The Influence of Ocean Surface Waves on Offshore Wind Turbine Aerodynamics

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What I’m going to wear today?

Do I need to leave early to get to work? Taking buss or riding bike?

Where will we drink caffe tomorrow after lunch?

What Im going to do in the weekend?
The initial and boundary conditions
An incomplete understanding of atmospheric processes

On average, a five-day weather forecast of today is as reliable as a two-day weather forecast 20 years ago!
Accurate weather forecast

- To protect life and property
- To enhance the global economy
More than 70% of the Earth’s surface is Oceans!

- How the weather forecast models deal with the ocean waves
- Is there any problem with that?
- Can we improve it?
- Wind energy as an example
SMHI

Historic data, measurement, numerical simulations

- Few hours, extrapolate
- Up to 12 hours, extrapolate and simulate
- 12 to 48 hours, extrapolate and simulate
- More than 72 hours, simulate

ECMWF

- The first cell is about $\Delta z = 10\text{ m}$
Surface layer model
- Monin-Obukhov similarity theory
- The turbulent fluxes are constant with height and equal to surface values
The mechanisms for the generation of ABL turbulence.

- Convective boundary layers: turbulence is generated by buoyancy.
- Stable boundary layers: turbulence is suppressed by buoyancy.
- Neutral boundary layer: turbulence is generated by wind shear.
Surface layer model

- The turbulent fluxes are constant with height and equal to surface values
- Monin-Obukhov similarity theory
Aerodynamic roughness
- Over land: is constant (tabulated values)
- Over sea:
  - Low wind regime, scales with kinematic viscosity
  - High wind regime, Charnock relation is used with constant charnock length or provided by a wave model
A wave model requires as initial conditions information describing the state of the sea.

A more critical input is the "forcing" by wind.

Solve the evolution of 2D ocean wave spectrum F, with a source term S.
A wave model requires as initial conditions information describing the state of the sea.
A more critical input is the "forcing" by wind.

Solve the evolution of 2D ocean wave spectrum $F$, with a source term $S$.

The wind input source function, where
Wind-Wave Interactions

- **Wind**
- **Roughness height**
- **Momentum**
- **Wind Stress**
- **Wave**: Surface wave (Growing sea C/U<1.2)

Growing sea is frequent in:
- Coastal region
- Enclosed sea
- High wind

Monin-Obukhov similarity theory
Double-peaked wave spectra
- 22% at the North Atlantic 1
- 11% at the Norwegian Coast 1
- 40% at the Baltic Sea 2

Swell
- Nonlocal waves generated remotely by storms.
- Uniform long waves that can propagate for a relatively long distance with little attenuation.
- May have any direction and velocity, independent of the local wind.

Swell effects

- Harris 1966: (wavetank experiment) wind follow the direction of the wave
- Smedman 1994: (Baltic sea) zero stress
- Donelan 1997: (Surface wave Dynamic Exp.) negative stress
- Drennan 1999: (lake Ontario measurement) near zero stress and some time negative
- Grachev and Fairall 2001: (Pacific Ocean) negative stress 10% of the time
Low level jet

- Smedman 1999, 2003: (Baltic sea measurements)
- Holland et al 1981
- Miller 1999
- Sullivan 2008: (LES),
- Hanley and Belcher 2007 (mixing length simulations)
Wind-Wave Interactions

Wind

Roughness height

Momentum

Wave

Swell
Nonlocal wave
(Decaying sea C/U>1.2)

Decaying sea is frequent in:
- Open oceans

Wind Stress

Monin–Obukhov similarity theory!!

Surface wave
(Growing sea C/U<1.2)
Wind-Wave Interactions

- ABL simulations to investigate
- Swell effect on ABL
- Wave to wind velocity ratio effects
- Wave height to wave length effects
- Validity of MO similarity theory
ABL simulations

- ABL
  - Neutral ABL
  - Fixed driving pressure force ($\rho u^*2/zi$)
  - Wave age ($C/U\approx1.25, 2, 2.5, (C/u*i\approx 45, 60, 90)$
  - No Coriolis force

- LES Solver
  - OpenFOAM 2.1.3, 2nd order spatial and temporal schemes
  - LES with Lagrangian-averaged dynamic Smagorinsky
  - Fixed reference of frame
    - Laplacian moving mesh solver

- Geometry & mesh
  - $(1200 1200 400)$ m
  - $(120 120 50)$ points, $\Delta z_{i+1}=1.044\Delta z_i$
ABL simulations

- **BCs**
  - Periodic in horizontal directions
  - No slip at upper boundary
  - Wall shear stress at lower boundary
  - Using MO locally and instantaneously

