Environmental data for planning and design of offshore wind farms

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Outline

• Introduction and motivation
• Required environmental data as input to design basis documents
• Wind
  - The atmospheric boundary layer (ABL)
  - Atmosphere models
  - Basic differences between oceanic and continental boundary layer
  - Wind measurements
• Waves
  - Wave effects
  - Wave models
  - Wave measurements
• Wind profiles
  - Power law
  - Log wind profile for neutral conditions
  - Wave-atmosphere interaction
  - Extension for stability effects (MOST)
• Other parameters
Extracting power from the wind

• Kinetic energy:

\[ E_{kin} = \frac{1}{2} m v^2 \]

• Mass passing the rotor disk of area A of a turbine at a given wind speed v per second:

\[ m = A \rho v \]

• Power (energy per second) passing the rotor disk:

\[ P = \frac{1}{2} A \rho v^3 \]

Electric output of turbine:

\[ P_{out} = \frac{1}{2} C_p A \rho v^3 \]
Wind energy conversion

Wind energy output

Source: http://glengro.com/wind_energy/energy.html
Extracting power from the wind

- the flow behind one (several) turbines is characterized by:
  - reduced average wind speed
  - increased turbulence level

- both factors affect the performance of the turbines behind negatively:
  - reduced power output
  - increased load and fatigue

- how fast (at which distance behind a turbine/wind park) these effects vanish depends strongly on atmospheric stability
Operation and Maintenance

Wave height
Wave period

Source: Anders Wikborg, Statoil
Why going offshore?

• offshore wind potential is usually higher
  • reduced friction => higher average wind speeds
  • homogeneous conditions (reduced turbulence)?

• matter of space

• land based turbine have come to a size limit due to transportation issues (in particular of the blades)

• limited tip speed for land based turbines (noise issues)

• environmental issues (e.g. danger for birds)

• acceptance problems for land based turbines (noise, shadows, esthetic detraction)
Environmental input to design basis documents

Separate design basis documents are needed for different parts of the work:

- Wind turbine (generator, blades)
- Applicable Standards
- Structural design
- Geotechnical investigation
- Fabrication of the structure
- Construction and installation
- Operation and inspection
- Intervention and maintenance
- Decommissioning
Wind
Global circulation

Source: https://en.wikipedia.org/wiki/Hadley_cell/
Jet stream

Wind Speed at 250 mbar
NCEP GFS 0.25°x0.25°

Thursday, Aug 13, 2015
Daily Average

Source: http://cci-reanalyzer.org/
Low pressure systems

Source: http://cci-reanalyzer.org/
Atmospheric boundary layer
or Planetary boundary layer
Flow over hills/mountains - stability

Froude number: relation between kinetic and potential energy:

\[ Fr = \frac{U}{hN} \]

Brunt-Väisälä frequency:

\[ N = \sqrt{\frac{g}{\theta} \frac{\partial \theta}{\partial z}} \]

Source: Stull, R. B., An Introduction to Boundary Layer Meteorology, 1997
Low level coastal jet

Source: Christakos et al., 2014
Gravity waves

**Figure 6.5:** Available offshore wind profiles, 24-25 April 2009.

Mean wind speed for Vestfjorden

- Mean of 10m wind speed from all Envisat ASAR scenes for Norway (500-1000 per location)
- OpenWind software (available on github)
- Thompson HH-to-VV polarization ratio

4 m/s

11 m/s
Wind stress curl

Wind stress
\[ \tau = \rho \, C_D \, |u| \, u \, e^{i\alpha} \]

\( C_D \) and \( \alpha \) estimated assuming neutral stability

Wind stress curl
\[ k \cdot (\nabla \times \tau) = \frac{d\tau_y}{dx} - \frac{d\tau_x}{dy} \]

Chelton et al. (2004)
Numerical models
HIRLAM (blue) and AROME2,5 (red) are both nested in EC

i.e. receive information on the border from the global model

observations

0 hours
analysis
+6
forecast
+12
......
+66 hours

NORA10

Yr.no + free data
Norwegian Reanalysis NORA10

56 year hindcast based on HIRLAM (left) and WAM (right) on the same 10km grid

**Wind** in 10, 50, 80, 100, 150m every 3rd hour

**Wave** parameters
Verification of NORA10

Significant wave height

Wind speed

Table 5. Anemometer Height, Number of Collocations, Slope of the Linear Regression Line Forced Through 0,0 and Statistics for Comparison of NORA10 With Anemometer Winds at Four Offshore Sites

