Introduction to offshore wind resources:

Hans Ejsing Jørgensen
Niels G. Mortensen & Charlotte Hasager
Wind Energy Department
Risø DTU

Thanks to
Rebecca J. Barthelmie and the WAsP team @ Risø DTU

Outline

- Advantages & disadvantages of moving offshore…
- Pre-construction
- Resource assessment
- Predicting offshore winds
  - Climate
  - Vertical profiles
- Impacts on offshore resources
  - Changes in roughness
  - Sea breezes, low-level jets
- Conclusions

Advantages and disadvantages

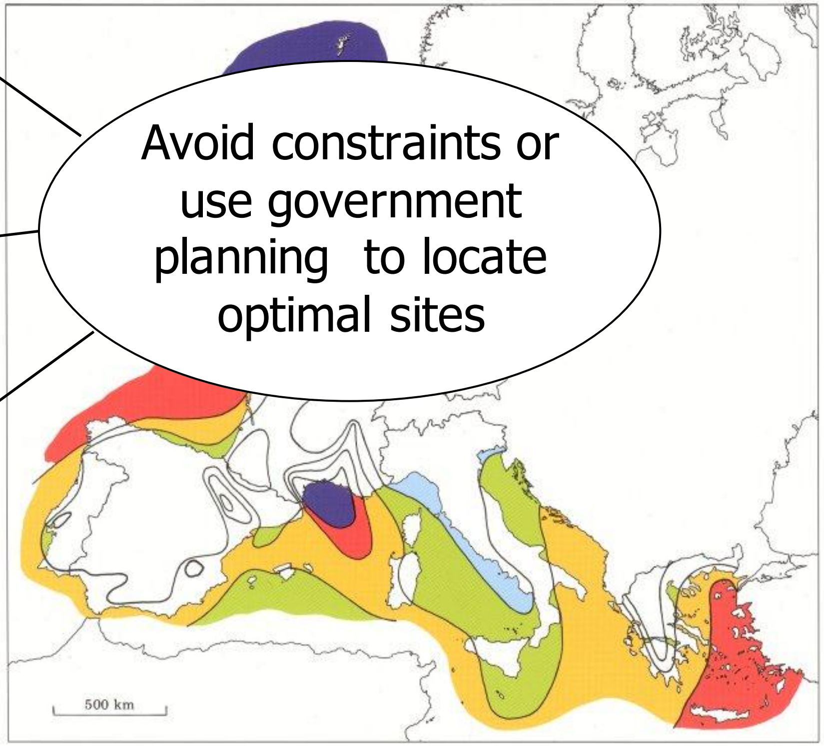
- Advantages
  - Lower roughness=Higher wind speeds
  - Greater persistence of power producing wind speeds
  - Lower turbulence
  - Lower wind shear
  - Large developments possible (availability of 'land') fewer 'stake-holders'
- Disadvantages
  - Lack of accurate measurements
  - Expensive to:
    - undertake measurements
    - undertake maintainence (access)

1991 First offshore farm at Vindeby.
11 450 kW turbines in two rows.
Hub-height 40 m.

Pre-construction

1. Identify potential areas (large-scale)
   - Existing atlases, maps e.g. Offshore wind atlas
2. Confirm resources (mesoscale)
   - Existing data (meteorological masts, ships etc)
   - Re-analysis data
   - Satellite data
   - Mesoscale modelling
3. On-site monitoring (site level)
   - Physical modelling
   - Statistical modelling
   - Meteorological mast
   - Sodar/lidar

Avoid constraints or use government planning to locate optimal sites



	10 m		25 m		50 m		100 m		200 m	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Wind resources over open sea (more than 10 km offshore) for five standard heights

http://www.windatlas.dk/Europe/oceanmap.html

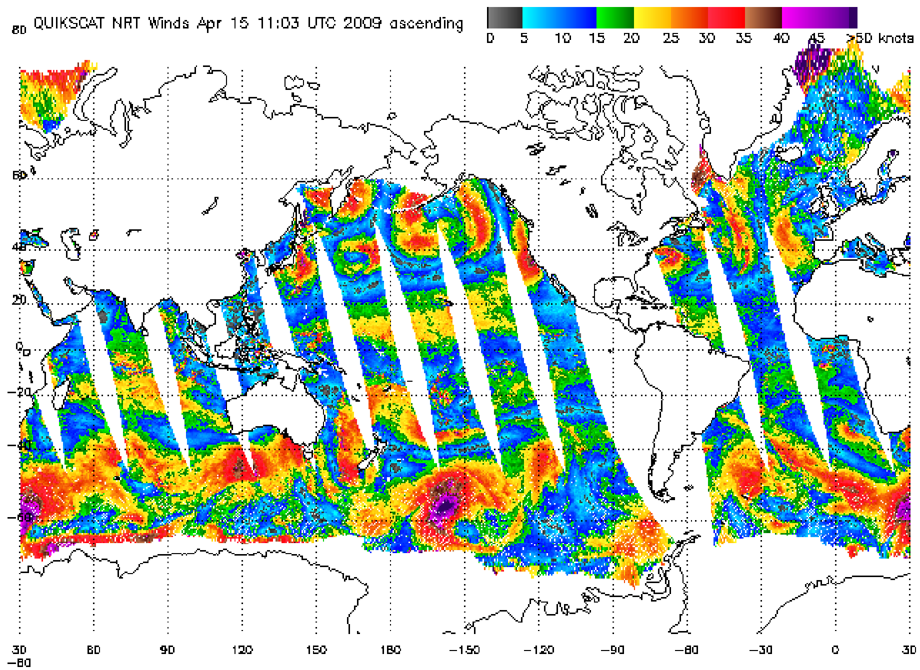
Large-scale: Compile existing data

- Unless these are purpose built meteorological masts. They are generally too problematic to use
- Why?
  - Bulky structures with flow distortion
  - Uncertain data retrieval/accuracy
  - Unrepresentative data periods

http://commons.wikimedia.org/wiki/File:Oil_platform_in_the_North_Sea.jpg

Large-scale: Satellite data

- QuikScat – 25 km by 25 km, twice daily
- Synthetic Aperture Radar – resolution to 100’s m, expensive
- Good spatial distribution, low accuracy, processing required
- Translate surface properties to wind speed



The number of <u>randomly</u> distributed observations required to obtain an estimate of the distribution parameters within ±10 % of the actual time series value for a confidence level of 90 % based on 30 min. average wind speeds measured at 48 m at Vindeby SMW computed with statistics derived from the initial database of > 100,000 observations.

Mean	Standard deviation	Skewness	Kurtosis	Weibull k	Weibull c	Energy density
56	150	9712	>10,000	174	71	1744

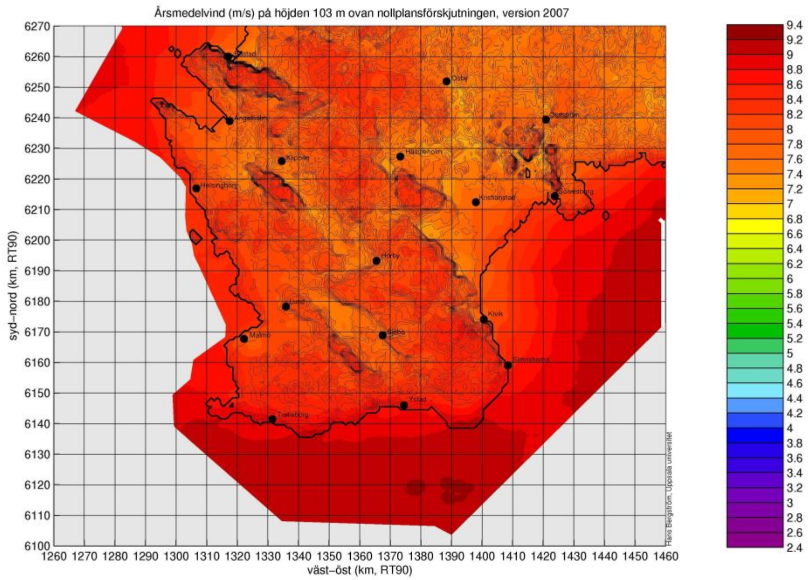
Mesoscale modelling

Examples:

Sweden 1 km resolution
    http://www.geo.uu.se/luva/default.aspx?pageid=13152&lan=1

Canada 5 km resolution

http://www.windatlas.ca/en/nav.php?no=64&field=EU&height=50&season=ANU

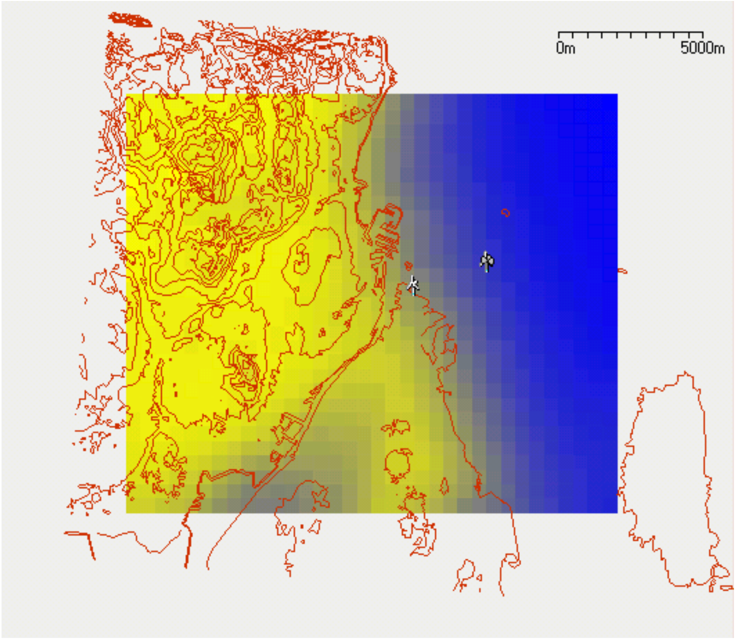


Southern Sweden 103 m wind (from MIUU)

http://www.geo.uu.se/luva/default.aspx?pageid=13152&lan=1

Site level: Physical modelling

- Useful where observations are lacking
  - E.g. vertical profile extrapolation
- Mesoscale numerical models (full physics, computationally demanding)
- Linearised models (less comprehensive, fewer inputs, PC based)



