Wake properties and power output of very large wind farms for different meteorological conditions and turbine spacings: A large-eddy simulation case study for the German Bight

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Motivation
Questions

• How does very large wind farms affect the boundary layer flow?
• How does the power output of very large wind farms depend on the turbine spacing and the meteorological conditions?
Setup and domain layout

- LES-model: PALM
- Wind turbines: 1063 / 2088
- Initialization: precursor run
- Roughness length: 1 mm
- Grid spacing: 20 m
- Grid points: 7.4 billion
- Simulated time: 10 h (6 h + 4 h)
- CPU time: 24 – 50 h
- Cores: 5120

- The work was supported by the North-German Supercomputing Alliance HLRN
- IEA 15 MW reference wind turbine
  - $D = 240\,\text{m}$
  - $z_{\text{hub}} = 150\,\text{m}$

- Wind turbine model in PALM
  - Actuator disc model
  - Including wake rotation

https://www.nrel.gov/news/program/2020/images/15-mw-reference-social-media.jpg
## Simulation overview

| short name      | Surface heating rate | Boundary layer height | turbine spacing (power density) |
|-----------------|----------------------|------------------------|---------------------------------|
| NBL_700_7D      | 0.00 K/h             | 700 m                  | 7D (5.3 MW/km²)                 |
| NBL_700_5D      | 0.00 K/h             | 700 m                  | 5D (10.4 MW/km²)                |
| CBL_700_7D      | 0.05 K/h             | 700 m                  | 7D (5.3 MW/km²)                 |
| CBL_1400_7D     | 0.025 K/h            | 1400 m                 | 7D (5.3 MW/km²)                 |
| SBL_300_7D      | -0.05 K/h            | 300 m                  | 7 D (5.3 MW/km²)                |

**Neutral boundary layer (NBL):**
Variation of turbine spacing

**Convective boundary layer (CBL):**
Variation of boundary layer (BL) height

**Stable boundary layer (SBL):**
Inflow profiles

- Wind speed (m/s)
- Wind direction (degrees), clockwise positive
- Potential temperature (K)

Hub height

NBL 700, CBL 700, CBL 1400, SBL 300
Ro = \frac{v_h}{L \ast f_c} \approx \frac{10 \frac{m}{s}}{100 \text{ km} \cdot 10^{-4} \text{s}^{-1}} = 1
NBL: Variation of turbine spacing

\[ Ro = \frac{u_h}{L \cdot f_c} \approx \frac{10 \text{ m/s}}{100 \text{ km} \cdot 10^{-4} \text{s}^{-1}} = 1 \]
NBL: Variation of turbine spacing

NBL_700_7D, $y = 120$ km

NBL_700_5D, $y = 120$ km
Turbulence intensity in the wake

NBL_700_7D, $z = 150$ m
Instantaneous vertical velocity

NBL_700_7D, z = 150 m

Vertical wind speed $w$ (m s$^{-1}$)
CBL: Variation of boundary layer height
SBL: Gravity waves in the free atmosphere
SBL: Entrainment of warm air, surface heat flux

SBL_300_7D, z = 150 m

SBL_300_7D
Power output: Comparison between small and large wind farms
Wind turbine power output

- Load factor = Mean turbine power / first row turbine power
Load factors: Wind farm size

- Load factor = Mean turbine power / first row turbine power
Load factors: Turbine spacing

- Small wind farm (N-1): 0.87 (-11 %)
- Large wind farm (Zone 3): 0.58 (-29 %)

NBL_700_7D  NBL_700_5D
Load factors: Boundary layer height

- Small wind farm (N-1)
  - CBL_700_7D: 0.87
  - CBL_1400_7D: 0.90

- Large wind farm (Zone 3)
  - SBL_300_7D: 0.84
  - CBL_1400_7D: 0.65

- Increase:
  - +3 % for CBL_700_7D
  - +18 % for CBL_1400_7D
Turbulent vertical kinetic energy flux
Energy input by pressure gradient force

- Pressure gradient force
- Wind velocity
- Friction
- Coriolis force
- Geostrophic component
- Ageostrophic component

CBL_700_7D, y = 120 km

- Pressure gradient
- Turbines

Work done by pressure gradient (W m$^{-2}$)

Power density (W m$^{-2}$)
Energy source model

Free atmosphere

Inversion layer (no influx)

Boundary layer

Energy input by pressure gradient
\( \sim 2 \text{ W m}^{-2} \)

Vertical turbulent kinetic energy flux
\( \sim 5 \text{ W m}^{-2} \) \( \rightarrow \) \( \sim 2 \text{ W m}^{-2} \)

Wind farm (energy extraction + dissipation)
\( \sim 5 \text{ W m}^{-2} \) \( \rightarrow \) \(< 2 \text{ W m}^{-2} \)

Horizontal influx of kinetic energy
\( \sim 500 \text{ W m}^{-2} \)
Conclusions

• How does very large wind farms affect the boundary layer flow?
  • All cases:
    • Boundary layer growth due to flow deceleration and mass flow conservation
    • Counterclockwise wake deflection due to reduced Coriolis force
    • Long wake (> 100 km) in terms of speed deficit, but short (~ 10 km) in terms of turbulence intensity
    • Stronger speed deficit for shallower boundary layers
  • SBL:
    • Short wake, wind speed in far wake is even higher than inflow wind speed
    • Excitation of gravity waves in the free atmosphere
    • Entrainment of warm air into the boundary layer
    • Modified surface heat flux

• How does the power output of very large wind farms depend on the turbine spacing and the meteorological conditions?
  • Mean turbine power (load factor) of large wind farms is much smaller than that of small wind farms.
  • Smaller turbine spacing leads to strong reduction of the load factor.
  • The boundary layer height has a significant influence on the load factor.
  • Main energy source for very large wind farms is the energy input by the pressure gradient.
  • Wake deflection to lower pressure enhances energy input by pressure gradient.