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>N</th>
<th>RMS (m/s)</th>
<th>Slope a (m/s)</th>
<th>Correlation</th>
<th>Anemometer Mean (m/s)</th>
<th>NORA10 Mean b (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ekofisk A</td>
<td>68</td>
<td>33275</td>
<td>0.93</td>
<td>1.84</td>
<td>0.93</td>
<td>10.1</td>
</tr>
<tr>
<td>Ekofisk B</td>
<td>114</td>
<td>33338</td>
<td>0.95</td>
<td>1.83</td>
<td>0.94</td>
<td>10.2</td>
</tr>
<tr>
<td>Gullfaks C</td>
<td>140</td>
<td>11892</td>
<td>0.93</td>
<td>1.96</td>
<td>0.95</td>
<td>11.4</td>
</tr>
<tr>
<td>FINO-1</td>
<td>100</td>
<td>19013</td>
<td>0.99</td>
<td>1.52</td>
<td>0.94</td>
<td>9.8</td>
</tr>
</tbody>
</table>

a A slope below 1 indicates that NORA10 underestimates compared to the observations.
b NORA10 winds are linearly interpolated from the nearest heights (10, 50, 80, 100, and 150 m) to the sensor heights.

Source: Reistad et al. 2010; Furevik and Haakenstad, 2012
Model winds compared to satellite

Envisat 70m

AROME 2.5km

Varaldsøy
Kvamsøy
Utne
Odda
Vangsnes
Takle

Models often have:
- weak gradients
- weak extremes
- seldom calm
And higher resolution gives poorer verification
Differences of ABL over land and sea

• large differences in the energy balance of land and sea surfaces
  • heat capacity
  • volume on which the energy is distributed
  • heat transport: molecular by heat conduction in soil, advective and turbulent in water
  • different importance of sensible and latent heat flux
  • advection of increased importance

• we have to deal with an non-stationary lower boundary (ocean waves) that depends on the wind speed

• relevant measurements over the ocean are sparse or non-existent
Diurnal course of temperature

Source: http://www.meted.ucar.edu/nwp/model_physics/print.htm
Non-stationary lower boundary
Wind wave interaction

As waves develop, they offer more surface area for the wind to press against (wind stress). Depending on both fetch and time, the size of the waves increases quadratically to a maximum. The energy imparted to the sea increases with the fourth power of the wind speed! As waves develop, they become more rounded and longer and they travel faster. Their maximum size is reached when they travel almost as fast as the wind. A 60 knot storm lasting for 10 hours makes 15 m high waves in open water.

Source: http://www.seafriends.org.nz/oceano/waves.htm
Phase speed of ocean waves

Source: http://hyperphysics.phy-astr.gsu.edu/hbase/waves/watwav2.html
Non-stationary lower boundary
Non-stationary lower boundary

Source: http://www2.warwick.ac.uk/fac/sci/eng/meng/waveenergy/
Wind measurements

Horns reef 2 and 1

Platforms /ships

Oil spill

Atmospheric gravity waves

Airflow around the Norwegian mountains

UK

DK

Envisat ASAR WSM V/V ASCENDING
09-FEB-2011 21:26:21
Winds from offshore installations – Ekofisk

Data available from http://eklima.met.no

Be aware of speed up effects and other disturbances

Source: K. Gjesdal, MET norway
Mean wind speed (54 years) 100m above the sea surface from NORA10

Source: Furevik and Haakenstad (2012)
Norwegian Meteorological Institute
• Ekofisk observations
  * NORA10
  o Radiosonde
Buoys

• Met-ocean buoys

Source:
http://www.imr.no/forskning/forskningsdata/stasjonm/index.html
http://oceanor.no/seawatch/buoys-and-sensor/Seawatch
Waves
Single waves – some definitions

\[ \eta \] – amplitude, wave height \( H = 2a \text{ [m]} \)

\( T \) – period [s], frequency \( f = 1/T \text{ [Hz]} \)

\( \lambda \) – wavelength [m], wavenumber \( k = 2\pi/\lambda \text{ [rad/m]} \)

\( c \) – phase speed (celerity) [m/s]

\( c_g \) – group speed [m/s]

\( h \) or \( d \) – depth [m]
Dispersion: Phase velocity \( c = \frac{\omega}{k} \)

Dispersion relation:
\[
c^2 = \left( \frac{g}{k} \right) \tanh(kh)
\]

Deep-water limit:
\[
\lim_{kh \to \infty} \tanh(kh) = 1 \implies c = \sqrt{\frac{g}{k}}
\]

Shallow-water limit:
\[
\lim_{kh \to 0} \tanh(kh) = kh \implies c = \sqrt{gh}
\]
Multiple waves 1D: superposition of two sinusoids
Particle movement due to deep water waves

The circular motion decrease rapidly with depth

\[ r = a \cdot e^{-k \cdot z} \]

where \( z \) is depth, \( k \) is wave number, and \( a \) is amplitude.

