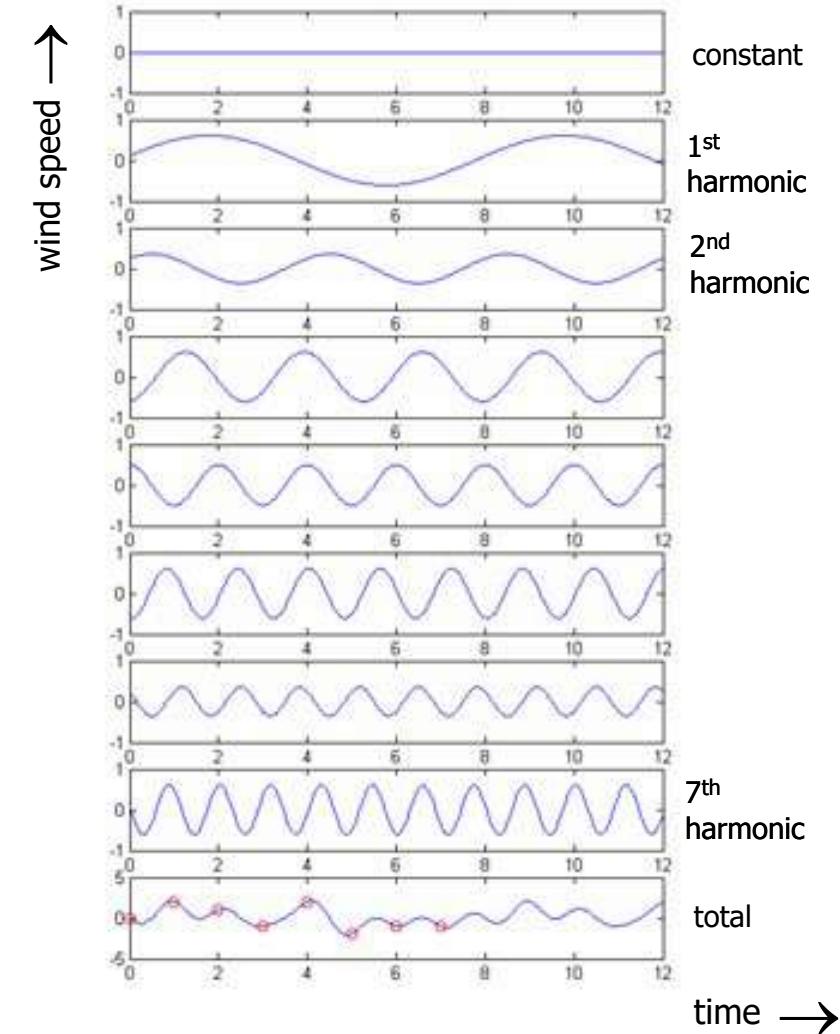
1st plus 2nd harmonic

Sum of 1st, 2nd and 3rd harmonic

Sum of 1st, 2nd, 3rd and 4th harmonic

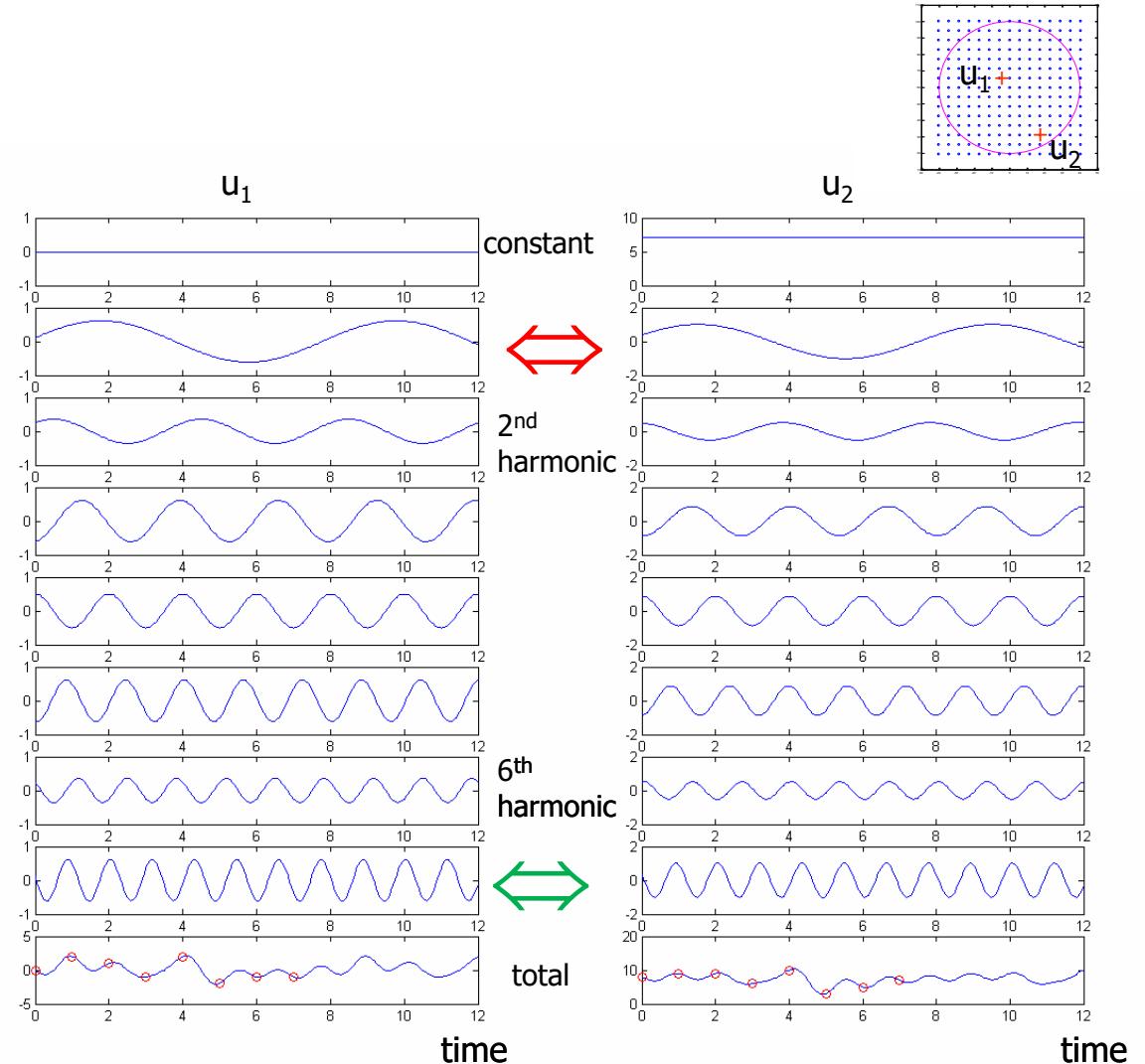
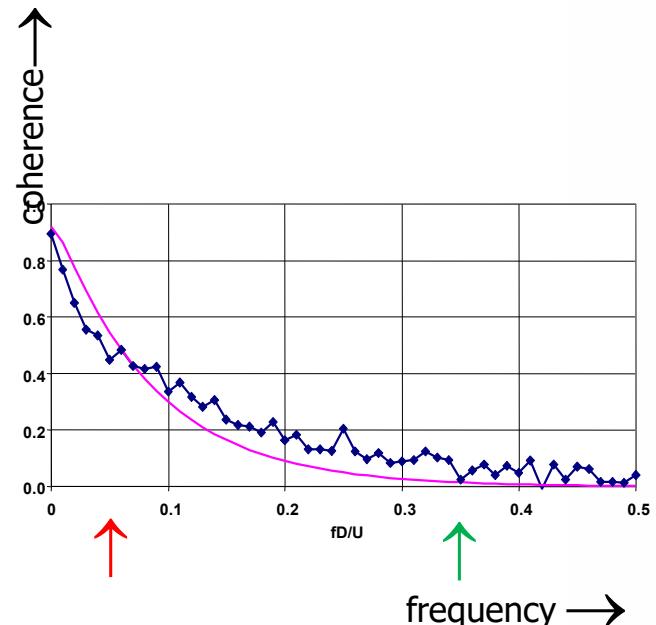
Intermezzo III: Fourier series turbulence

- take 10 min. series;
- assume it to be periodic
- decompose wind speeds into harmonics
- amplitude \sim square root spectrum

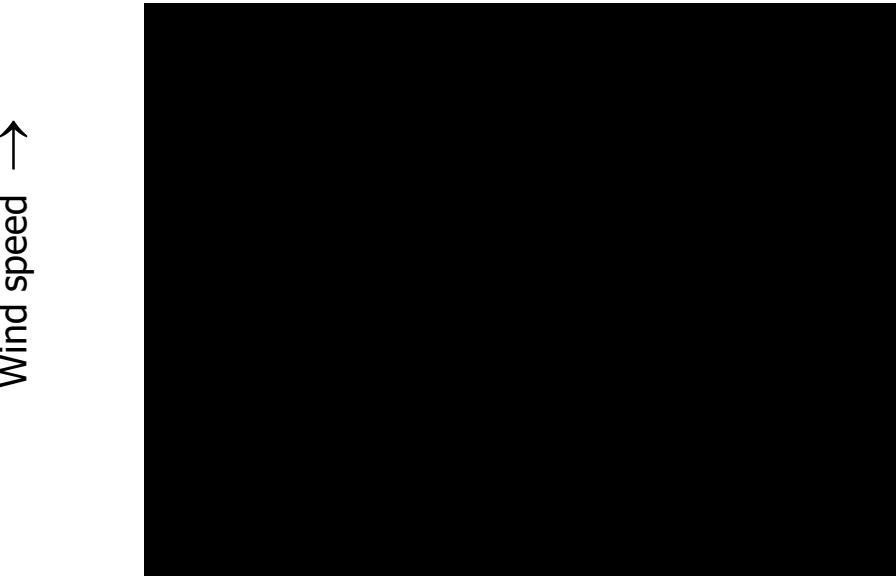


Intermezzo IV: coherence

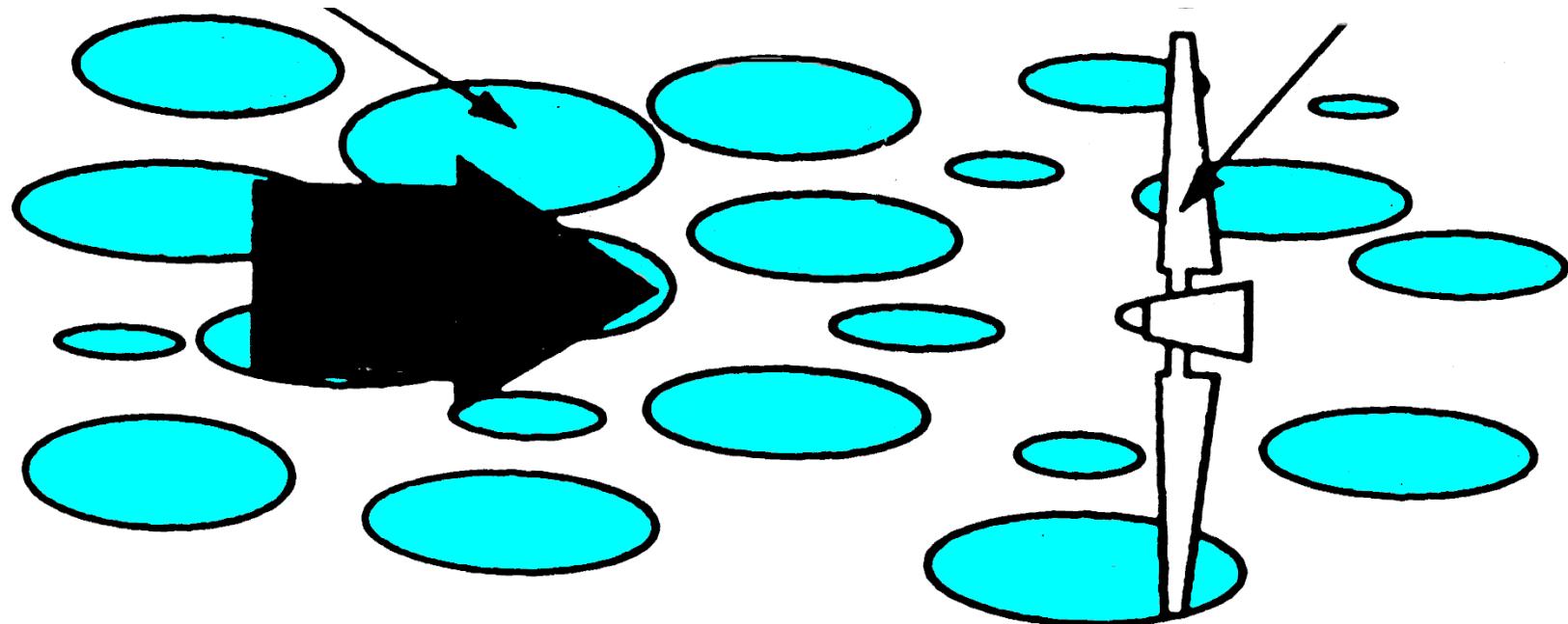
- coherence $\sim \cos \varphi$
with φ : phase difference
- function of frequency f and
distance D