Example from the WASP model

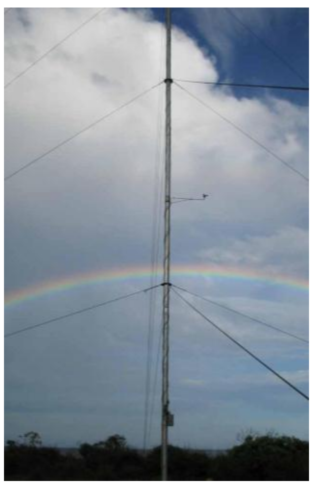
Site-level: Statistical modelling

- Based on observations: e.g. Measure-Correlate-Predict

Long-term wind speed & direction measurements e.g. met service

Long-term wind climate at site

Short-term wind speed & direction measurements e.g. prospective site



Subset

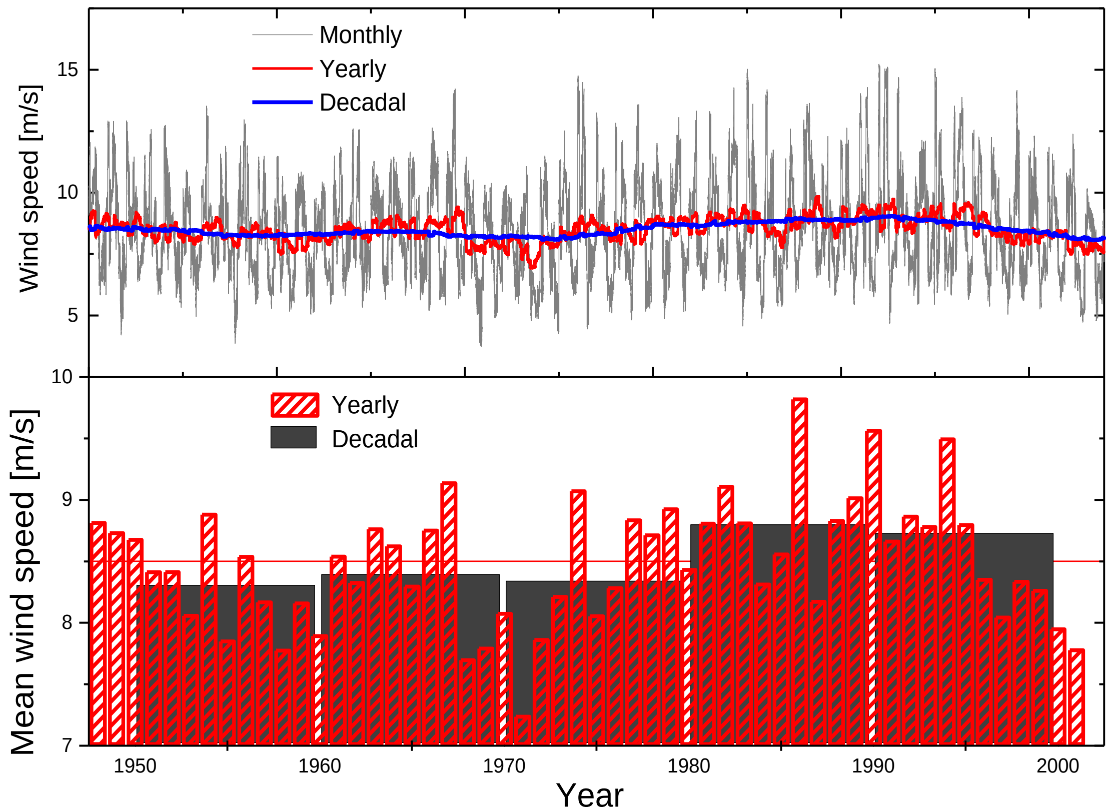
Short-term wind speed & direction measurements

Establish relationship

$U_{site}=U_{long\text{-}term}*X + \text{Constant}$

Ref: Rogers J *Wind Eng Ind Aer 2005 93 243*

Long-term wind climate variations

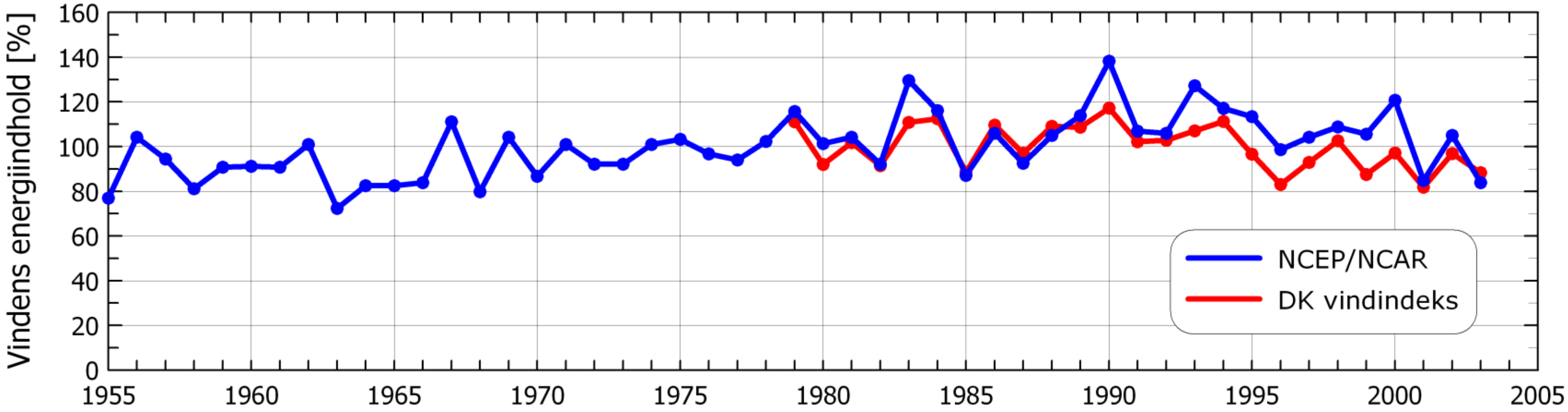


Running means

Sharp means

Data from NCEP/NCAR reanalysis for a site in Ireland

Wind index and reanalysis data for Denmark



- The Danish wind index is determined from actual wind turbine power productions:
  - wind turbines all over Denmark
  - reported since 1979
  - regional indices exist as well
- NCEP/NCAR reanalysis data for Denmark (56.2°N and 9.4°E)
  - data are mean annual power densities @ 10 m a.g.l.

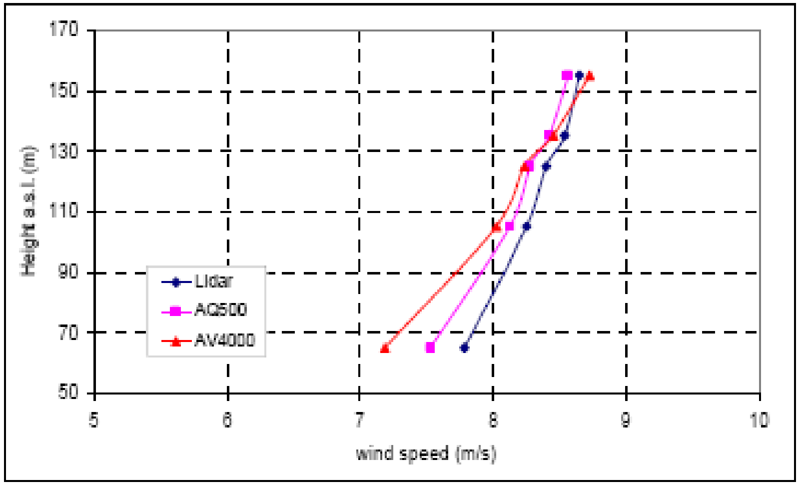
Site: Meteorological masts

- Bankable data, should be of high quality providing mean wind speed, wind shear, direction, turbulence (plus…)
- Can be expensive/time consuming to erect plus time delay
- Can collect data at hub-height
- Mast should be slim/open /uncluttered
- Booms need to be long (possibly reinforced)
- Safety/visibility/access are important
- Power supply & data recovery method

Ref: Barthelmie *J Solar Energy Eng 2005 127 170*

Site: Use of sodar/lidar

- Aim is measurements of wind profile to and above tip height
- Experiment at Nysted wind farm 2005: First operation of lidar offshore
- Big advantage: Wind speed profile without expense of a tall mast
- Disadvantage: Requires skilled operation and data processing