For \( z = \lambda/2 \) we have

\[ r = a \cdot e^{-\pi} \approx 0.04 \cdot a \]

**Example**: The radius has decreased to 4 cm for a wave of 2 m height at \( z = 37 \) m for \( T = 7 \) s or at \( z = 300 \) m for \( T = 20 \) s.

For practical purposes we can neglect the particle motion for \( z > \lambda/2 \).
Wave shoaling

As waves enter shallow water the wave height increases and the wavelength decreases while the frequency remains constant.
Refraction

Bay

Headland

Bay

Isobaths

Orthogonals
Wave spectrum: $F(f, \theta)$
Empirical spectra (2): JONSWAP spectrum for fetch-limited sea, Hasselmann *et al.* (1973)

\[
S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\frac{5}{4} \left(\frac{\omega_p}{\omega}\right)^4\right] \gamma^r
\]

\[
r = \exp\left[-\frac{(\omega - \omega_p)^2}{2 \sigma^2 \omega_p^2}\right]
\]

\[
\alpha = 0.076 \left(\frac{U_{10}^2}{F g}\right)^{0.22}
\]

\[
\omega_p = 22 \left(\frac{g^2}{U_{10} F}\right)^{1/3}
\]

\[
\gamma = 3.3
\]

\[
\sigma = \begin{cases} 
0.07 & \omega \leq \omega_p \\
0.09 & \omega > \omega_p 
\end{cases}
\]
Modern ocean wave prediction systems are based on statistical description of ocean waves (i.e. ensemble average of individual waves).

The sea state is described by the two-dimensional wave spectrum $F(f, \theta)$. 
Wave models

General formulation - The energy balance equation:

\[
\frac{\partial F}{\partial t} + \nabla \left( c_g F \right) = S_{\text{in}} + S_{\text{nl}} + S_d
\]

\(F(f, \theta, \varphi, \lambda, t)\) is the spectral wave energy density
\(f\): frequency, \(\theta\): direction, \(\varphi\): latitude, \(\lambda\): longitude, \(t\): time

\(c_g\) is the group velocity

Source terms:
\(S_{\text{in}}\) the energy input due to wind forcing
\(S_{\text{nl}}\) the non-linear energy transfer between groups of resonant waves
\(S_d\) the dissipation of energy due to whitecapping
Spectral source terms

Rate of growth ($S$)

Energy density ($E$)

$S_{nl}$

$S_{in}$

$S_{ds}$

$E(f)$

met.no WAM.50km SPECTRUM

Position: 59.8N 1.9E Time: 2005-09-01 12:00 UTC (-12)

HMO= 3.0m Tp= 8.4s DDP= 151.5 deg
Ocean Wave Modelling

• For example, the mean variance of the sea surface elevation $\eta$ due to waves is given by:

$$\langle \eta^2 \rangle = \int \int F(f, \theta) df d\theta$$

• The statistical measure for wave height, called the significant wave height ($H_s$):

$$H_{m0} = 4 \sqrt{\langle \eta^2 \rangle}$$

$$\approx H_s$$

The term significant wave height is historical as this value appeared to be well correlated with visual estimates of wave height from experienced observers. It can be shown to correspond to the average $1/3^{rd}$ highest waves ($H_{1/3}$).
Freak waves

DRAUPNER 01.01.1995

26m «New year wave»

Hs: 20-minute average of the sea state: 11.9m
What is $H_s$?
Wave period is important

Havsul offshore wind farm project.
Installation of foundations for a 100m metmast on Skråpen summer 2011

”Skråpen”

• http://www.youtube.com/watch?v=ZobF8-1YxzM
Frequency of occurrence (%)
Fine-mesh wave model
Scatter diagram Hs-Tz (mean period)
Extreme values