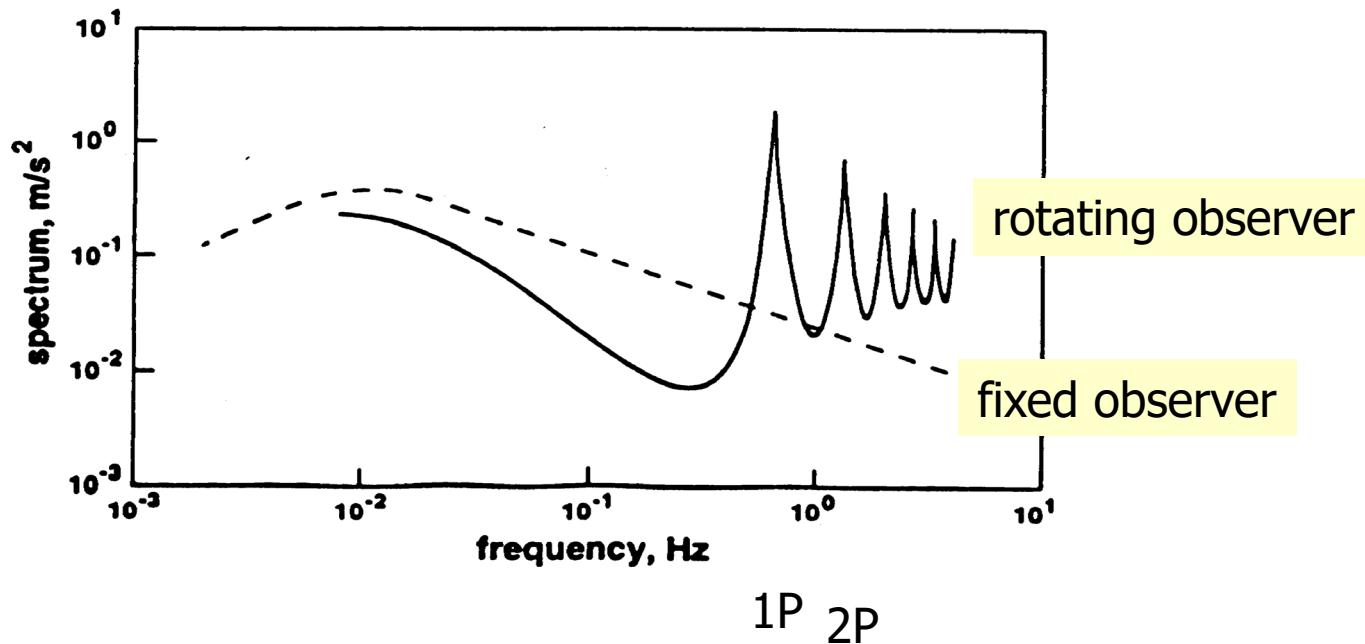
Stochastic wind simulation; field II



Rotational sampling I eddy slicing



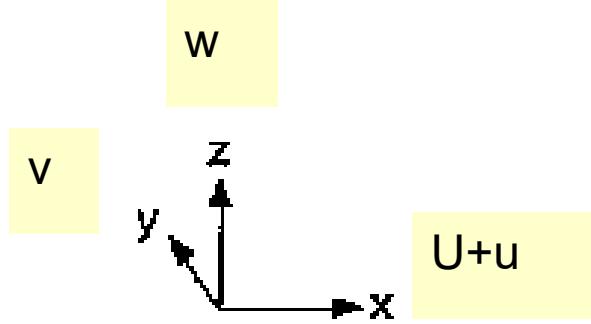
Rotational sampling II



3D Stochastic wind simulation

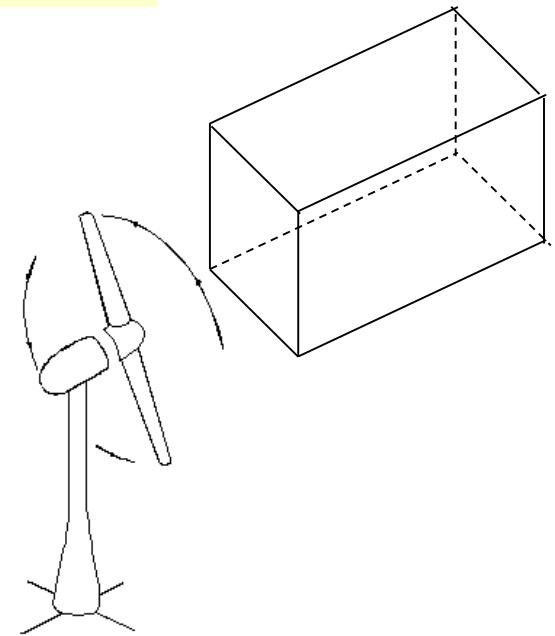
3 components:

- Longitudinal u
- Lateral v
- Vertical w



Methods:

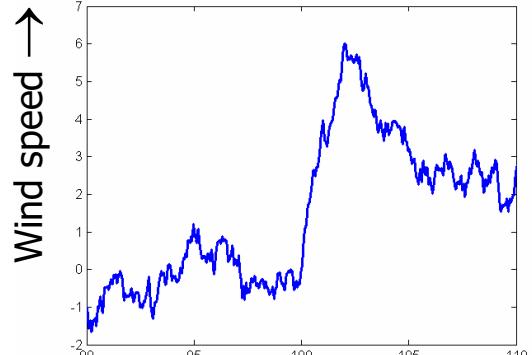
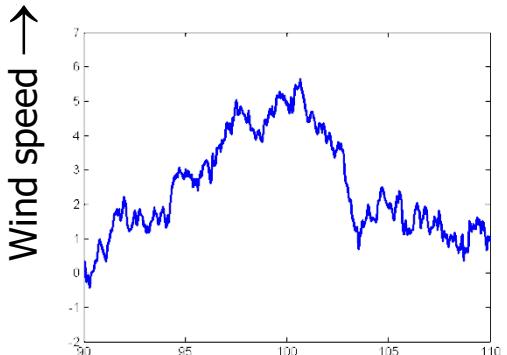
- simple: assume 3 comp. to be uncorrelated:
Sandia (Veers) model
not correct: esp. u and w correlated (wind shear)
↓
- simulate first wind inside a box (space domain); push box through rotor plane (with mean wind speed U ; Taylor's frozen turbulence hypothesis)
Mann model



3) Extreme gusts

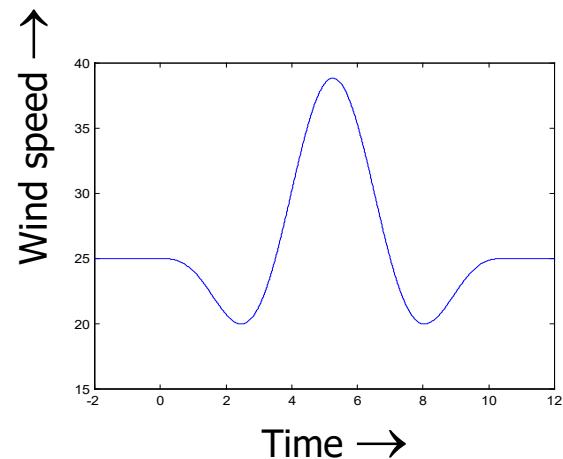
'Real'

- maximum amplitude
- maximum rise time



IEC:

- deterministic gust
- uniform over rotor plane
- also:
 - extreme direction change
 - combination
 - extreme wind shear (vertical and horizontal)

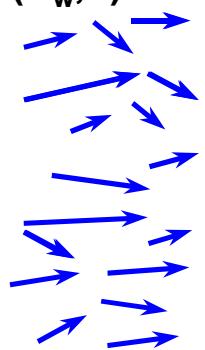


Wind turbine simulation tools

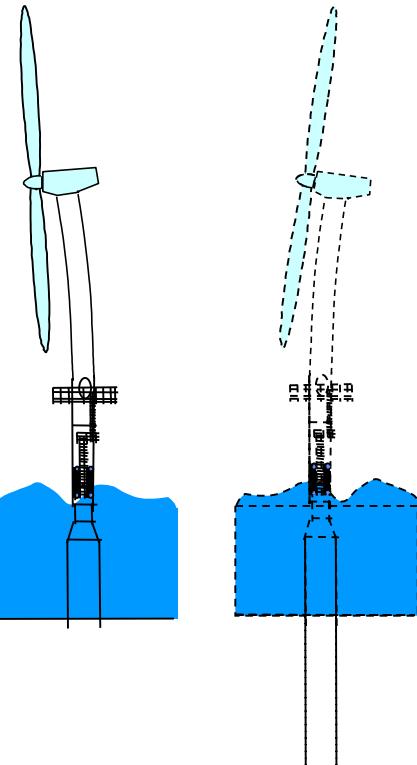
1. Design packages
2. Types of excitation
3. Dynamic modelling

1) Design packages

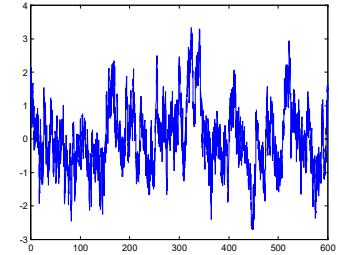
turbulence
(V_w , I)



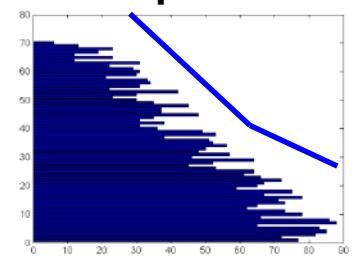
random sea
(H_s , T_z)



load time history



load spectrum

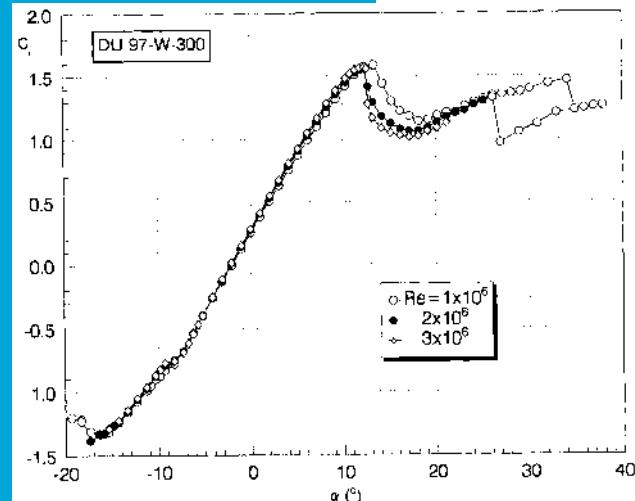


- Wind field generation
- Dynamic model
 - aerodynamics (BEM)
- Post processing
 - rainflow counting
 - spectral analysis
 - ...

Purpose

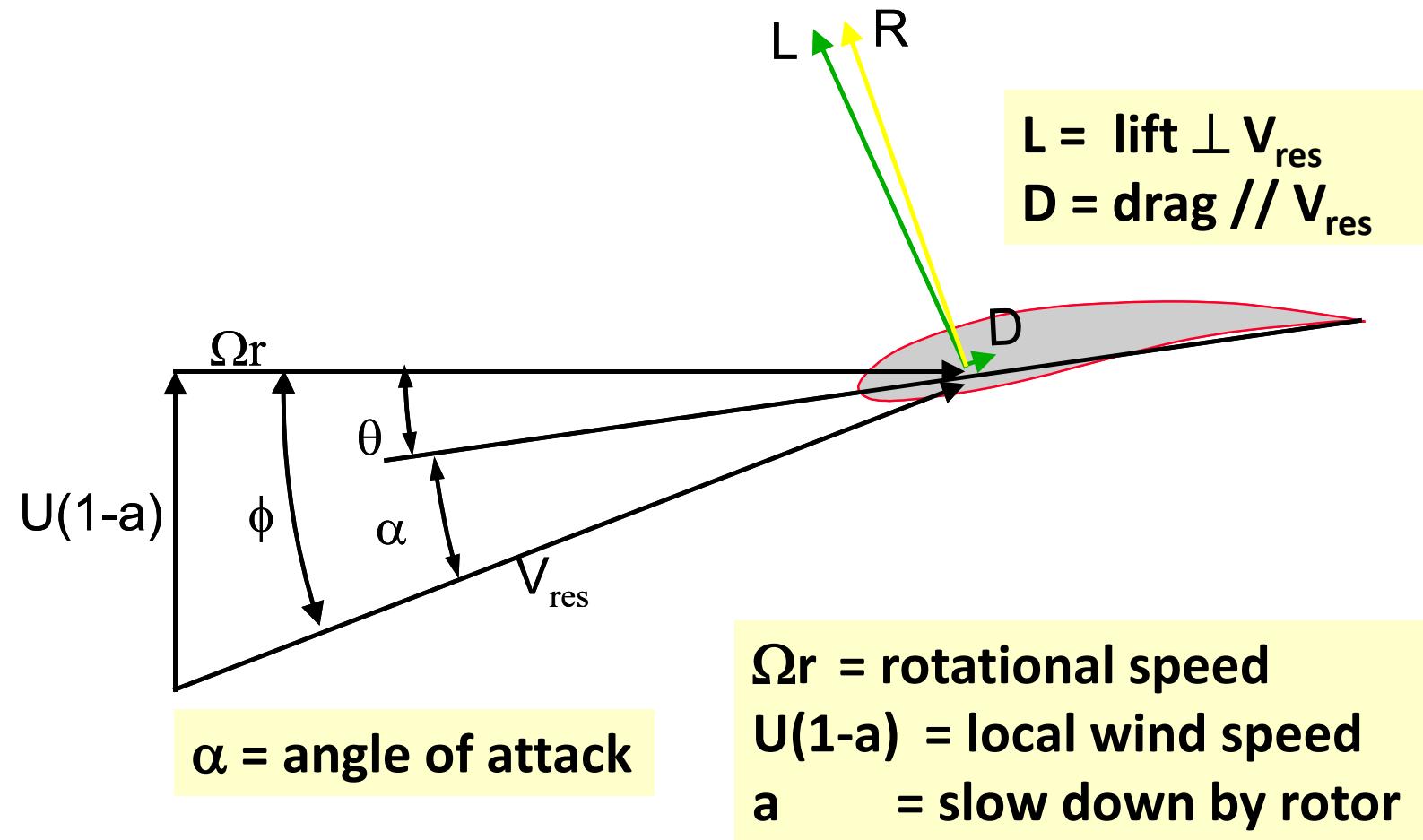
- fatigue analysis
- ultimate loads
- blade tower clearance
- design of control system
- ...