- Prescribed wave motion
  - \( \eta(x,t) = a \cos(2\pi(x/\lambda - t/T)) \)
  - Wave length 100 m
  - Wave amplitude 1.6 m, 2.5 m
  - Wave slope \( (2 \pi a/\lambda = 0.1, 0.157) \)

- Swell attenuation is neglected
- Swell aligned with wind
- Unresolved waves are modeled as roughness height \( (z_0 = 0.2 \text{ mm}) \)
ABL simulations

- C/u*i = 45
  - Small effect on ABL
  - Weak coupling in w-velocity
    - + w at crest leeward, - w at downward

- C/u*i = 60
  - Stronger coupling
  - Higher streamwise velocity

- C/u*i = 90
  - Very strong coupling
  - Higher velocity near the surface than at the bulk of ABL
ABL simulations

- Non breaking swells propagate in wind directions
  - Increases wind velocity
  - Wind velocity increase with
    - wave age increase
    - wave slope increase
  - Wind velocity profiles deviate from logarithmic shape at high wave age

- Geostrophic balance
  - wind $\uparrow$
  - Pressure gradient Fixed
  - Coriolis force Zero
  - Wind stress $\downarrow$

C/u*i = 45  C/u*i = 60  C/u*i = 90
Time- and horizontal normalized averaged velocity
ABL simulations

- Total surface stress
  \[ \tau_{\text{tot}} = \tau_{\text{viscous}} + \tau_{\text{turbulent}} + \tau_{\text{wave}} \]
- Wave induce stress
  \[ \tau_{\text{wave}} = \frac{1}{\lambda} \int_{-\infty}^{\infty} \delta \left( \frac{d\eta}{dx} \right) \, dx \]
- Total surface stress
  - Decrease with wave velocity and/or wave slope increase
  - Can be negative, i.e. from wave to wind (accelerate the surface wind)

Time- and horizontal averaged normalized total shear stress

C/u*i = 45
C/u*i = 60
C/u*i = 90
ABL simulations

- Total surface stress decreases
- Velocity gradient decreases
- Less mechanical generated turbulent
- Less turbulent intensity

C/U=1.25
C/U=2.5
C/U=2

Time- and horizontal averaged turbulent intensity
Wind-Wave Interactions

- ABL + WT simulations to investigate
  - WT wake strength
  - WT wake length
  - WT power productions
ABL + WT Simulations

- NREL 5MW turbine
  - 126m Diameter
  - 90m hub-height
  - Actuator Line
  - 40 points/blade

\[
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = -2\varepsilon_{ijk} \Omega_j \bar{u}_k - \frac{\partial \bar{p}^D}{\partial x_i} - \frac{\partial}{\partial x_i} \left( R^D \right) + \left( \frac{\rho_b}{\rho_0} - 1 \right) g_i - \left( \frac{\partial p}{\partial x_i} \right) + f_i
\]
ABL + WT Simulations

- ABL + WT
  - Neutral ABL
  - Wave age (C/U ≈ 2, 2.5)
  - No Coriolis force

- Geometry & mesh
  - (2100 1200 400) m
  - (290 180 100) points
  - Turbine @ (x=600, y=600)
  - 40 points/ turbine radius

- Inlet: from ABL simulations
- Outlet: zero gradient
- Sides: periodic
- Bottom: moving mesh with wall shear stress
- Top: no slip
ABL + WT simulations

- C/U=2
  - Higher velocity upwind and downwind the WT

- C/U=2.5
  - Higher velocity upwind and downwind the WT
  - The WT wake shifted upward

- Instantaneous velocity normalized by U_calm
  - sea @ 400
Summary

- Swell moving in wind direction
  - ABL simulations
    - Decrease wind stress (can even be negative)
    - Increase wind velocity
    - Decrease wind vertical gradient
    - Decrease turbulent intensity
  - Swells effects increase by
    - Increasing wave age
    - Increasing wave slope
  - The validation of MO depend on
    - Wave age
    - Wave slope

- ABL + WT simulations
  - Higher velocity both in upwind and downwind the WT
  - In high wave age case wake flow extends to longer WT downwind distance
  - Slower deficit recovery
  - Lower turbulent intensity in near wake but higher near the surface in far wake
  - Higher power productions
How to explicitly model Do
- Moving reference of frame
- Buoyant solve, Boussinesq approximation, TKE
- Geostrophic balance terms
- Modify GenEddyVisc, add variable length scale \( f(\text{stability}) \)
- Modify oneEqEddy, add buoyant term, add variable Prt
- Change the surface stress model, \( f(\text{stability}) \)