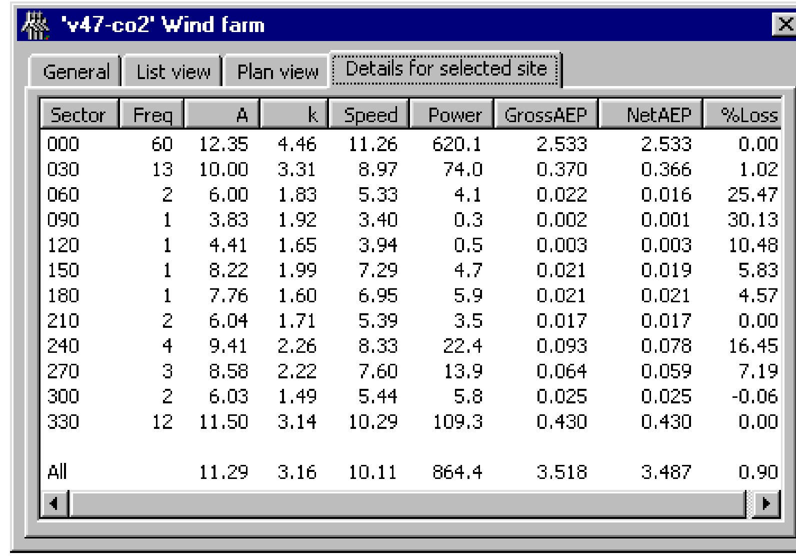
Impacts on offshore wind resources

1. Coastal topography ~50 km
2. Low roughness, dependence on U (Charnock realtionship)
   - Low turbulence
   - Impacts wind shear, wind turbine loads, wind turbine wakes
3. Temperature change=atmospheric stability
   - Impacts wind shear, wind turbine loads, wind turbine wakes

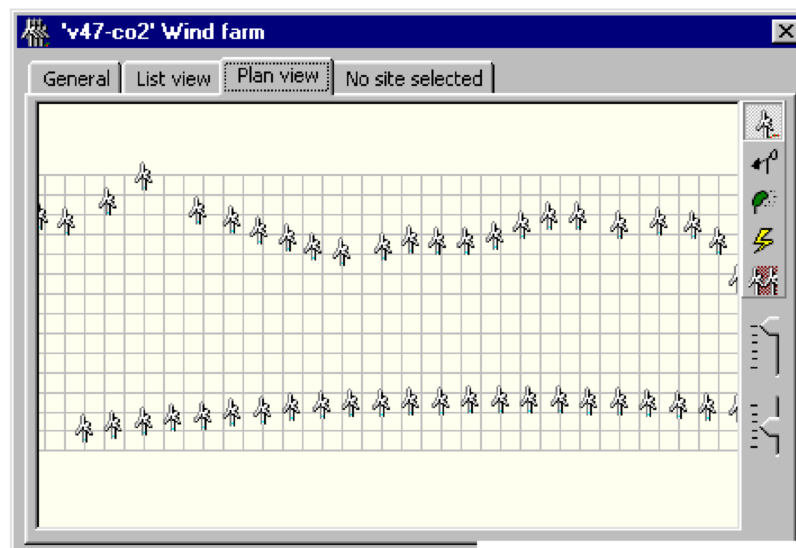
1, 2 and 3 can have equal impact on wind resources

Predicting wind resources

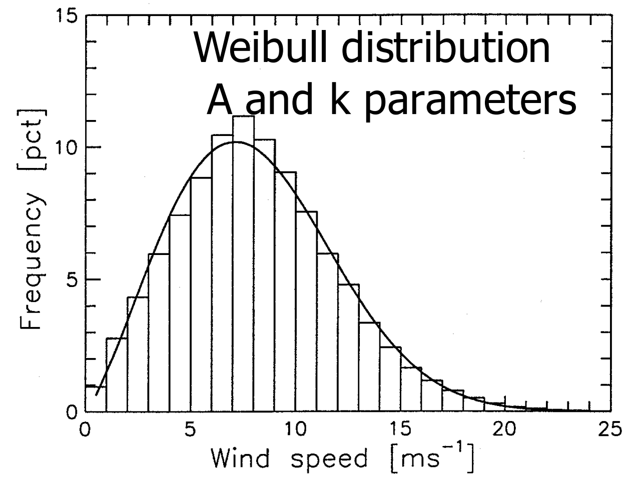
- Accurate prediction of resource and power output requires:
  - Wind speed distribution
  - Account for long-term variations (climate)
  - Vertical profiles

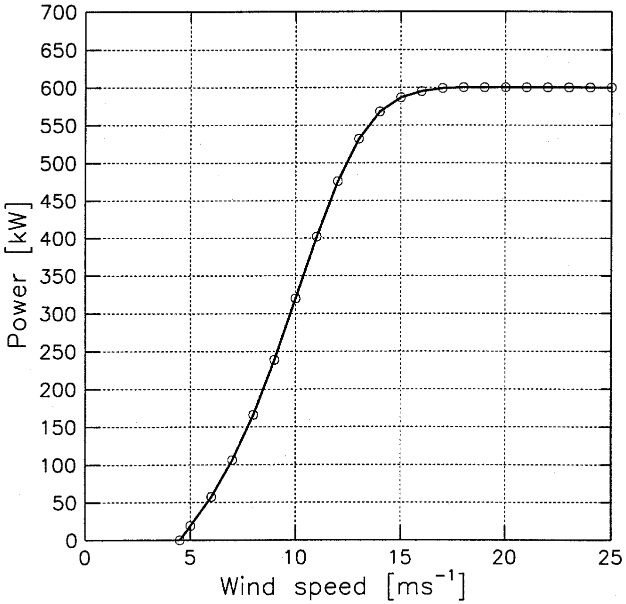


Sector	Freq	A	k	Speed	Power	GrossAEP	NetAEP	%Loss
000	60	12.35	4.46	11.26	620.1	2.533	2.533	0.00
030	13	10.00	3.31	8.97	74.0	0.370	0.366	1.02
060	2	6.00	1.83	5.33	4.1	0.022	0.016	25.47
090	1	3.83	1.92	3.40	0.3	0.002	0.001	30.13
120	1	4.41	1.65	3.94	0.5	0.003	0.003	10.48
150	1	8.22	1.99	7.29	4.7	0.021	0.019	5.83
180	1	7.76	1.60	6.95	5.9	0.021	0.021	4.57
210	2	6.04	1.71	5.39	3.5	0.017	0.017	0.00
240	4	9.41	2.26	8.33	22.4	0.093	0.078	16.45
270	3	8.58	2.22	7.60	13.9	0.064	0.059	7.19
300	2	6.03	1.49	5.44	5.8	0.025	0.025	-0.06
330	12	11.50	3.14	10.29	109.3	0.430	0.430	0.00
All		11.29	3.16	10.11	864.4	3.518	3.487	0.90



Power production





- Understanding power production requires the entire distribution
- Weibull distribution is usually appropriate (k~2.0 for offshore)
- Probability density function (gives frequency of occurrence)

$$p(U) = \left(\frac{k}{A}\right)\left(\frac{U}{A}\right)^{k-1} \exp\left[-\left(\frac{U}{A}\right)^{k}\right]$$

- Mean wind speed (ms^{-1})

$$\overline{U} = A\Gamma\left(1+\frac{1}{k}\right)$$

- Power density (Wm^{-2})

$$E = \frac{1}{2}\rho A^{3}\Gamma\left(1+\frac{3}{k}\right)$$

  - k is the shape parameter (related to the variability)
  - A is the scale parameter (related to the mean wind speed)
  - Γ is the gamma function

Wind resource calculation

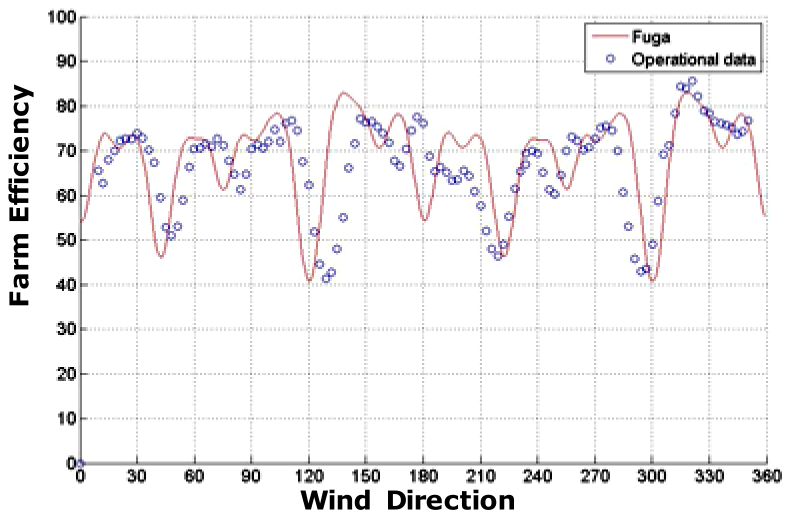
- Short term records do not capture long-term variability
- Compare with long-term sites
- Three methods
  - MCP
  - Weibull
  - WAsP model
- Uncertainty
  - Record length
  - Estimated as ±5%