lift coefficient



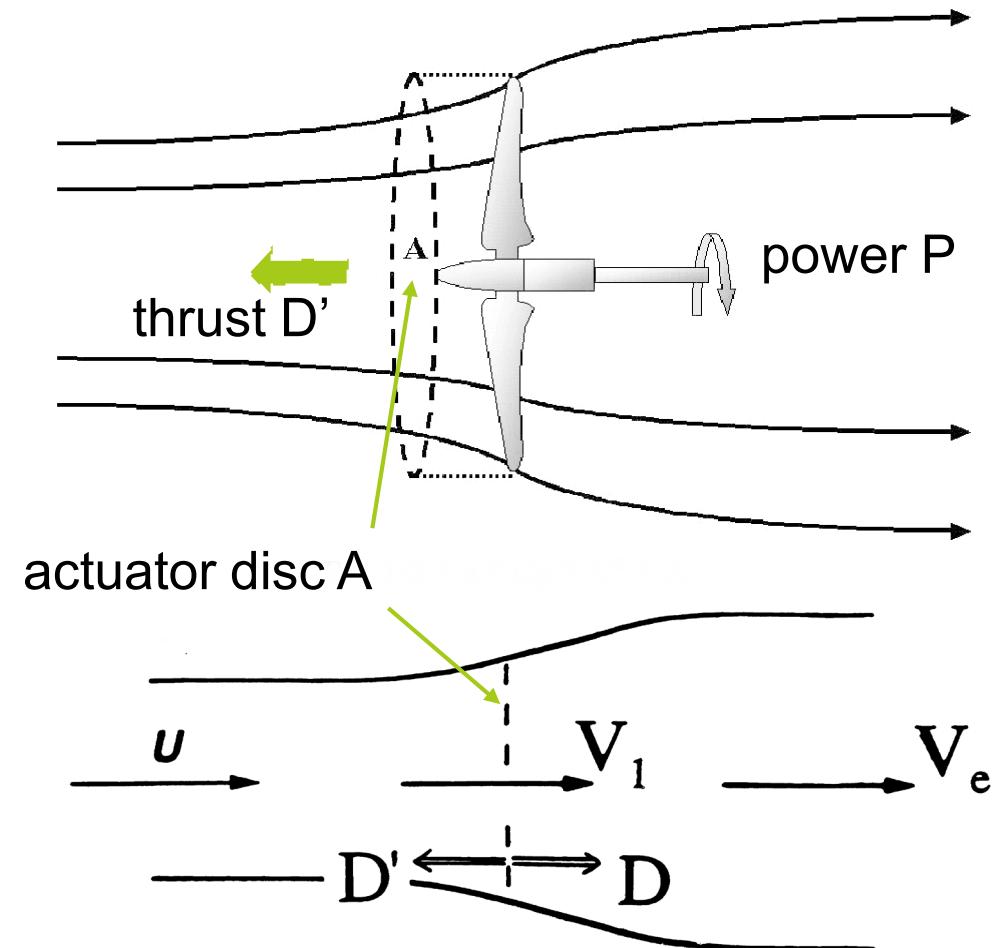
angle of attack

Blade Element method



Momentum theory

rotor in uniform flow



**actuator disc A
represents rotor:**

- exerts axial rotor force (thrust) D' on air flow
- extracts power P from flow

Blade element momentum method

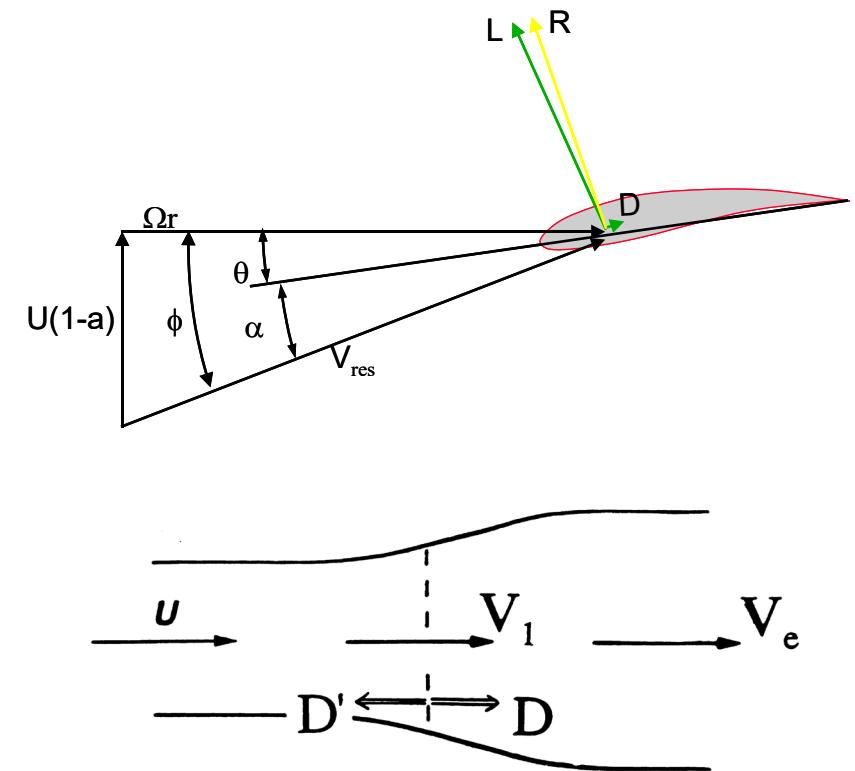
Blade element method

- Forces can be calculated based on the velocities
- Problem: what is induction factor a ?

Momentum theory

- The induction factor a can be calculated from the force
- Problem: what is thrust D ?

**Solution: combine methods!
blade element momentum method (BEM)**

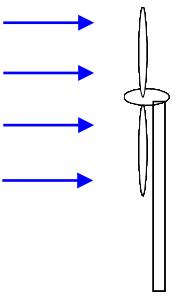


Different loads

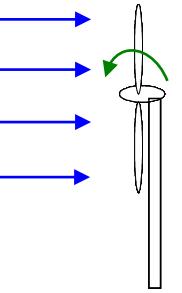
- Aerodynamic; hydrodynamic
- Gravity
- Inertia
 - centrifugal (rotation of rotor)
 - gyroscopic (yawing)
- Operational
 - start / stop
 - yawing
 - pitching
 - grid connection



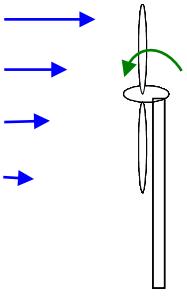
2) Different types of excitation I



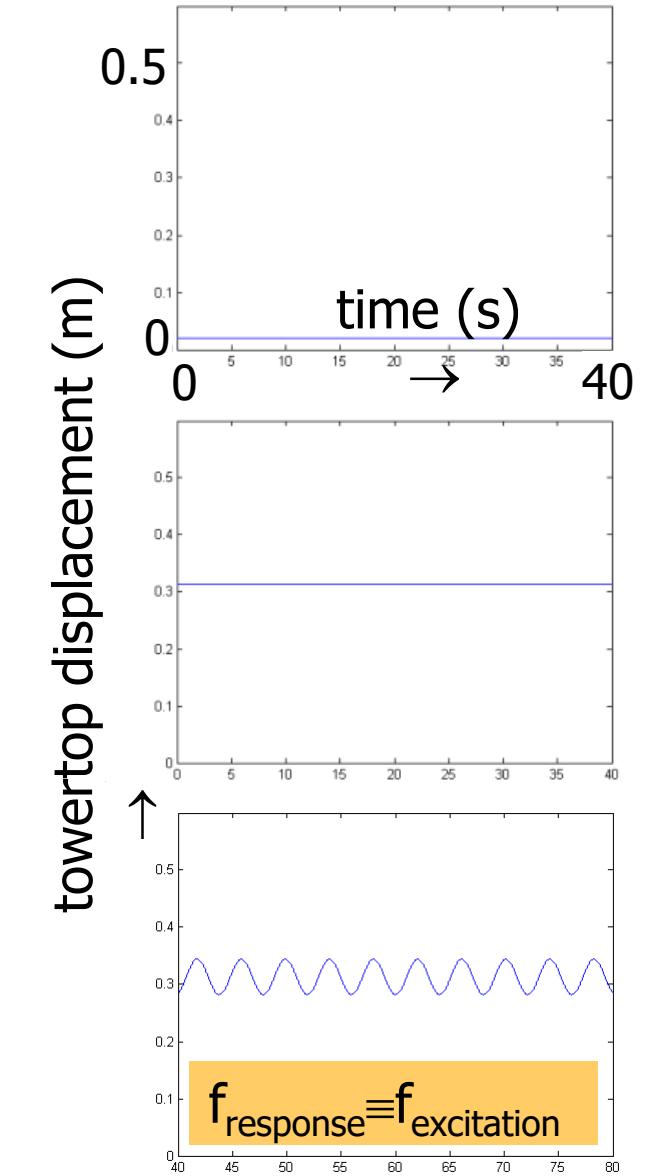
Static



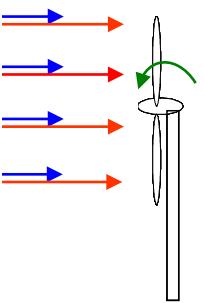
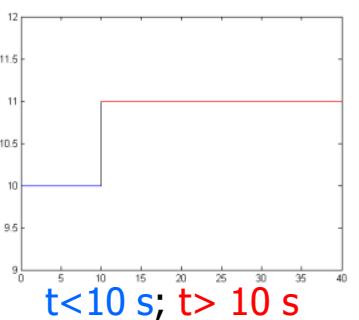
Steady



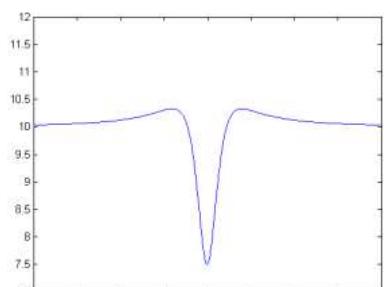
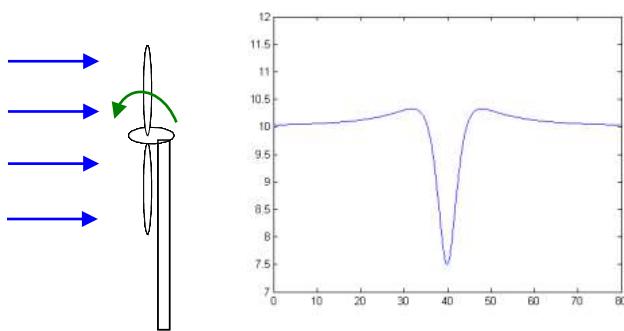
Cyclic
1P, 2P, ...



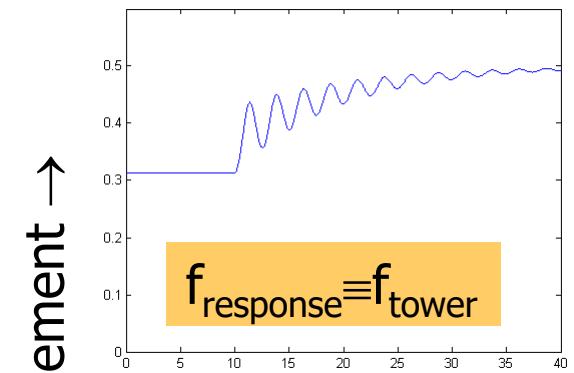
Different types of excitation II



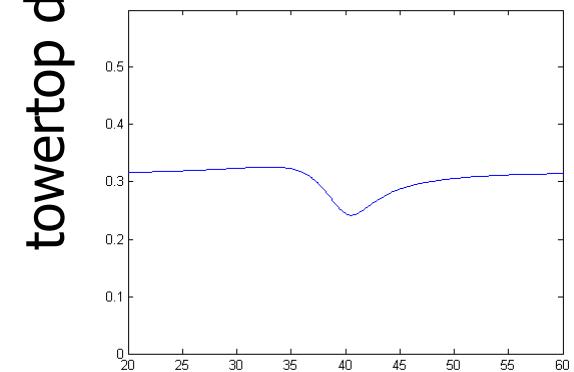
Transient
(severe gust)



Impulsive
(tower shadow)

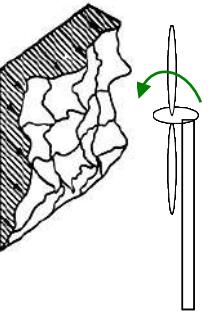


$f_{\text{response}} \equiv f_{\text{tower}}$

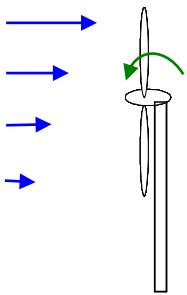


time →

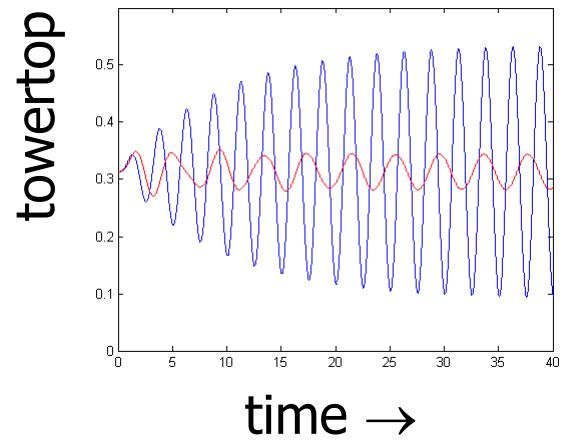
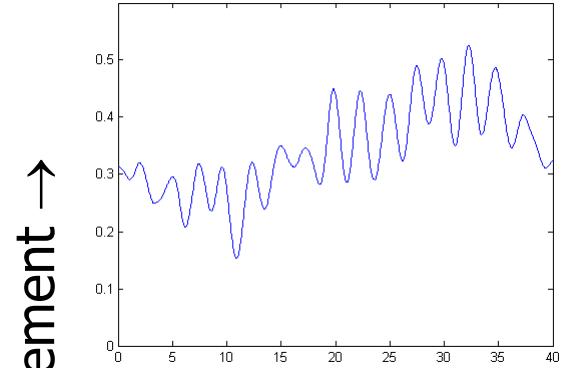
Different types of excitation III



