Description and parameterization of turbulence in the marine atmospheric boundary layer

VERITAS TUFFO

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Supervisor

Coordination
Meteorological challenges for offshore wind parks:

- marine atmospheric boundary layer is different:
  - shallow atmospheric boundary layer
  - wind speed-dependent roughness and turbulence
  - wind direction and season-dependent atmospheric stability and turbulence
  - stability-independent vertical gradient of atmospheric humidity

- necessity for reliable wind field models with correct description/parameterization of turbulence
Turbulence

- influences loads on wind turbines (negative)
- influences harvests from wind turbines (positive)
- influences wind park efficiency (positive)
- influences wake lengths behind turbines and wind parks (positive)

more turbulence  less turbulence

VERITAS results
VERITAS (July 1, 2008 to December 31, 2011)

Verification of turbulence parameterization and description of the vertical structure of the maritime atmospheric boundary layer in numerical simulation models for wind analysis and forecast

became work package 5 of OWEA (see sessions 3 and 5 this morning)

investigators:

Richard Foreman M. Sc. (his PhD work, successfully completed Nov 31, 2011)
Prof. Dr. Stefan Emeis

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drag coefficient (neutral thermal stratification)

usual approach:

\[ C_{Dn} = \frac{u^2}{U^2} \]  
(friction velocity over 10 m wind speed)

\[ = \frac{\kappa^2}{\ln^2(z/z_0)} \]  
(over land: logarithmic profile)

\[ C_{Dn} \text{ is function of surface properties only} \]

\[ = \frac{\kappa^2}{\ln^2(gz/\alpha u^2)} \]  
(over sea: Charnock’s relation)

\[ C_{Dn} \text{ depends on wind speed as well} \]

empirically:

\[ C_{D10n} = 0.000063 U_{10} + 0.00061 \]  
(Smith 1980)
no wave data available:

within the fully turbulent regime:

friction velocity:
\[ u_* = 0.051 \, U_{10} - 0.14 \]

input to the definition of \( C_D \):
\[ C_{D_{10n}} = \frac{(0.051 \, U_{10} - 0.14)^2}{U_{10}^2} \]

\[ C_{D_{10n}} = \frac{(C_m \, U_{10} - b)^2}{U_{10}^2} \]

approaches:
\[ C_m^2 = 0.051^2 = 0.0026 \]

for large \( U_{10} \)

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VERITAS result #1

Comparison with data:

<table>
<thead>
<tr>
<th></th>
<th>( C_m )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literatur</td>
<td>0.051</td>
<td>0.14 m/s</td>
</tr>
<tr>
<td>FINO Jan 2005</td>
<td>0.057</td>
<td>0.26 m/s</td>
</tr>
<tr>
<td>FINO Feb 2005</td>
<td>0.042</td>
<td>0.01 m/s</td>
</tr>
<tr>
<td>FINO Nov 2005</td>
<td>0.048</td>
<td>0.02 m/s</td>
</tr>
</tbody>
</table>

\( C_{D10n} \) still depends on wind speed (but at least: \( C_m \) does not)

The plot shows a non-dimensional variable plotted against a dimensional one.
wave data available:

\[ C_{D10n} = a \left( \frac{H_s}{\lambda_p} \right)^2 \]  
(from dimensional analysis)

the drag coefficient should not approach zero for vanishing waves. Therefore a minimum is set:

\[ C_{D10n} = 0.0009 \]  
(smooth surface)

fit between both extremes:

\[ (C^{1/2}_{D10n})^n = 0.03^n + \left( \frac{H_s}{\lambda_p} \right)^n \]

empirically \( n \approx 3 \)

(Churchill and Usagi 1972)
turbulence parameterization in meso-scale wind field models such as MM5 or WRF:

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>A2</th>
<th>B1</th>
<th>B2</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>MY 1982</td>
<td>0.92</td>
<td>0.74</td>
<td>16.6</td>
<td>10.1</td>
<td>0.08</td>
</tr>
<tr>
<td>MYJ 2002</td>
<td>0.660</td>
<td>0.657</td>
<td>11.878</td>
<td>7.227</td>
<td>0.00083</td>
</tr>
<tr>
<td>new</td>
<td>0.91</td>
<td>0.54</td>
<td>28.76</td>
<td>13.08</td>
<td>0.15</td>
</tr>
</tbody>
</table>

plus an adaptation of turbulent length scales following Nakanishi (2001)

new values are based on modern laboratory data
- at very high Reynolds numbers
- with very small velocity sensors close to the wall

VERITAS result #3

comparison of model results with offshore (FINO1) and onshore (Caughey et al. 1979) data

turbulence intensity at 80 m height
February 2005

old                                new
vertical profiles of normalised turb. kin. energy
January 2005

turbulence intensity at 80 m height
November 2005

old                                new
TUFFO idea
TUFFO (August 1, 2011 to July 31, 2014)

Detection and assessment of the impact of turbulent humidity (Feuchte) fluxes on turbulence in offshore wind parks

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humid air is lighter than dry air

sea surface is a perfect humidity source

- near surface air is nearly saturated
- air aloft is less saturated

- less static stability (in 30 to 50% of all cases: humidity profile decides on static stability)
  (Sempreviva and Gryning 1996, Edson et al. 2004)

- more turbulence

- more loads on turbines
- less wake lengths behind turbines and wind parks
new approach in TUFFO:

deployment of high-speed humidity sensors to FINO 1 co-located with ultra-sonic anemometers

- high-resolution humidity data
- turbulent vertical humidity fluxes
- better static stability information

assessment of impact on turbulence at hub height

assessment of impact on wind parks (efficiency, wake lengths)

update of turbulence parameterization in meso-scale wind field models
Summary:

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sea surface drag description

no wave data: sea surface drag flattens off for high wind speeds

with wave data: sea surface drag depends on wave steepness squared

meso-scale wind field models

enhanced turbulence parameterization which gives higher (more realistic) turbulence intensities in the lower part of the atmospheric boundary layer

TUFFO

vertical humidity structure in the marine boundary layer

leads to more unstable static stratification ➔ more turbulence
Thank you very much for your attention