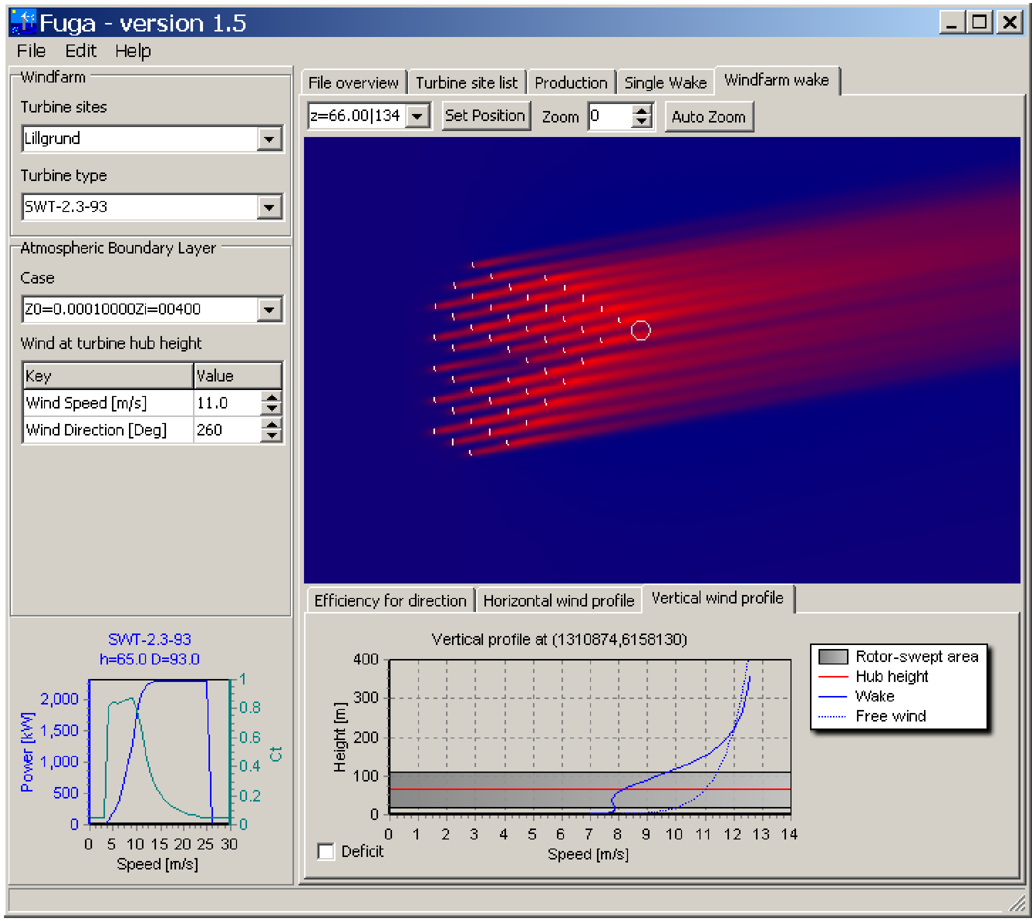
Middelgrunden 50 m

Method	U (m/s)	A (m/s)	k	E (W/m^2)
Weibull	7.3	8.3	2.26	415
WAsP	7.6	8.6	2.12	492
MCP	7.1	8.0	2.21	373
Observed	7.1	8.0	2.57	338

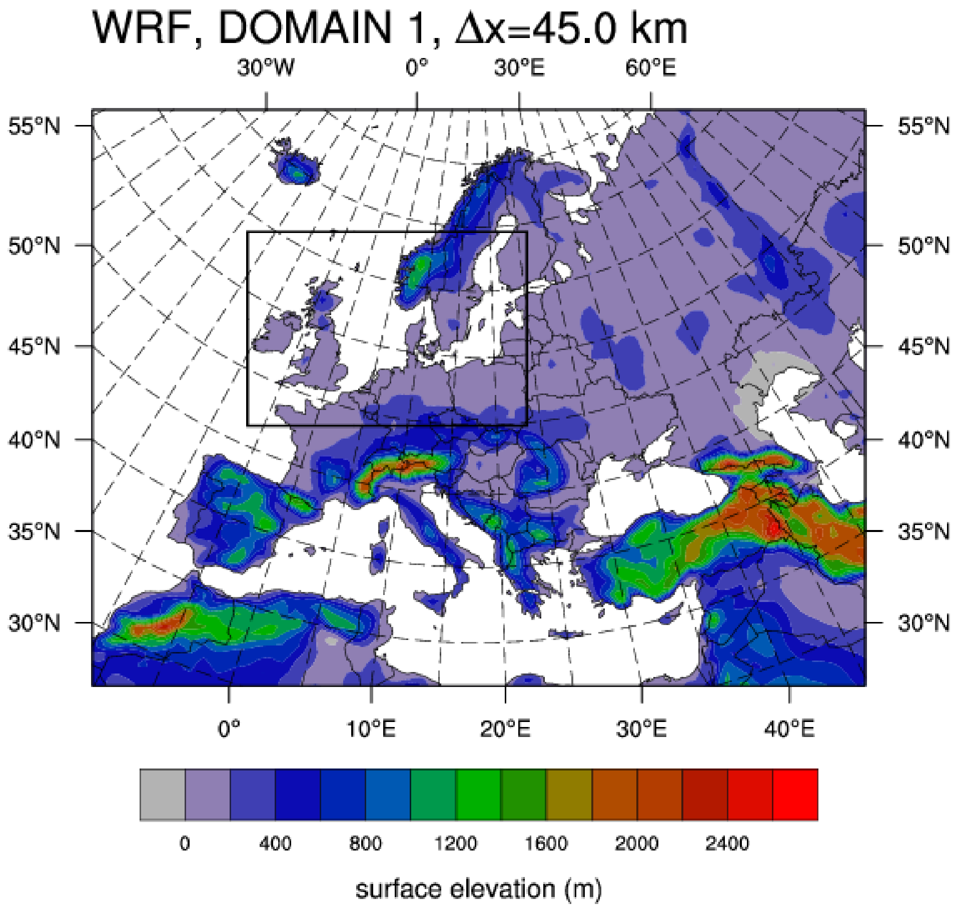
Fuga – a new wake model

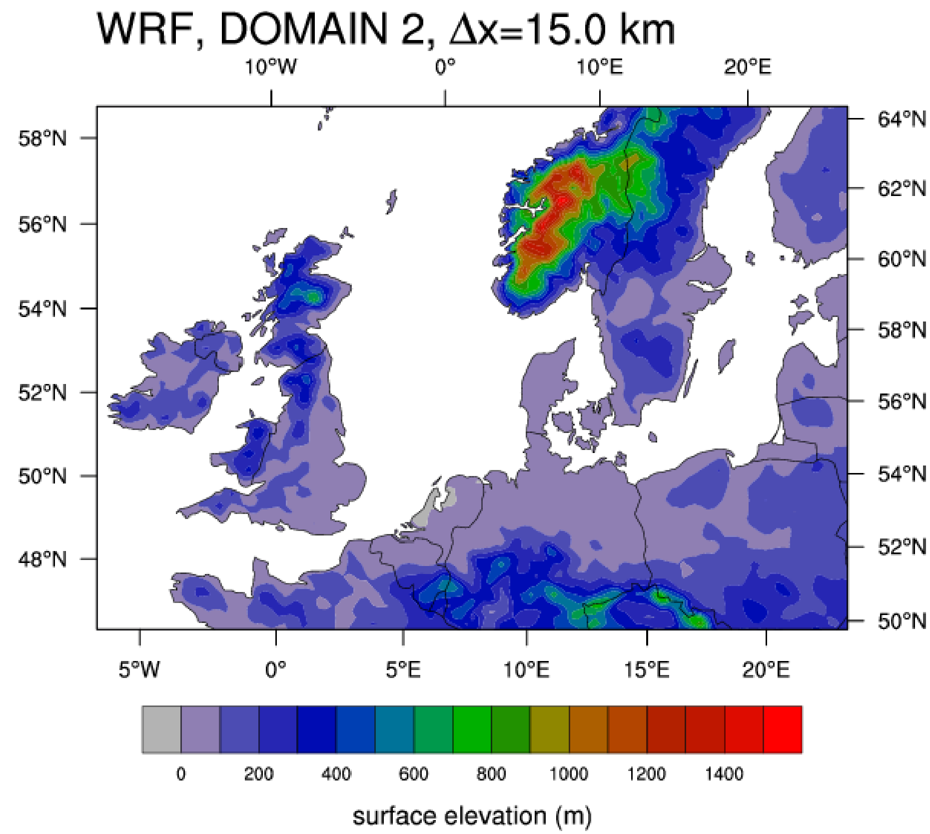
- Linearised CFD
- 10^6 times faster than conventional CFD
- Supported by Carbon Trust
- Useful for all types of optimization