Stochastic

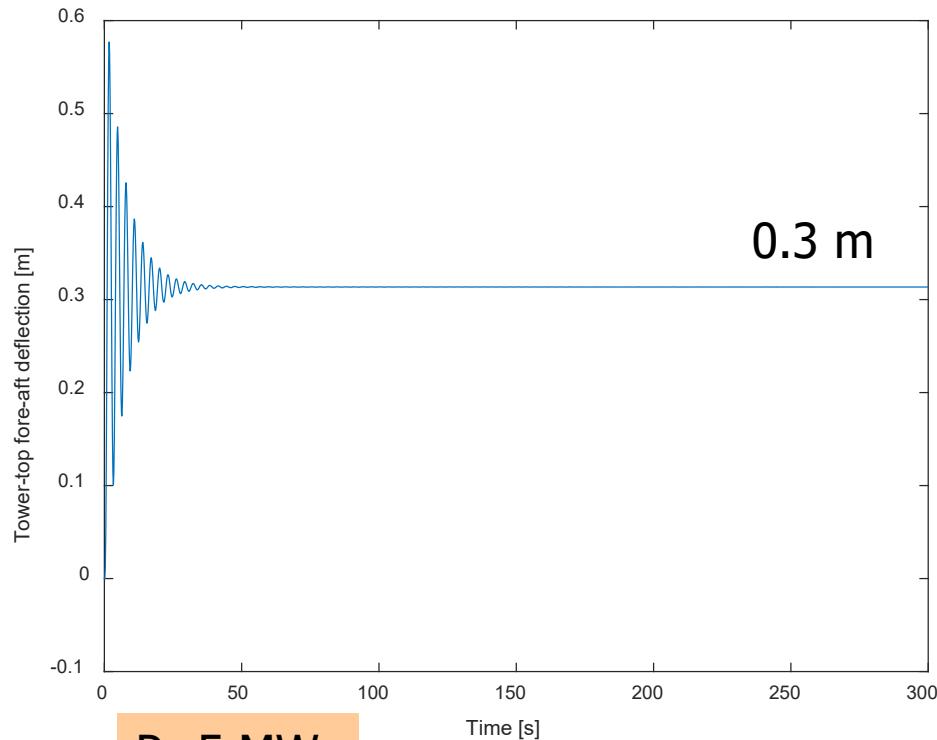


Resonance
 $(1P \equiv f_{\text{tower}})$



FAST simulations

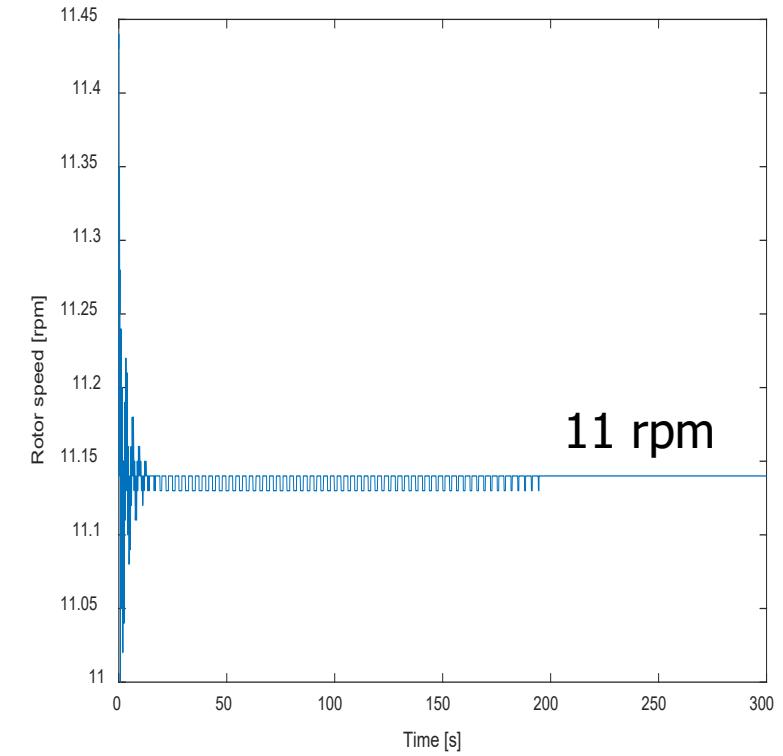
Towertop displacement [m]



P=5 MW
D=126 m
3-bladed

U=10 m/s

Rotor speed [rpm]

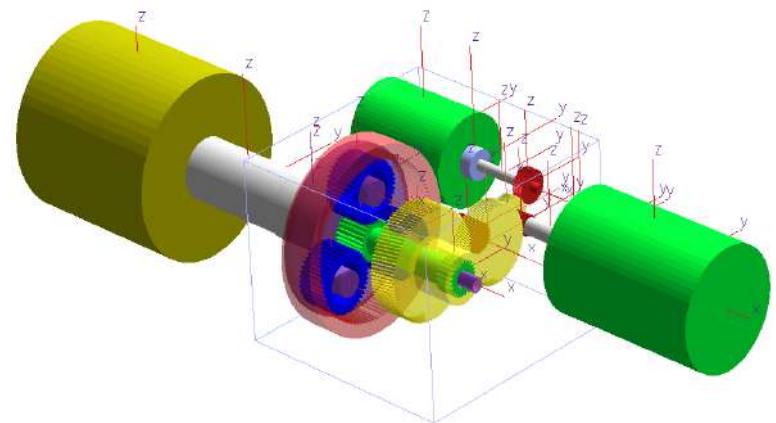
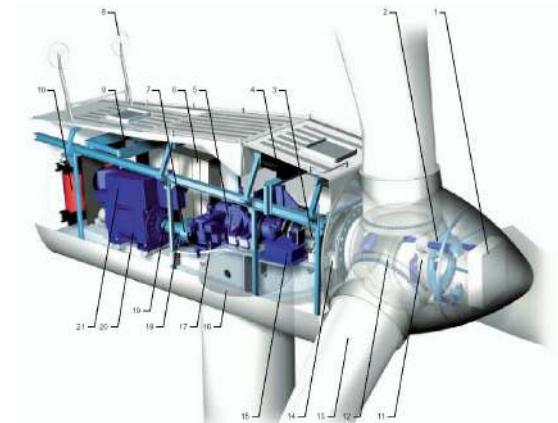
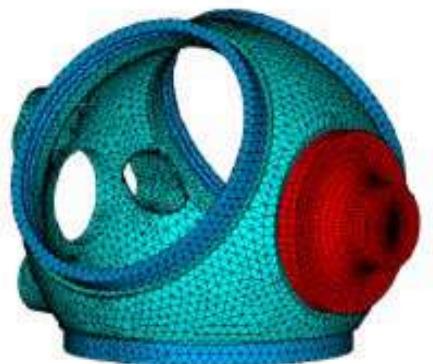


Make this sense ?

3) Dynamic modelling

Time domain

- Modal analysis
- Multi Body Systems (MBS)
- Finite Element
 - details e.g. hub

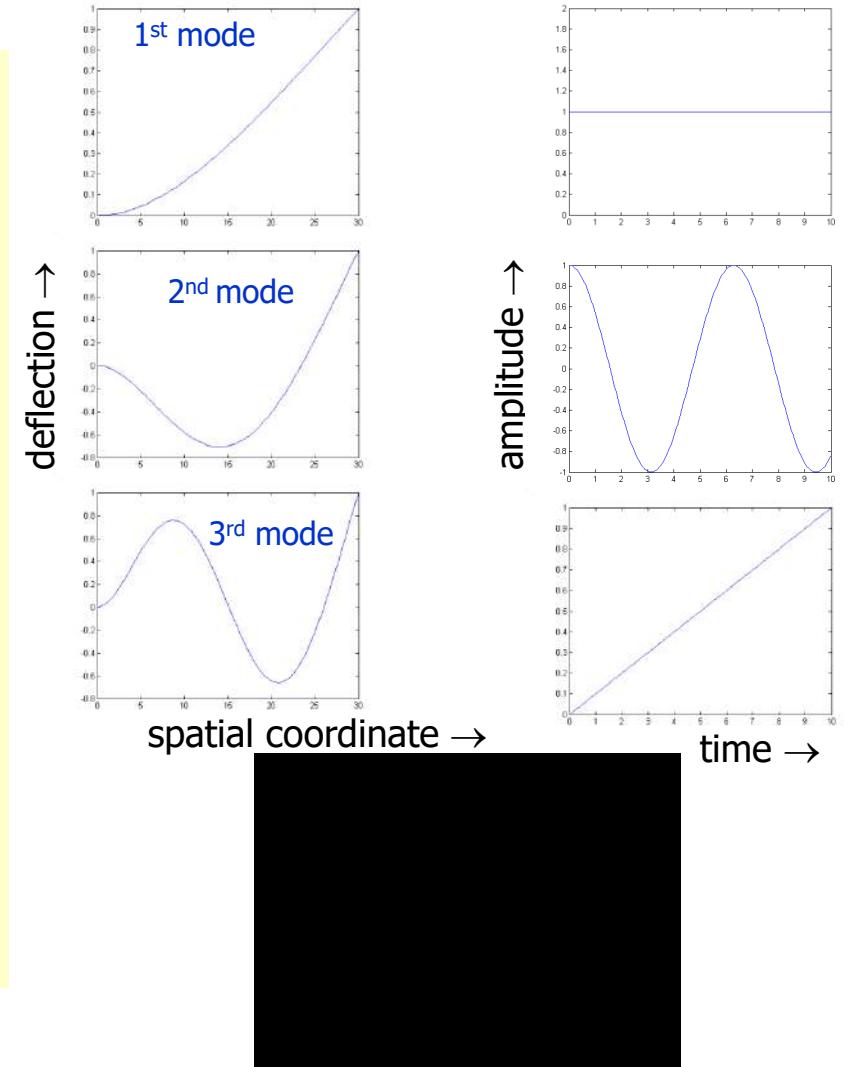


Modal analysis

just an example

- Blade motion:
superposition of blade modes
- Substitute into equations of motion
- Decouple equations of motion
 - blade modes are orthogonal
 - proportional damping

↓
- Each mode ('degree-of-freedom'): (generalized) mass-spring-damper system
- Analogous for tower, transmission



Conclusion

Most widely used:

Modal analysis

- Flex5 (Stig Øye, TU Denmark)
- Bladed (Garrad Hassan, UK)
- Fast (NREL, US)

MBS

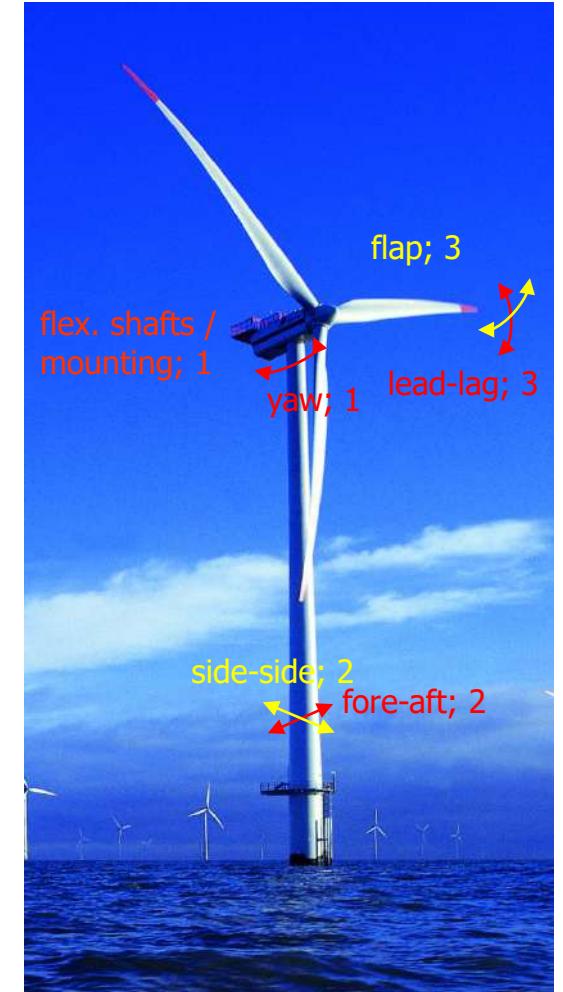
- Adams WT / AeroDyn (NREL, US)

Finite Element

- Focus6 (WMC, NL)

Be aware

- use packages as a tool!