• Selecting the highest values – annual maximum

Blocking:
• Annual maximum → AM-model
• $r$-largest order statistic → $r$LOS-model

\[
G(z) = \exp \left\{- \left[1 + \frac{\xi}{\mu} \left(\frac{z - \mu}{\sigma}\right)\right]^{\frac{1}{\xi}} \right\}
\]

Extreme values

- Selecting the highest values – Peaks above a threshold

Extreme values

Results may be sensitive to POT threshold and choice of methods

Figure 4.1: Top: Time series of $H_3$ from NORA10 over the period 1958-2012 at the position 72°N 5°E marked in gray. Peaks-over-threshold (POT) data separated by a minimum of 48 hours with the threshold set at the 97-percentile (green dots), 99.3-percentile (black circles) and 99.7-percentile (red dots). Bottom: Return value plots of the generalized Pareto (GP) (dashed red) and the exponential distribution (EXP) (dashed black) fitted to the different POT-data. Corresponding 100-year return value estimates are given in the legend and indicated by the pink and gray dashed lines, respectively.

Extreme values - Hs

Meteorological buoys

• Buoys measure the vertical acceleration
• Directional buoys also measure the movement in the three directions (heave, pitch and roll)
Directional waverider buoy

1D spectrum
Peak direction
Wave verification

Figure 15: Scatter plots of Hs, Tp, Pdir, Tm02, Tm-10 and energy of SWAN against buoy
Wind profiles
Use of wind profiles

- Extrapolate wind recordings
- Wind shear over rotor
- Wind resources

http://www.nmf.no/default.aspx?pageid=155&articleid=1
Power law expression of wind shear

Simple power law description of the vertical wind shear

\[ u(z) = u_{ref} \left( \frac{z}{z_{ref}} \right)^\alpha \]

- \( u(z) \): wind speed at level \( z \)
- \( u_{ref} \): wind speed at a given reference height
- \( z_{ref} \): reference height
- \( \alpha \): empirical wind shear exponent
Power law expression of wind shear

**Fig. 15.8.** Wind shear exponent for various terrains [4]

Power law expression of wind shear

Fig. 15.7. Vertical profile of the wind speed, calculated with various shear wind exponents

Marine wind profiles

Power law

Stable
\( \alpha = 0.09 \)

neutral
\( \alpha = 0.05 \)

unstable
\( \alpha = 0.04 \)

NORSOK standard

Figure 5. Mean RS wind profiles (solid lines) for stable (circles), near-neutral (asterisks) and unstable (squares) and estimated profiles (dashed lines) based on \( U_0 \) and \( \Delta T \). (left) Estimated mean profiles from the wind power law approximations with the power coefficients given in Table 6 (PL3). (right) Estimated mean profiles using the NORSOK wind profile (N1).
Power law expression of wind shear

![Graphs showing TKE vs. Power law exponent for different wind speed ranges.](Image)
Logarithmic wind profile

Describes the increase of wind speed with altitude for neutral atmospheric conditions

\[
\bar{U} = \frac{u_\ast}{k} \ln \frac{z}{z_0}
\]

\[
\frac{\bar{U}}{u_\ast} = \frac{1}{k} \ln \frac{z}{z_0}
\]

Independent of \( z \) in the surface layer

Source: Stull, R. B., An Introduction to Boundary Layer Meteorology, 1997
Find $z_0$ at wind speed $= 0$

Source: Stull, R. B., An Introduction to Boundary Layer Meteorology, 1997
Charnock relationship

But: \( z_0 \) is not a constant over the ocean!!

Based on dimensional arguments Charnock proposed the following simple relationship that is still most widely used:

\[
z_0 = a \left( \frac{u_*^2}{g} \right)
\]

assumptions:

- winds blowing steadily and long enough for the wave field to be in equilibrium with the wind field
- the surface is aerodynamically rough

the empirical “Charnock constant” \( a \) ranges between 0.01 and 0.035 (typical value 0.018) - depends on wave age \( c/u \)
Wind wave interaction

rather complex as speed and shape of waves are dependent of:
• wave age C/u
• wavelength of the wave
• water depth/vicinity to the shore
in addition wave direction and wind direction are not necessarily the same