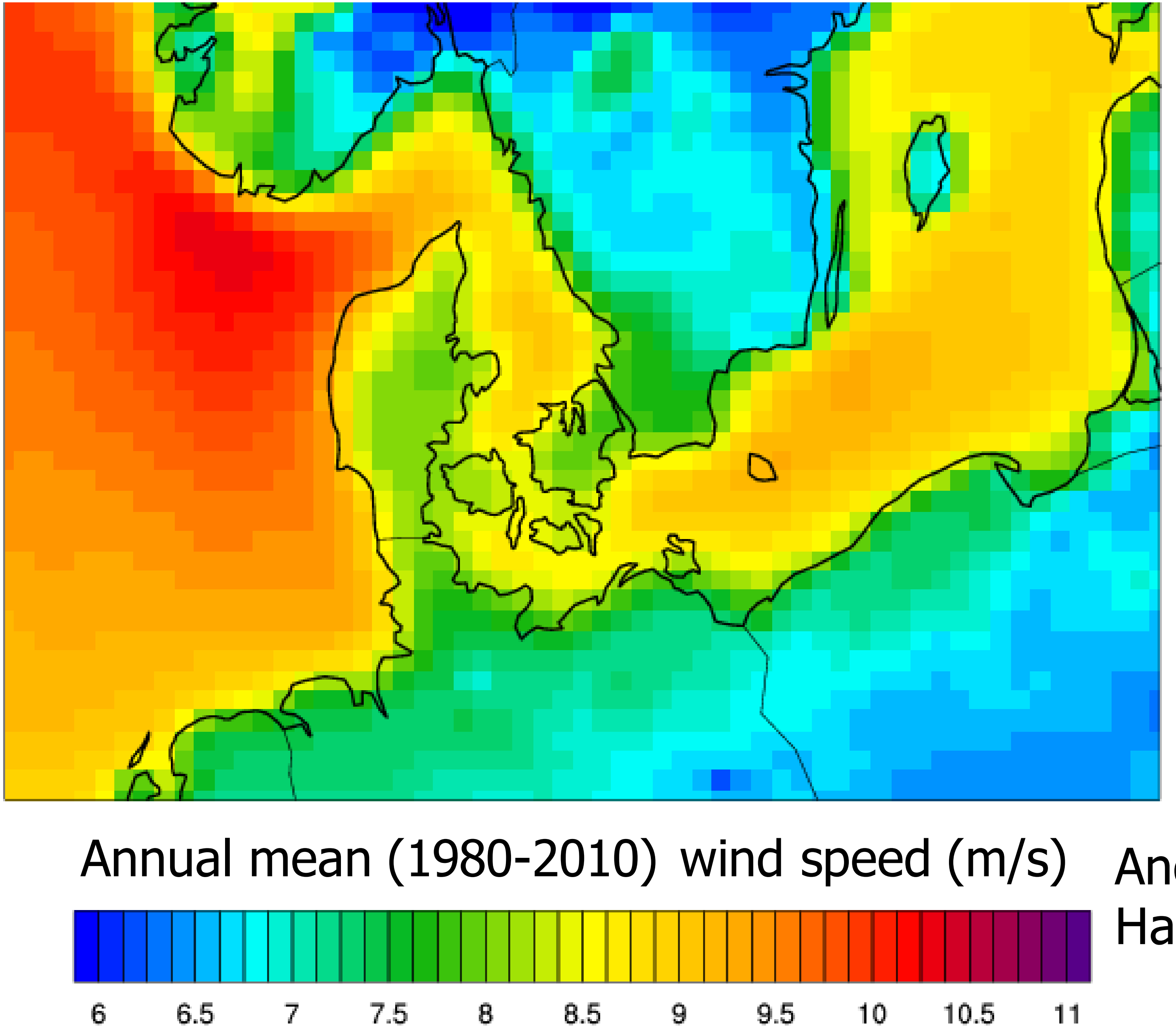


Domain and grid configuration
Polar-stereographic projection



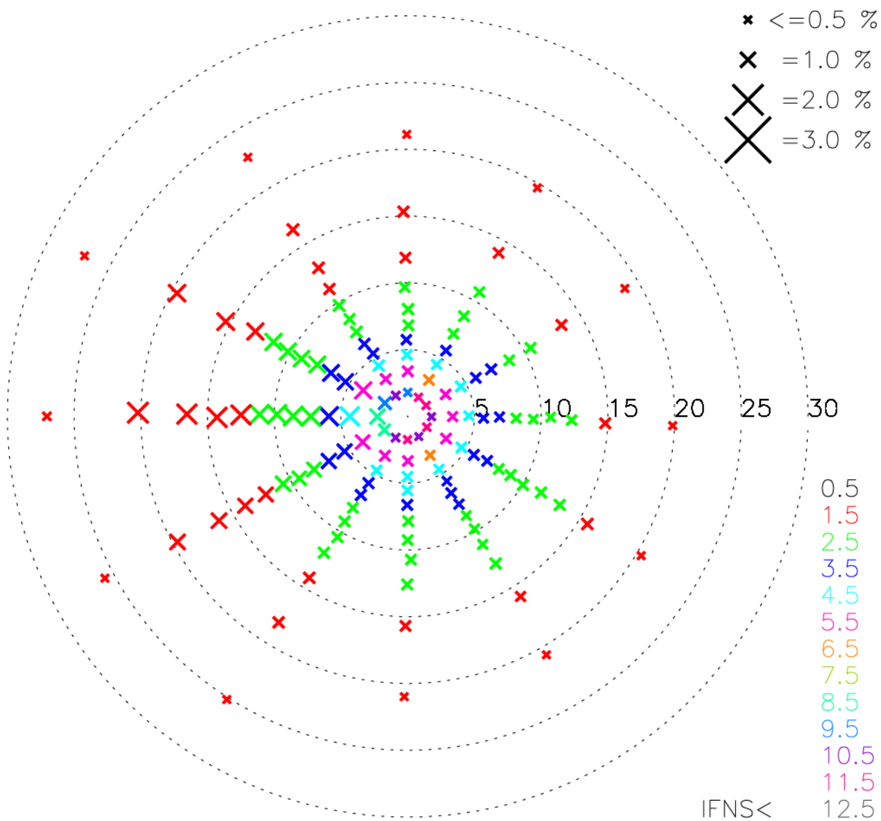


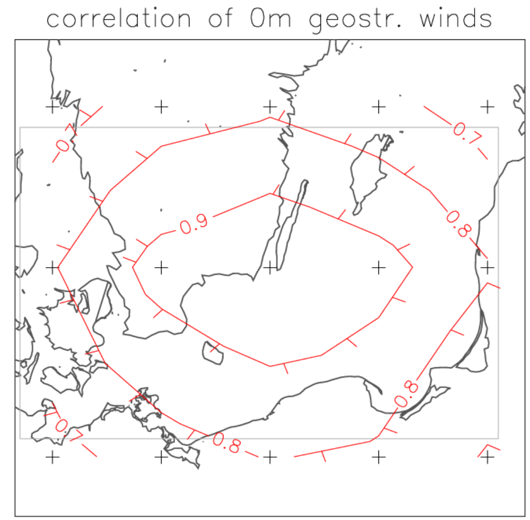
Wind speed generated by WRF – 18 km horizontal resolution



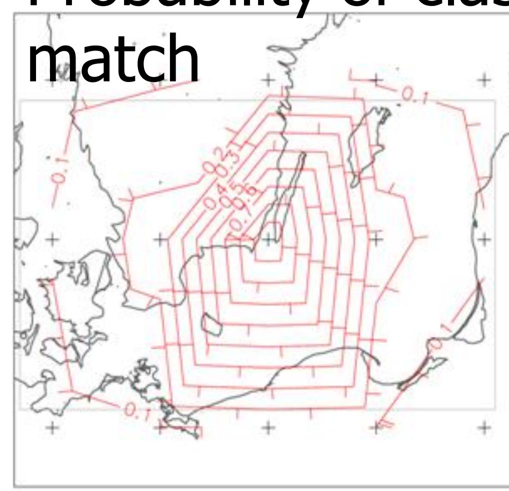
Andrea Hahmann

Wind classes defined using NCEP/NCAR reanalysis geostrophic winds at 16.25E 56.25N at sea level years 1980 – 2009 (30 years)

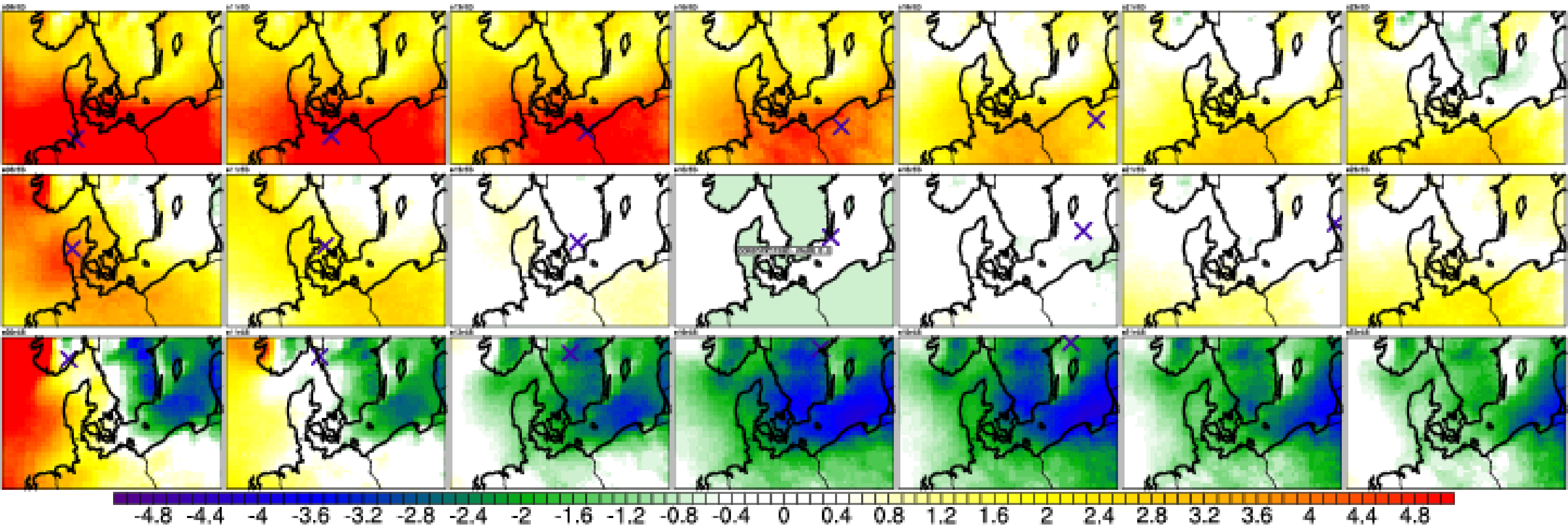




Probability of class match



Variation in annual averaged wind speed due to variations in the frequency of occurrence of wind classes