Offshore wind climate

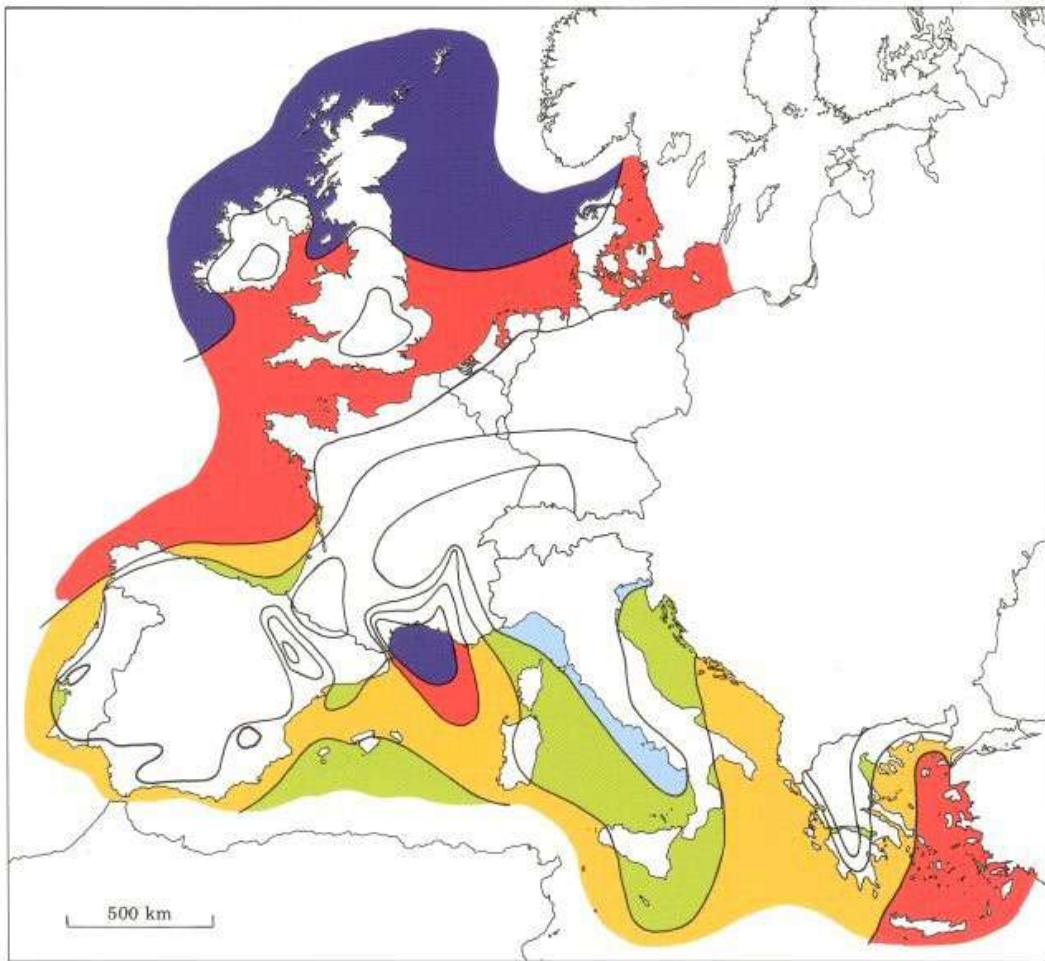
1. European offshore wind map
2. Offshore versus onshore
3. Dedicated wind measurements offshore
4. Variation of offshore wind speed
5. Coastal effects
6. Ongoing research



Princess Amalia

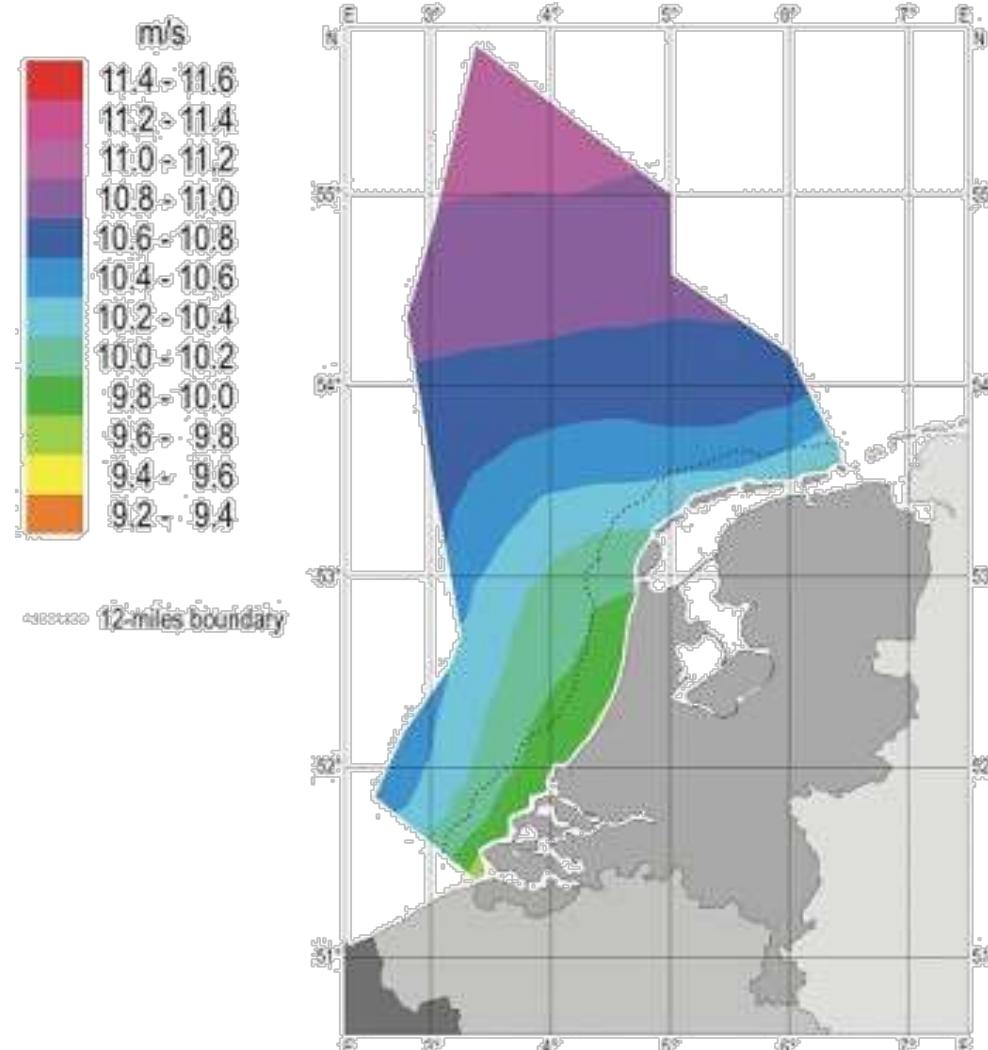
1) European offshore wind map

- Extrapolation from land measurements
- To evaluate offshore potential
- Not suitable for energy yield calculation
- Coastal effects cause main problems



European offshore wind map

- Netherlands' Exclusive Economic Zone
- Derived from pressure data (1997-2002)
- Height: 120 m
- Distribution available for 5 locations



© ECN

Geostrophic wind

Top of ABL

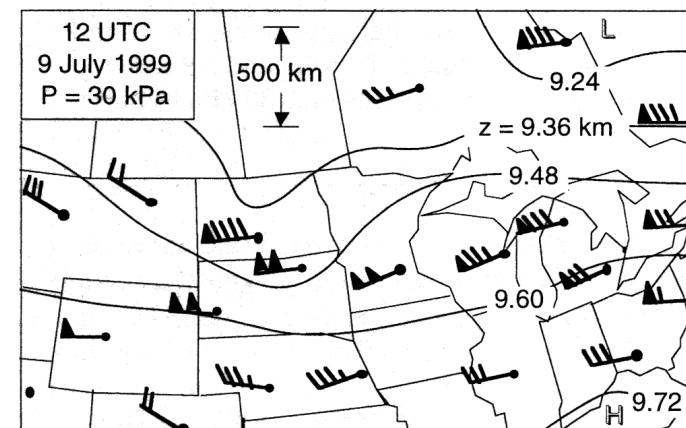
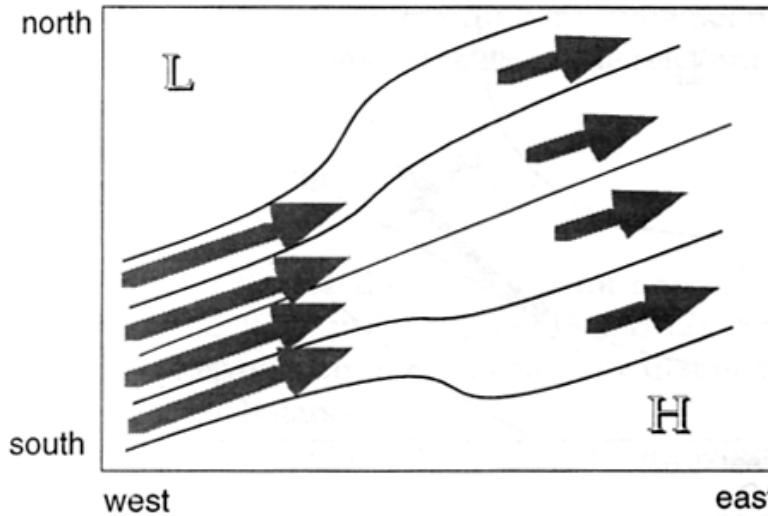
No friction / steady state:

- Balance between pressure gradient and Coriolis force
- Wind parallel to isobars

$$U_G = -\frac{1}{\rho f_C} \frac{\Delta P}{\Delta y}$$

$$V_G = +\frac{1}{\rho f_C} \frac{\Delta P}{\Delta x}$$

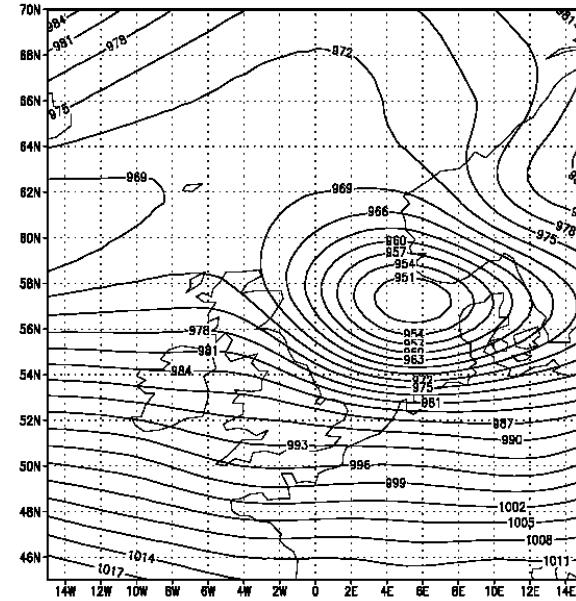
- Can be derived from (measured) pressures gradients
 - Routinely measured
 - Reanalysis data



Surface wind

Geostrophic wind G

- From pressure gradients (or radiosonde above ABL)
- Routinely measured at many met-stations (~ 200 for Europe)
- Every 10–20 min; over many years

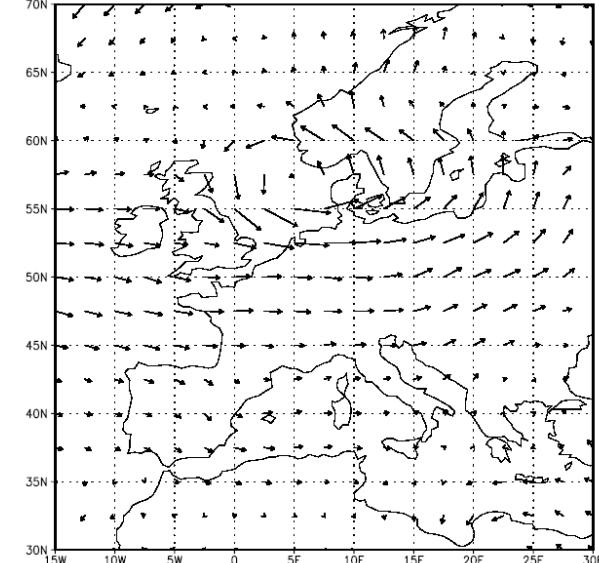


Friction velocity u_*

- From geostrophic drag law (f and z_0 known)

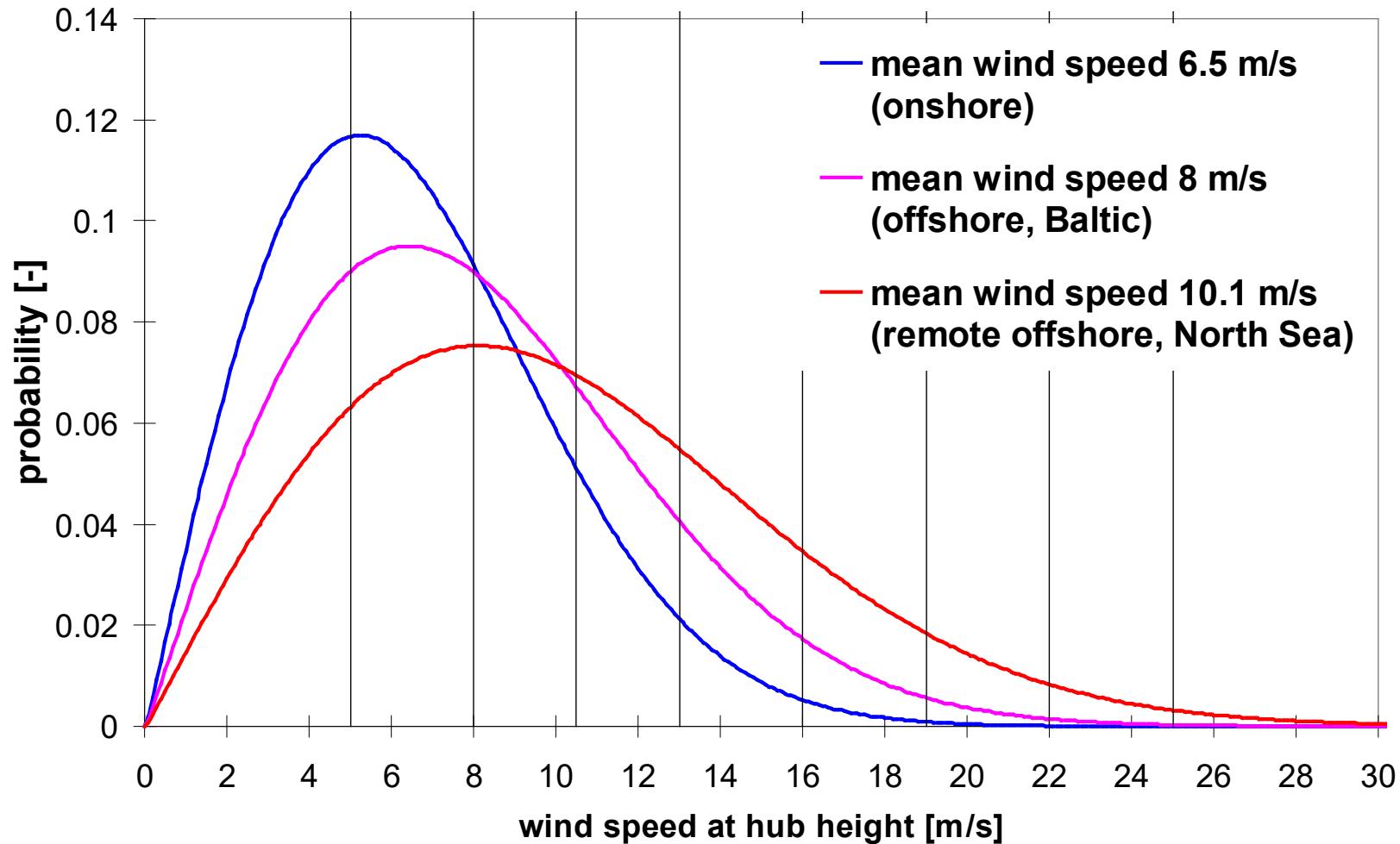
Surface wind (between 10 m and 200 m)