<table>
<thead>
<tr>
<th>waves</th>
<th>C/U</th>
<th>C</th>
<th>origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>growing sea</td>
<td>&lt; 0.8</td>
<td>slow</td>
<td>local wind</td>
</tr>
<tr>
<td>young waves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mixed sea</td>
<td>0.8...1.2</td>
<td>fast</td>
<td>distant storms</td>
</tr>
<tr>
<td>mature waves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>swell</td>
<td>&gt; 1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>old waves</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Drag law

from mean wind observations at a standard reference height $z_r$ (typically 10 m) the surface stress can be estimated using the drag relation:

$$\tau_0 = \rho u_*^2 = \rho C_D U_r^2$$

$$u_* = \sqrt{u'w' + v'w'}$$

$\tau_0$: surface stress
$C_D$: dimensionless drag coefficient
$U_r$: wind speed at reference height
$u_*$: friction velocity

Cd depends on wind speed, wave age, reference height, stability

Neutral Drag Coefficient as a function of wind speed

Stability effect on the wind profile

Figure 3.23. Wind speed profiles (i.e. variation with height) for a flat terrain characterised by a roughness length of 0.01 m and for a friction velocity of \((\tau/\rho)^{1/2} = 0.5 \text{ m s}^{-1}\). The three different curves correspond to an atmosphere, which is neutral (has an adiabatic lapse rate), stable or unstable. The stability is expressed in terms of the Monin–Obukhov length (based on Frost, 1975).

Source: Sørensen, B., Renewable Energy, Elsevier Academic Press, 2004
Businger-Dyer relationship

Extension of the logarithmic wind profile to non-neutral conditions

Definition of dimensionless profiles as function of stability

\[
\frac{kz}{u_*} \frac{\partial \bar{U}}{\partial z} \equiv \phi_M = \begin{cases} 
1 + \left( 4.7 \frac{z}{L} \right) & \text{for } \frac{z}{L} > 0 \quad \text{(stable)} \\
1 & \text{for } \frac{z}{L} = 0 \quad \text{(neutral)} \\
\left[ 1 - \left( 15 \frac{z}{L} \right) \right]^{-\frac{1}{4}} & \text{for } \frac{z}{L} < 0 \quad \text{(unstable)}
\end{cases}
\]
Monin-Obukhov length $L$

$$ L = \frac{-\overline{\theta_v} u_*^3}{k g \left( \overline{w'\theta_v'} \right)_s} $$

$$ u_*^2 \equiv \sqrt{u'_w^2 + v'_w^2} = \frac{\tau_{\text{Reynolds}}}{\rho} $$

physical interpretation:

$L > 0$ for negative (downward) surface buoyancy fluxes, i.e. stable stratification

$L < 0$ for positive (upward) surface buoyancy fluxes, i.e. instable stratification
Monin-Obukhov length L

Problem:
Measurements at high towers show, that these wind profiles based on surface-layer theory and Monin-Obukhov scaling are only valid up to ca. 50-80 m

- Need to account for the atmospheric boundary layer height under stable conditions

Literature:
MABL observations (needed)

- Average wind speed
- Wind shear over the rotor disk
- Turbulence intensity

These parameters depend on:
- Synoptic situation
- Temperature stratification
- Underlying ocean wave field
- Proximity to land

The main problem:
- Massive lack of observational data in the relevant altitude range (30-250 m)

Wind profiles are not always increasing with height!

Source: Furevik and Haakenstad (2012)
Polarfront 1999-2009

Mean wind profiles

Model
Rawinsonde

Source: Furevik and Haakenstad (2012)
Available observations – FINO platforms
Cup anemometers

The classical and robust wind measurement method (and at the moment the only “bankable” one)

Typical accuracy of in flow with low turbulence intensity in the order of 0.1 m/s

Known problems/uncertainties:

- Non-zero start up speed (typically 0.3-0.5 m/s)
- Over-speeding in turbulent flow
- Errors in the presence of vertical wind component
- Moving parts; ball bearings
- Subject to icing problems
Flow distortion FINO3

Ratio of 2 identical wind sensors at the same altitude (90 m) at opposite directions of the FINO3 mast

Other parameters
Currents

- In situ measurements
  - Buoys
  - ADCP
- High-frequency (HF) radar network (picture)
- Ocean models
  - Currents (rather large uncertainties in baroclinic currents)
  - Salinity
  - Sea temperature
  - Water level
Turbulence

Natural frequencies
Blades
Tower
Floater

Source: presentations from FG Nielsen and J Reuder, Workshop on times and scales in wind energy, 2014.
Water level important for fixed installations

Boat houses at Sotra after the storm ”Inga”
Norwegian Meteorological Institute