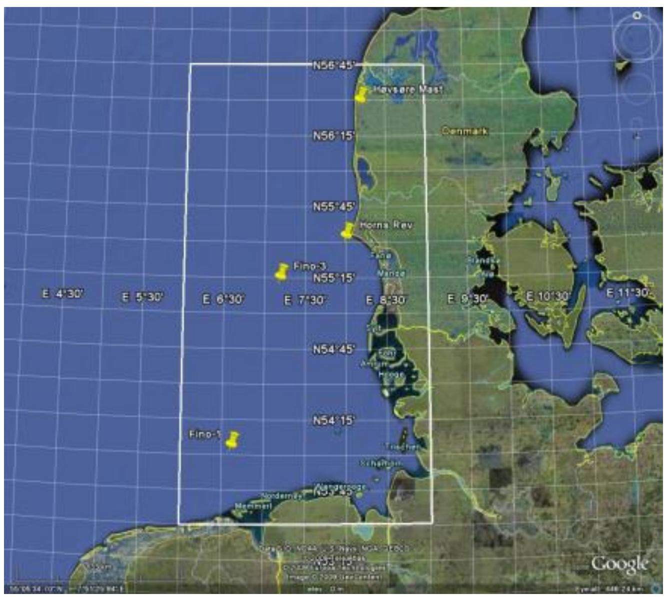


In %

Combine information

- Wind class statistics – weighting function
- Using SAR

Recent results from the North Sea

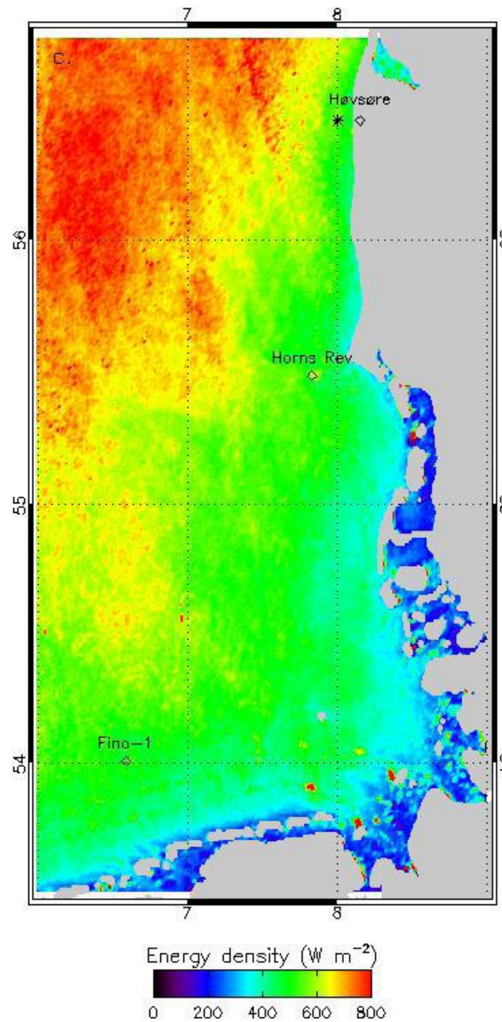


Within±5% for:
Mean wind
Weibull A

Within±7% for: Power density
Weibull k

Mesoscale:
Typical 10 to 15%

Badger, M. et al. 2010



Vertical profiles

- Important for wind power estimates (extrapolating above measurement height).
- Errors are larger as extrapolation distance increases and for lower starting points
- Profile typically <u>not</u> logarithmic
- Causes
  - Roughness changes: wind-wave interactions
  - Mast shadow effects: impacts directional distribution
  - Internal boundary layers: important if fetch < ~ 10 km
  - Atmospheric stability
  - Wave/Ekman layer
  - Not constant flux

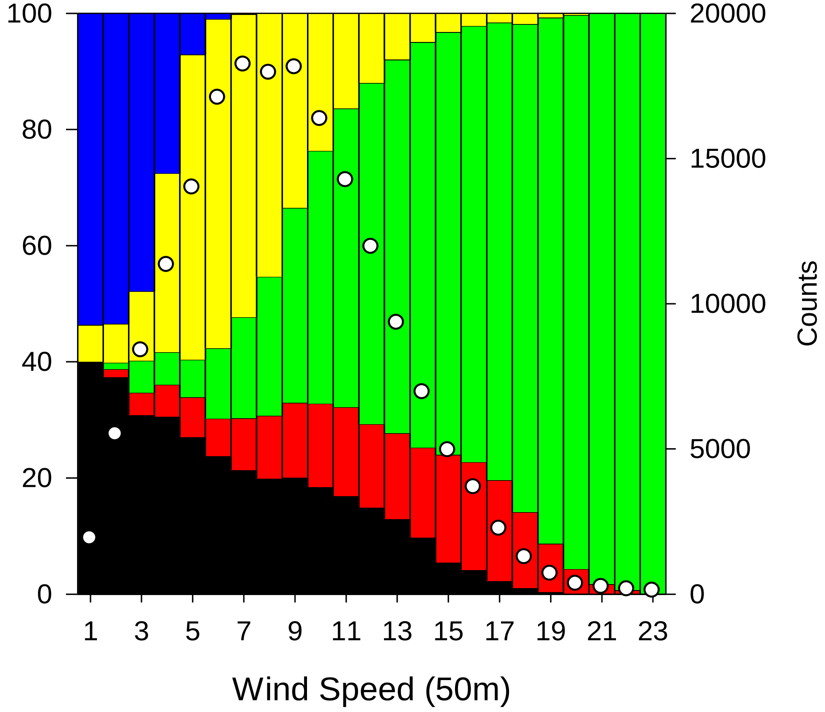
Atmospheric stability

- Calculated using measured temperature difference at two heights
- Extrapolated to 50 m from 10 m observations at Rødsand. Difference from observed (%)

$$U = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right)$$ Log

$$U = \frac{u_*}{k} \left[\ln\left(\frac{z}{z_0}\right) + \Psi\left(\frac{z}{L}\right)\right]$$ Stability

	Log	Stability	WAsP
Wind speed (m/s)	-4%	-0.5%	-1.4%



Ref: Motta Wind Energy, 2005. **8 219**

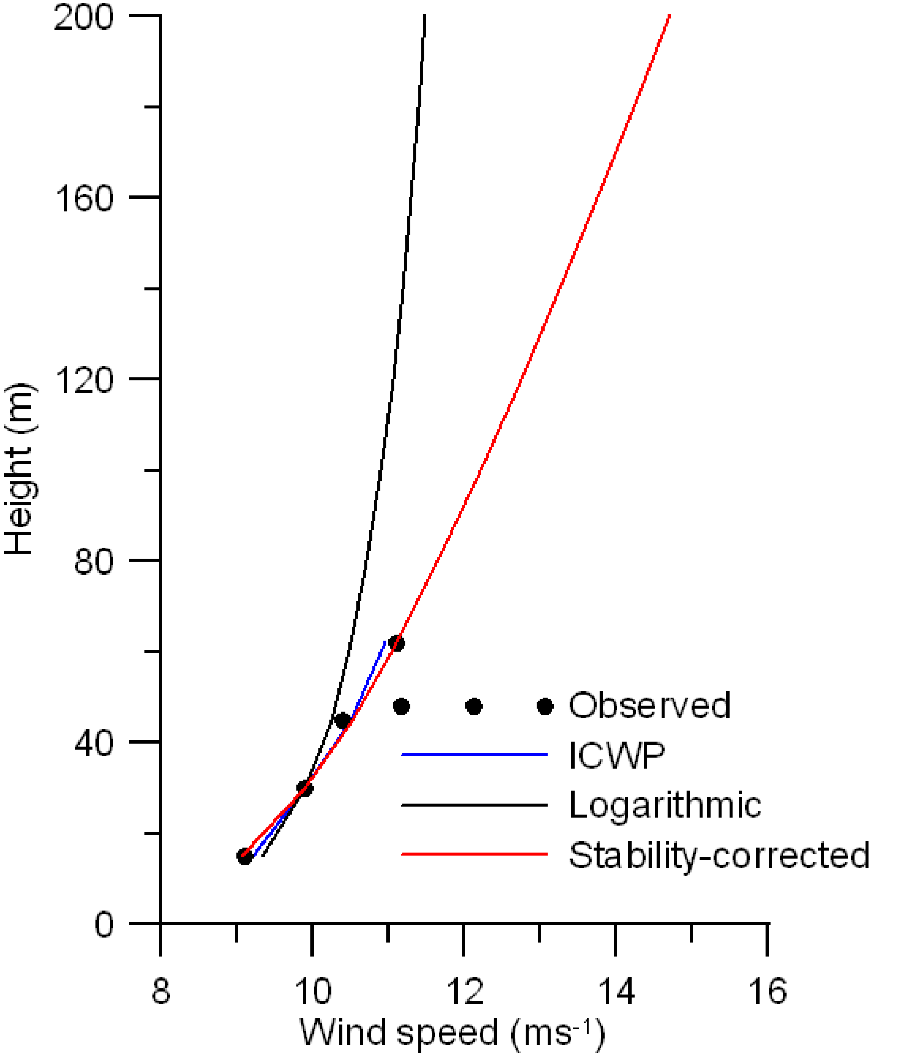
Wind speed profiles

- Use of logarithmic profile worked to heights ~ 50 m
- At hub-heights of 100 m errors are larger
- 3 models:
  1. Constant flux (stability-corrected)
  2. ICWP