- From logarithmic wind profile



2) Offshore versus onshore

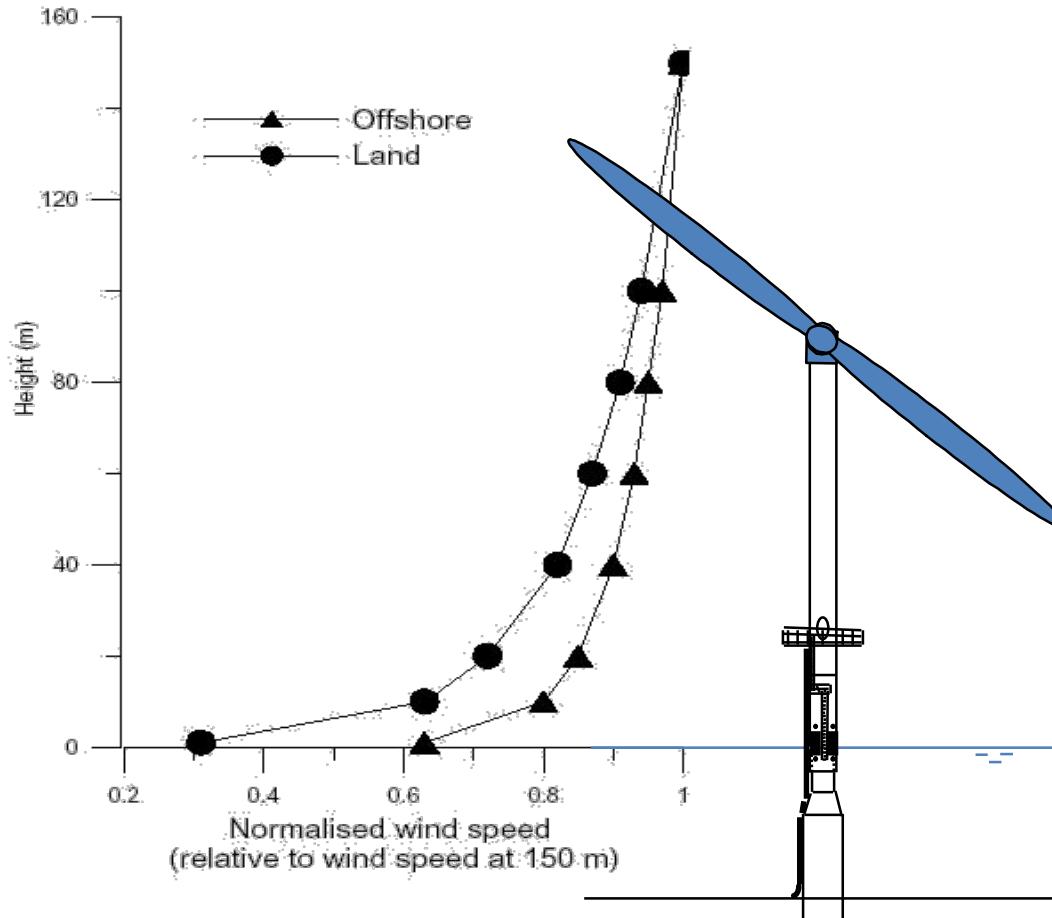
– Weibull distribution



Offshore versus onshore

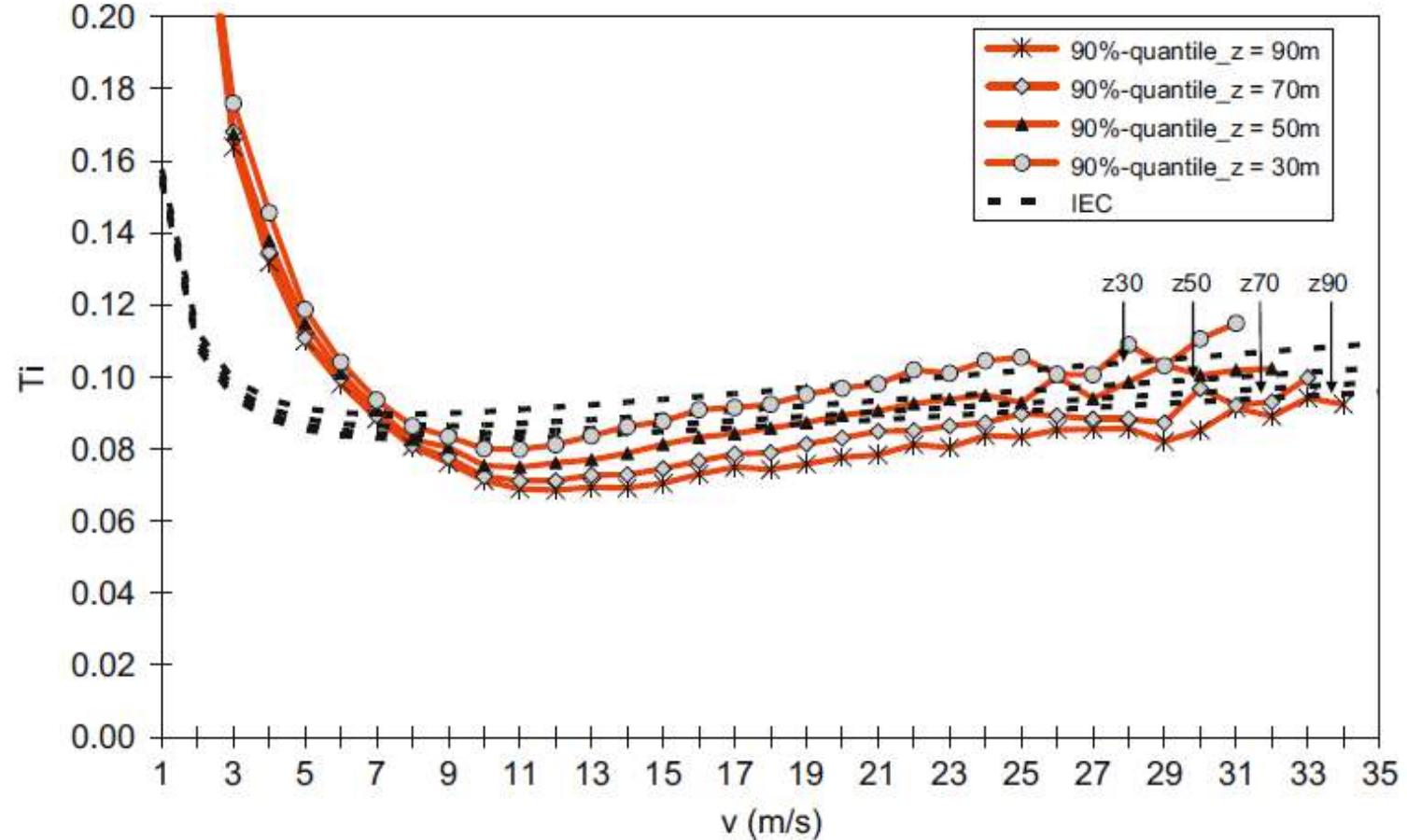
– Wind shear

- z_0 depends on wave height (Charnock); 0.2 mm good estimate
- Stability effects more important
- Offshore verification ongoing



Offshore versus onshore

– Turbulence



Available offshore weather stations

Platform data (since '80)

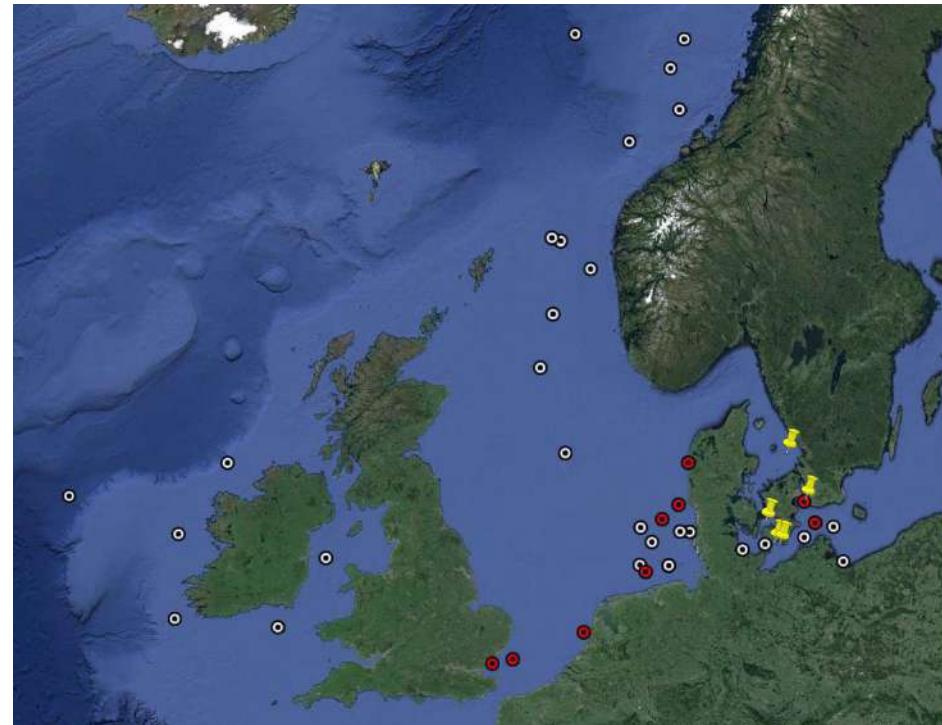
- (Meteo) stations (limited w.r.t. land)
- Wind and wave data

Meteorological masts (since '93)

- Offshore wind energy projects

Other sources

- Light ships
- Voluntary Observing Ships
- Pressure data / satellite data
- Databases (e.g. NESS / NEXT)



3) Dedicated wind measurements offshore



Risø/SEAS
5 locations in Danish seas
(50 m high)



FINO 1 platform
German part of the North
Sea (105 m high)



Platform OWEZ
Mierij Meteo; 3 levels, 3
sides (120 m high)

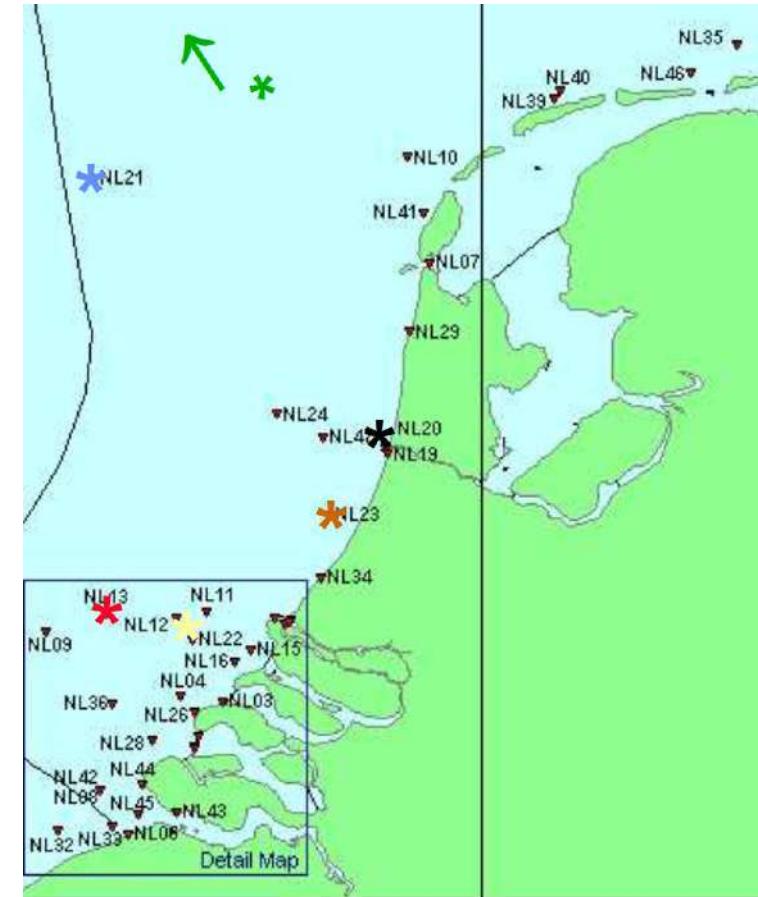
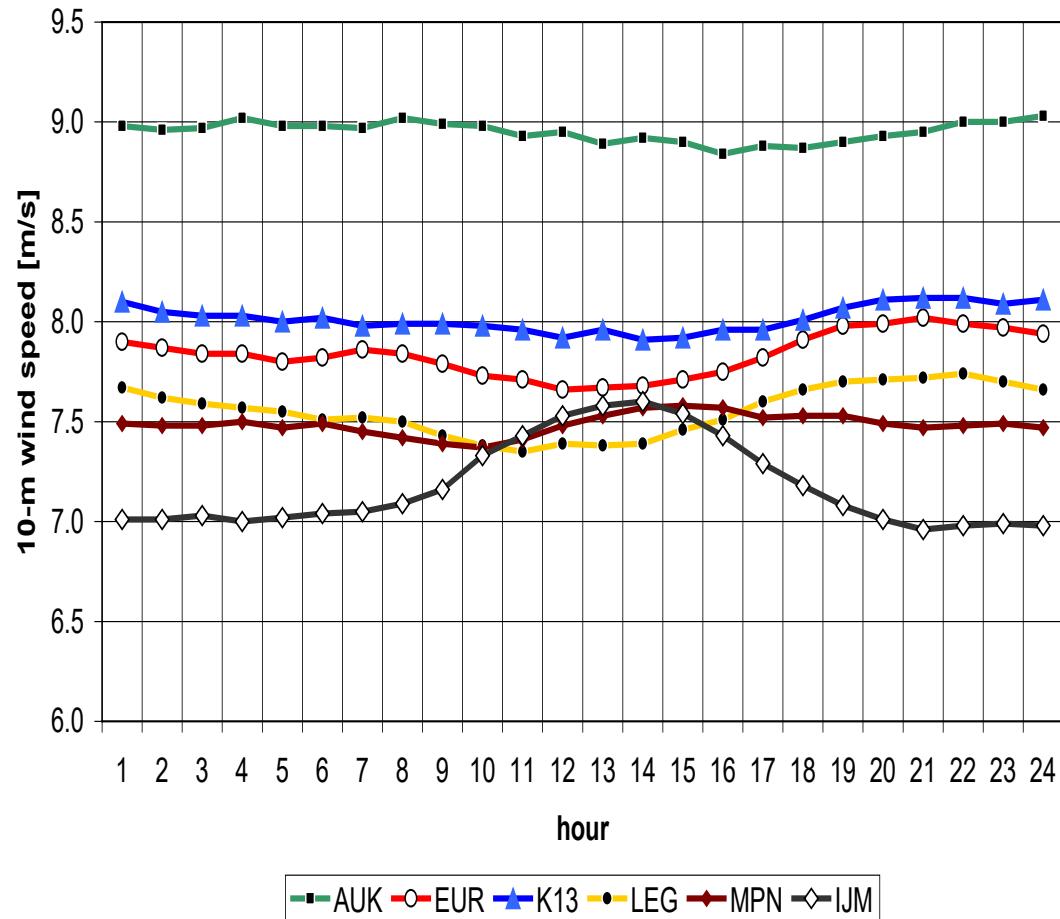
Dedicated wind measurements offshore