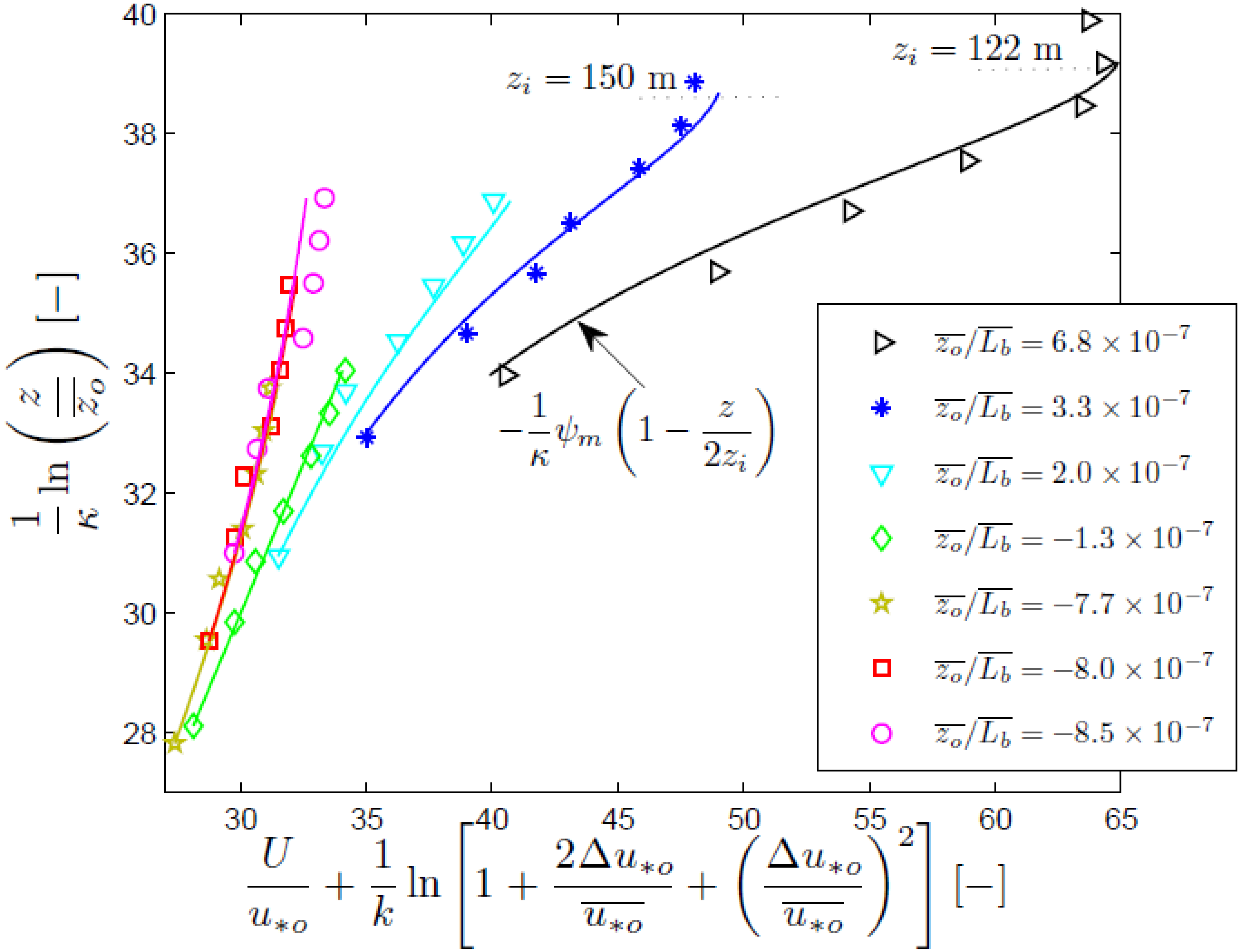
     Ref: Tambke Wind Energy 2005; 8:3–16
  3. Mixed layer depth

     Ref: Pena Bound.-Layer Met 2008 129:479

- Implications:
  - Simple models (log, power law based on surface layer theory) are not appropriate
  - Need to measure as high as possible (pref. to hub-height)

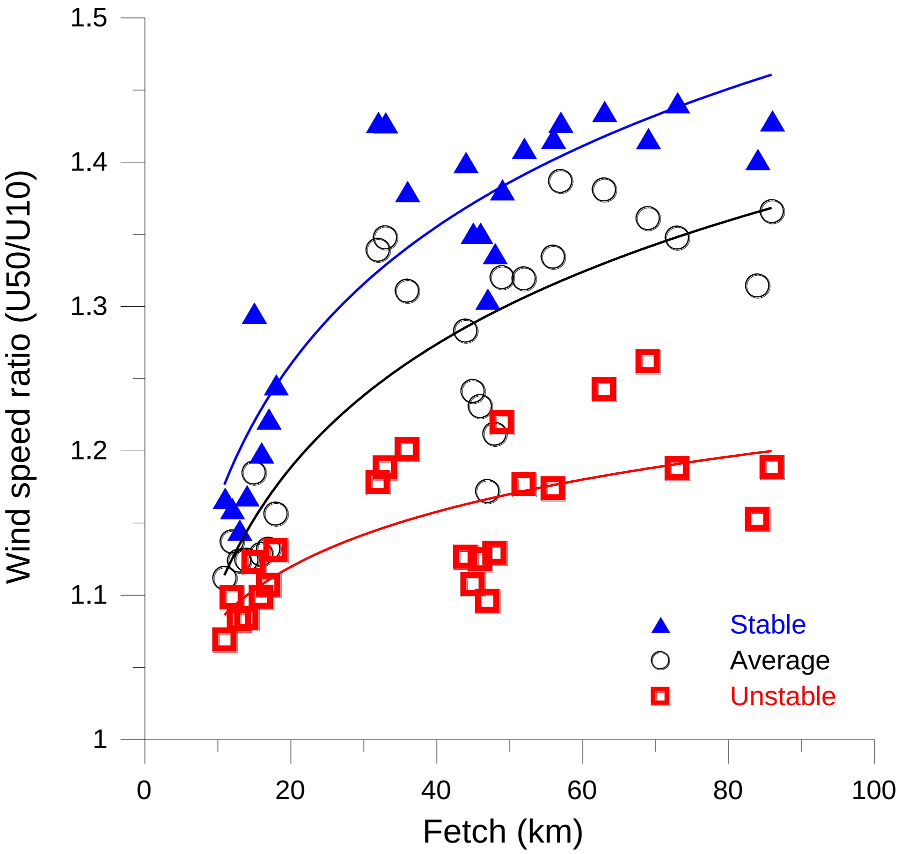


Advanced wind profiles (using stability and inversion heights)



Atmospheric stability impacts

- Lower roughness offshore means stability has a bigger impact
- Wind resource
- Vertical U profiles to 200m
- T.I variability with U and height
- Wake recovery
- Width of the coastal zone/spatial variation over large wind farms
- Persistence and predictability of flow and power