Wind data available online

<https://www.shell.nl/energie-en-innovatie/wind/noordzeewind/rapporten.html>

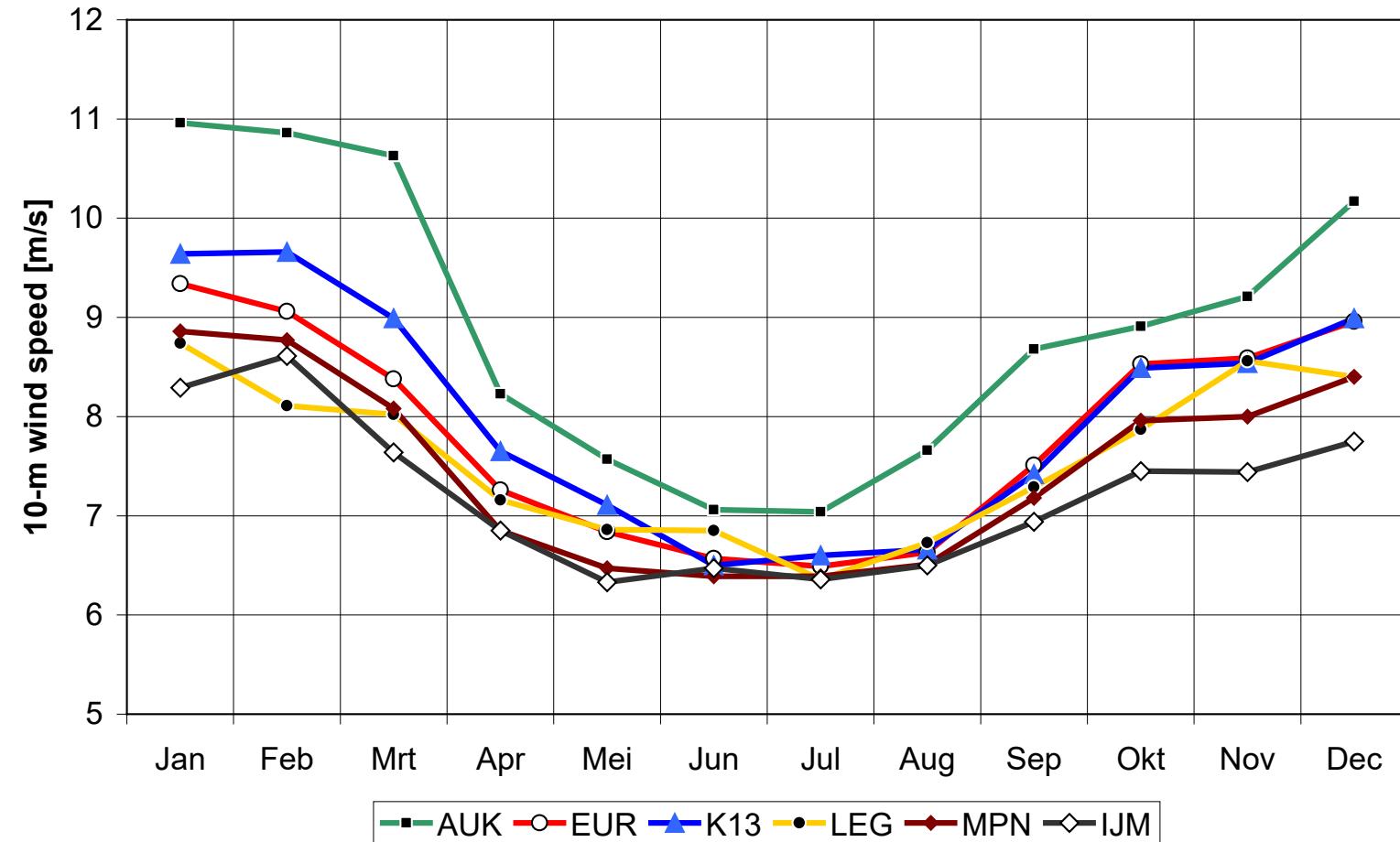


4) Variation of offshore wind speed – Hourly



Variation of offshore wind speed

– Monthly

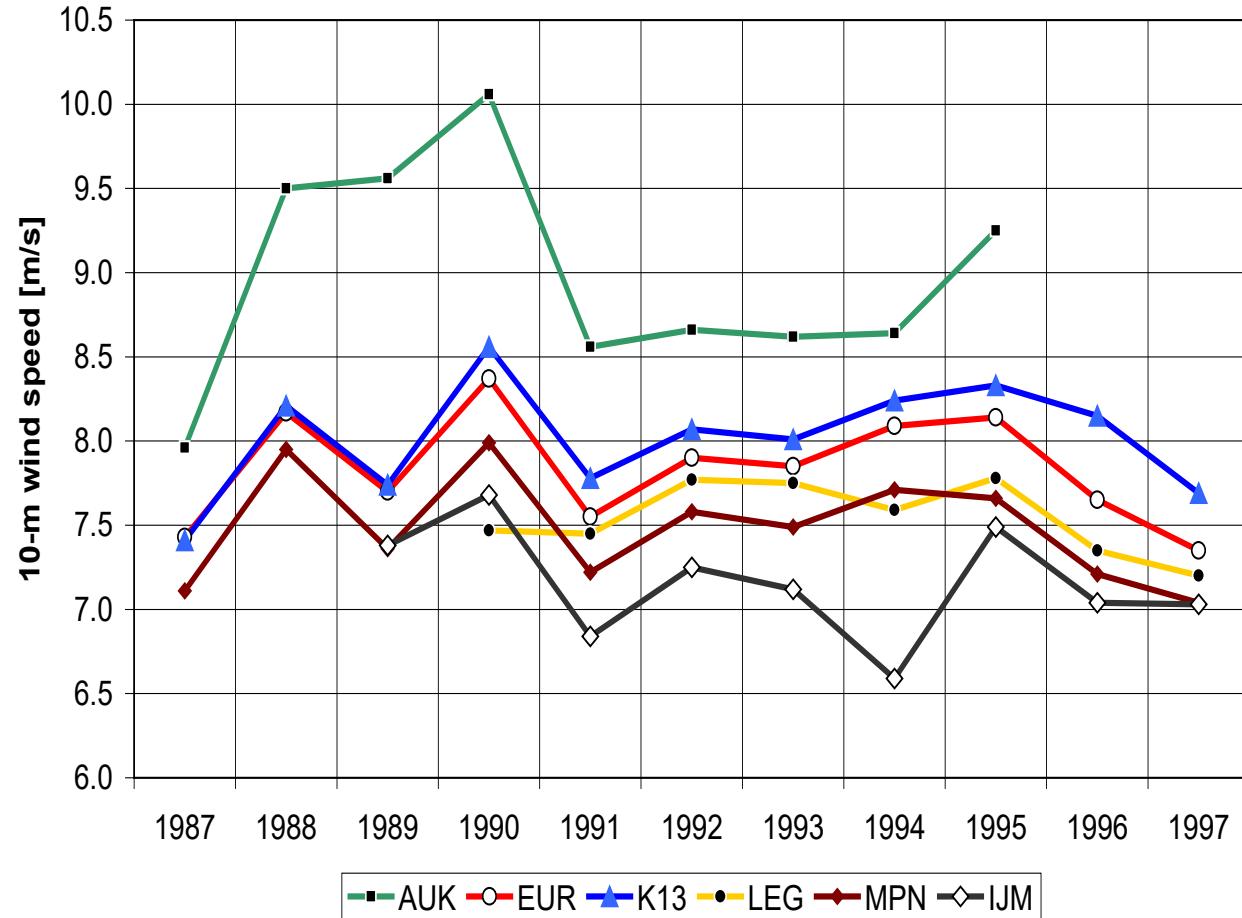


Variation of offshore wind speed

– Yearly

Consequences

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



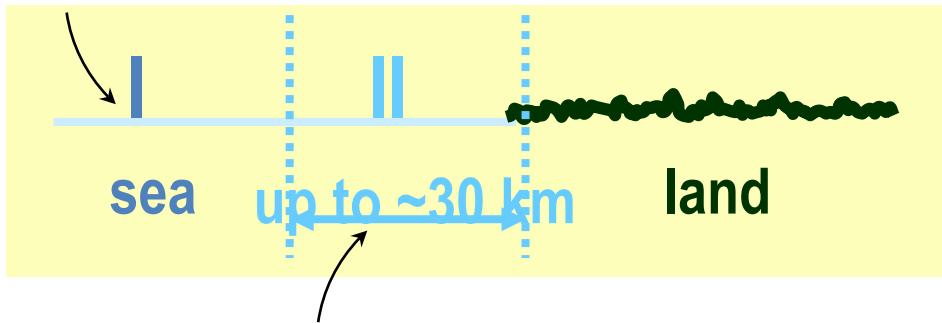
Wind climate offshore versus onshore

	Onshore	Offshore
<i>Diurnal pattern</i>	Daily maximum	Uniform
<i>Seasonal pattern</i>	Less pronounced	More pronounced
<i>Stability</i>	Diurnal pattern	Seasonal pattern
<i>Wind profile</i>	“Unstable” on average	“Neutral” on average
<i>Mean wind speed</i>	Decreasing inland	Higher than on land