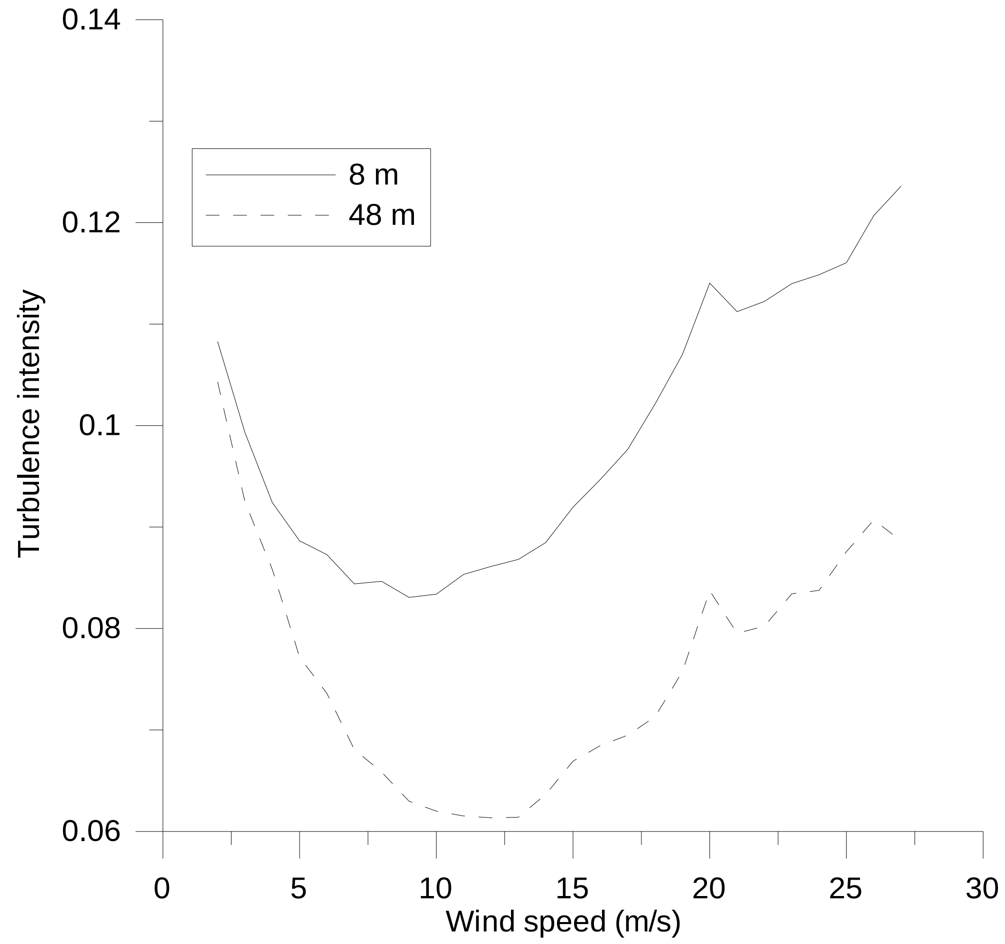


Turbulence intensity offshore

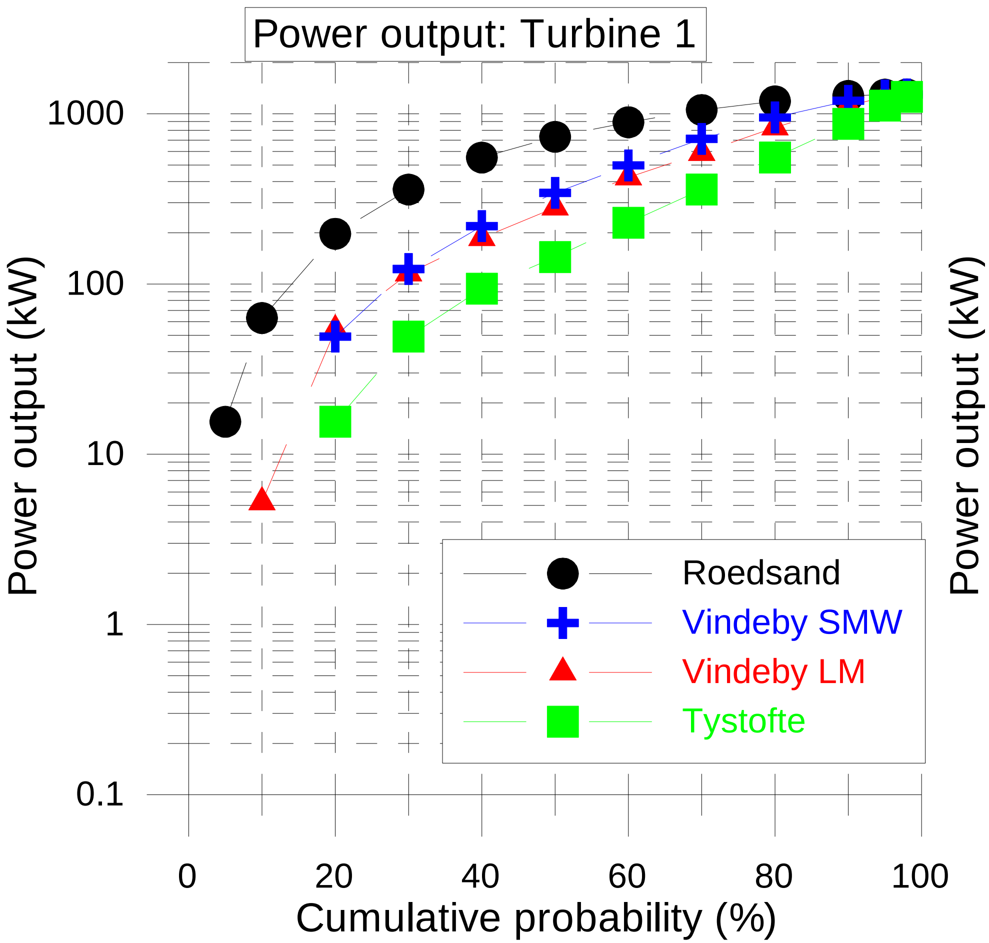
- Important for wakes & loads
- Calculated using standard deviation (so averaging time dependent)

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

- TI min at U = 8-10 m/s
- Decreases approx. linearly with height
- Typical TI:
  - ~10% over land at 50 m
  - 6-8% in offshore regions at ~50 m height
  - Decreases moving offshore (~10-50 km to attain offshore values)



Persistence: Power output



- Wind speeds **above rated are more** frequent and persistent at offshore sites.
- Implications for power quality - significantly fewer hours without power generation offshore; significantly higher probability of greater power output offshore
- Useful in forecasting. Short-term forecast errors tend to be lower.

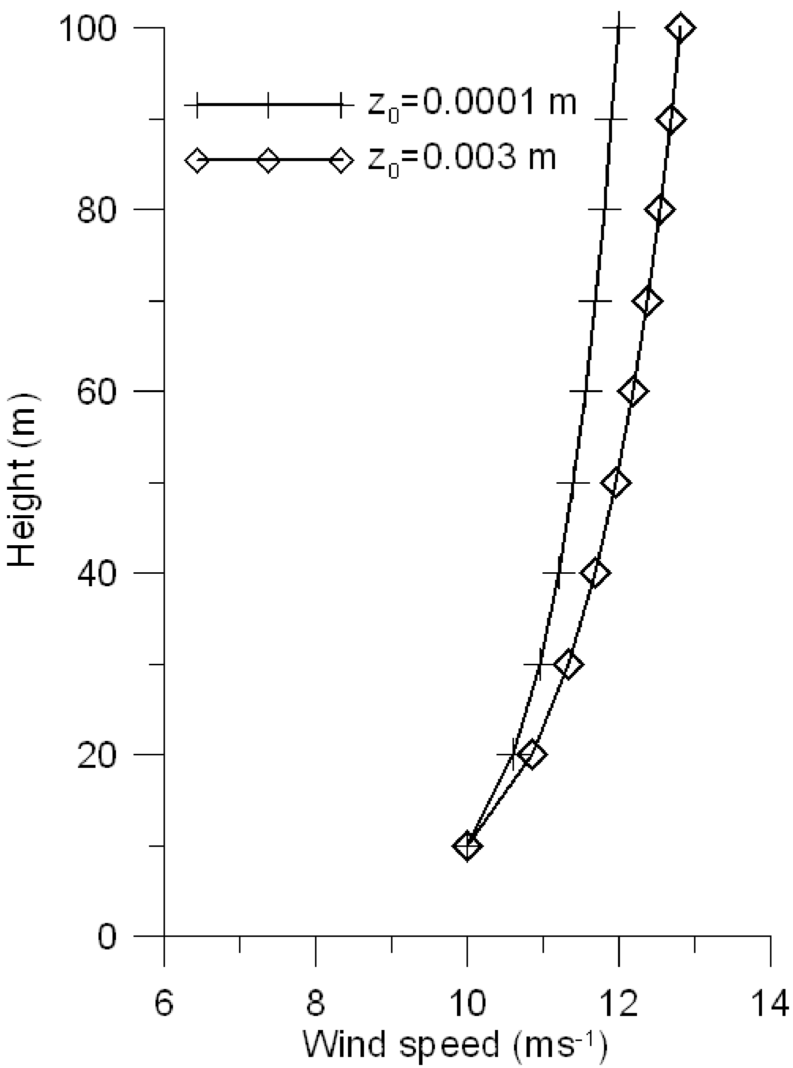
Other impacts on wind resources

- Changes in the surface roughness
  - Waves
  - Currents
  - Tides
  - Ice
- Coastal/offshore phenomena
  - Sea-breeze
  - Low-level jet
  - Roll vortices
- Extreme wind
  - Gusts
  - 50 year return wind
  - Hurricanes/Typhoons

Roughness/Waves

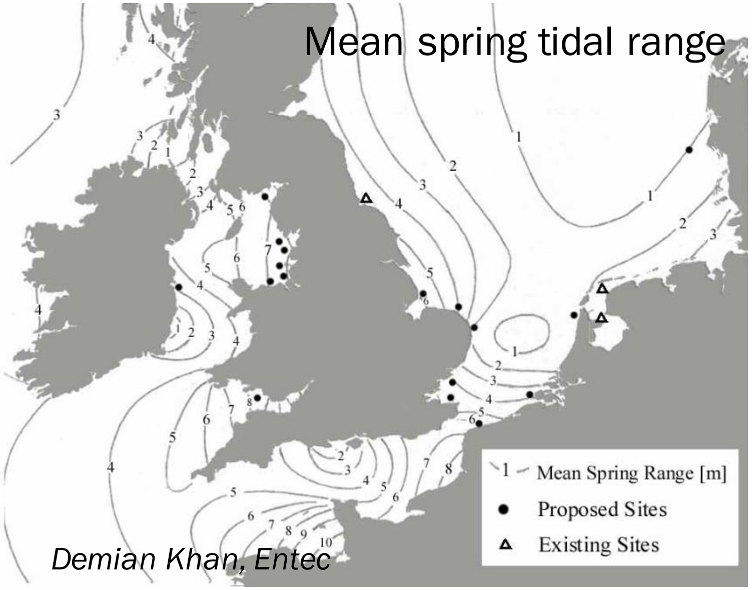
- Important for loads on foundations/tower
- For wind resources, surface roughness of 0.0002 m is usually assumed
- Roughness via Charnock equation: $$z_0 = a\frac{u_*^2}{g}$$
- Even large changes of u_* have a moderate impact on the wind speed profile
  - $u_* = 0.25\ ms^{-1}$, $z_0=0.0001$ m
  - $u_* = 1.25\ ms^{-1}$, $z_0=0.003$ m

- Ref: Barthelmie 2001 Wind Energy 4 99-105



Impact on resources: Tides, ice & currents

- Tidal and ice variations have a small influence on wind resource
- UNLESS areas that were previously water/ice surfaces become exposed (e.g. at low tide)
- Also impacts stability
- Surface changes may be important for other reasons e.g. ice loading on foundations
- Ref: Khan 2003 Wind Engineering 26 287-299



Offshore phenomena

- Sea breezes
  - Low wind speed phenomena
  - Cold sea/warm land
  - Mainly directional changes
  - Ref: Simpson JE, *Sea breeze and local winds. 1994,Cambridge University Press.*
- Low-level jets
  - Stable atmosphere phenomena
  - Frequent in Baltic – average height 600 m
  - High wind speeds, turbulence wind shear
  - Ref: Smedman *Wind Engineering, 1996.* 20: 137.
- Roll vortices
  - Unstable atmosphere phenomena
  - Scale several km
  - Ref: Etling *Boundary-Layer Meteoroloogy, 1993.* 65: 215.

Conclusions

- Predicting long-term resources offshore
  - Requires in situ measurements
  - Uncertainties reduced with longer records
- Vertical wind speed profiles
  - Logarithmic or power law likely inadequate for higher hub-heights
  - New models currently being evaluated
  - Lidar measurements beneficial
  - Limit errors by measuring to hub-height
- Special to offshore?
  - Impacted by atmospheric stability and low/variable roughness
    - Higher persistence
    - Higher wake losses
  - Coastal/offshore phenomena e.g. Sea-breezes