5) Coastal effects

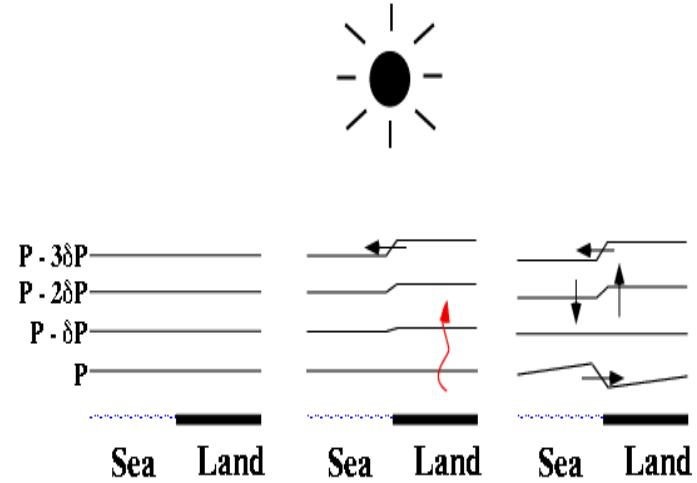
Wind atlas methods more or less apply

- z_o depends on U

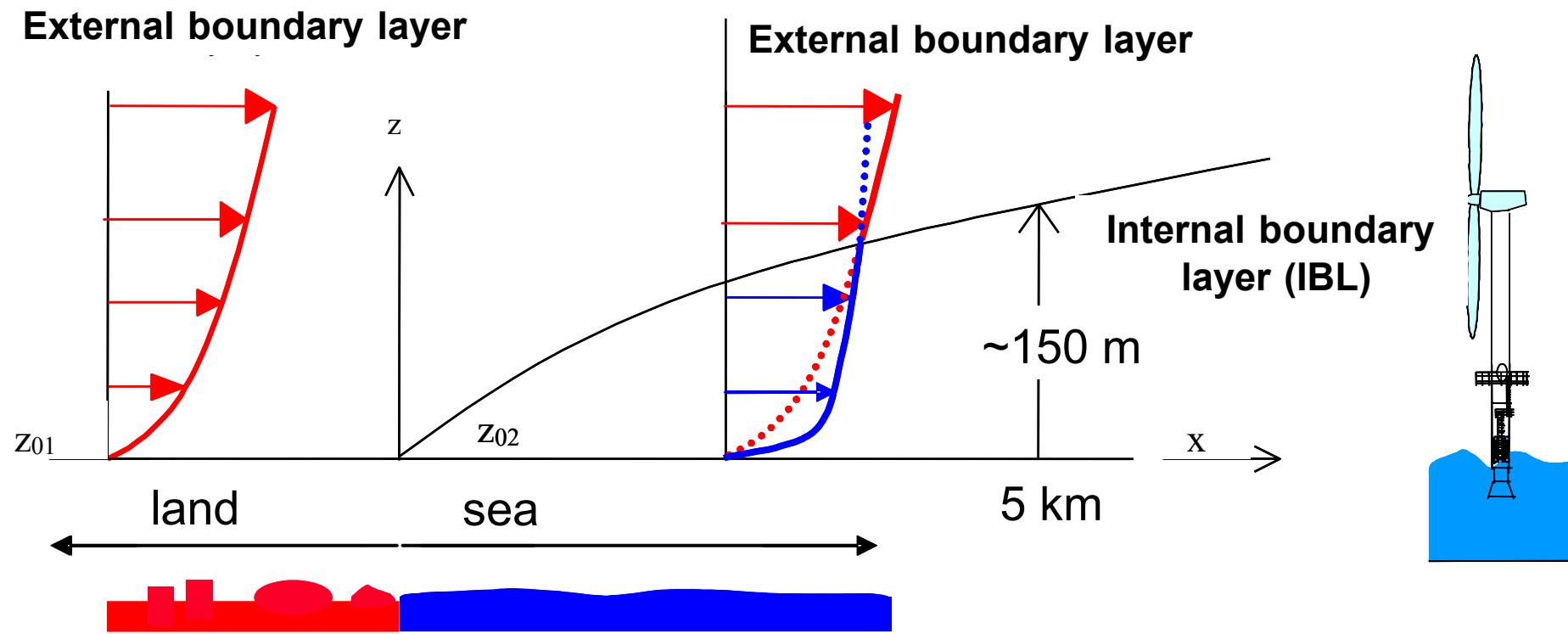


Coastal discontinuity, caused by

- Strong variations in air/sea temperature gradient (*winter ~ summer, onshore ~ offshore wind*)
 - Resulting strong effect of stability
 - Further complicated by internal boundary layer effects
- *Model improvement still underway*



Coastal effects



Wake effects

Onshore wake

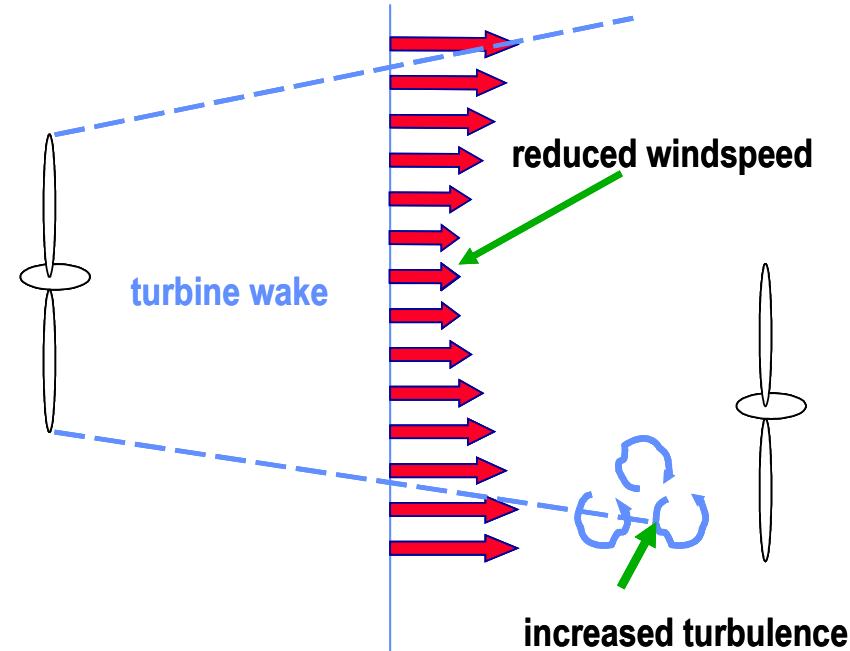
- Decreased mean wind speed:
Spacing $3\text{--}5D$ (commercial packages available to estimate farm efficiency)
- Increased turbulence (especially for stall turbines)



© Risø

Offshore wake

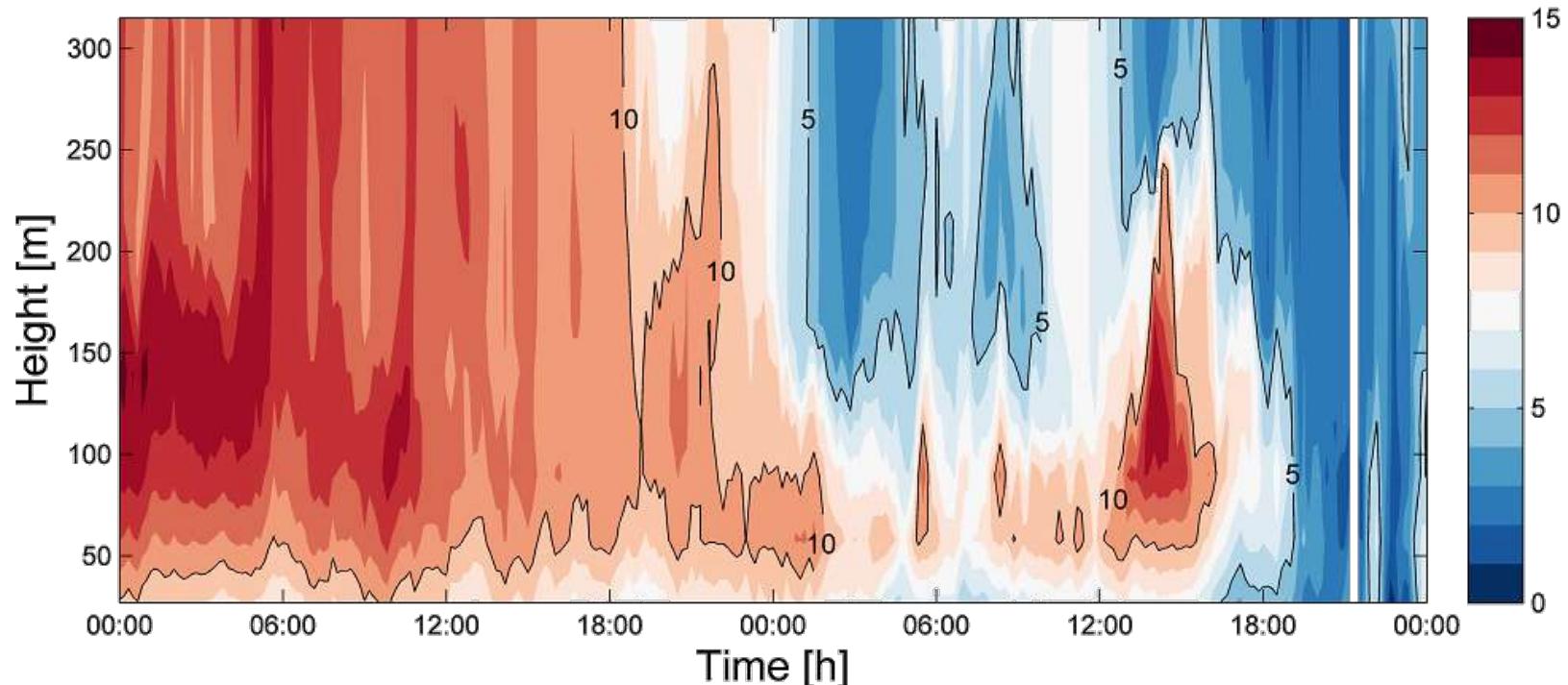
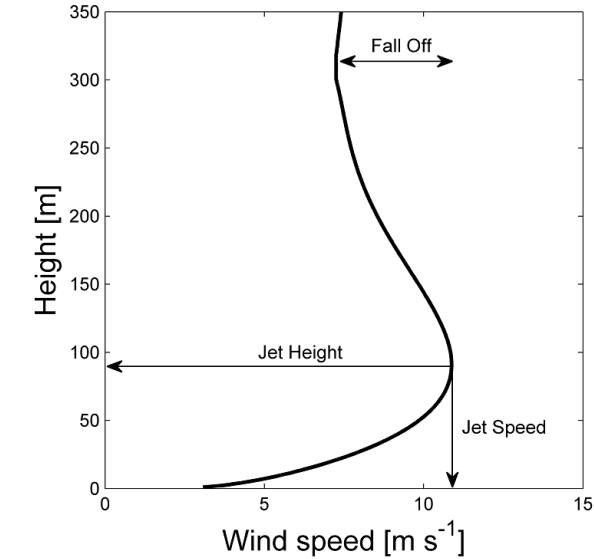
- Larger extension due to lower ambient turbulence



6) Ongoing research

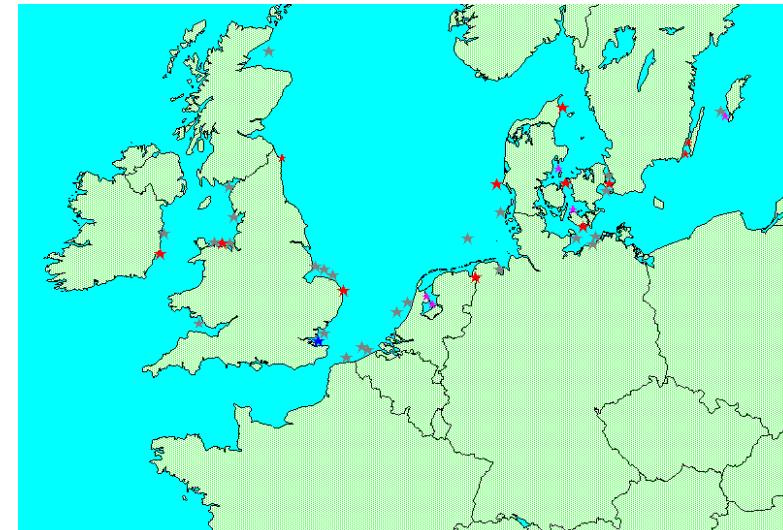
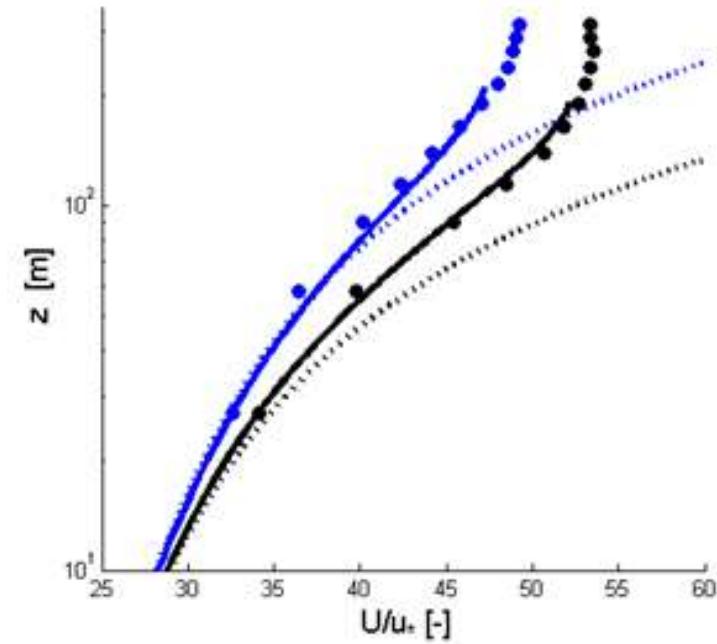
Low level jets

- Maximum at relatively low levels (100–150 m)
- Dynamic effect, overshoot



Ongoing research

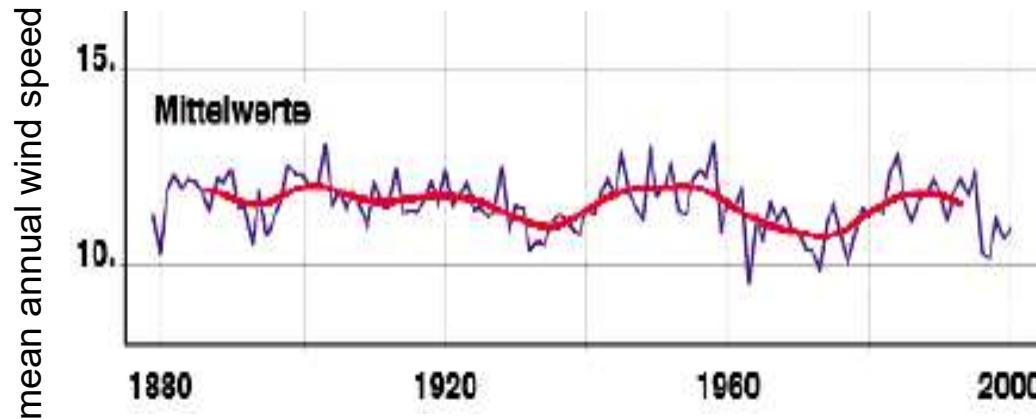
- Verification of wind shear
- Stability more important than roughness
- $H \geq 120 \text{ m}$, $D \geq 120 \text{ m}$; blades rotates (partially) above surface layer
- Mutual effect of farms w.r.t. wind climate



Ongoing research

Climate change

- Large annual variations
- Dominant period ~ 35 y
- NO long-term trend w.r.t. wind potential
- Periodicity not consistent enough for predictions



Ongoing research

Climate change

- Large annual variations
- Dominant period ~ 35 y
- NO long-term trend w.r.t. wind potential
- Periodicity not consistent enough for predictions
- Wind variations correlated with NAO (North Atlantic Oscillation)

