The hidden dynamics of air and water in Next-Generation offshore wind farms

Interaction of atmospheric boundary layers and oceanic mixed layers with very large turbines in offshore wind farms

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In Short

- Large offshore wind farm
- Atmosphere ocean coupling
- Mesoscale wake effects and interaction between atmosphere and ocean
- The PALM model system
- German Bight

Offshore wind energy is a central element of the European strategy to achieve energy independence and climate neutrality. As part of this objective, Germany is planning to significantly increase the installed offshore capacity in the german bight to 70 GW by 2045. In order to ensure the safe, economical, system friendly and ecologically compatible operation of the planned wind farm clusters a comprehensive understanding of their interaction with the atmosphere and the ocean becomes crucial. It requires a thorough characterization and modeling of challenging atmospheric conditions to identify potential stress situations that will become important due to the huge diameter of future wind turbine rotors. Currently, the interactions of these large wind farms in the atmospheric and oceanic boundary layer are not sufficiently studied and understood, to avoid potential overloads.

So far, the interactions between wind turbines and the atmospheric boundary layer have been analyzed in numerous scientific studies using various methodological approaches. Most publications focus on investigating interactions between a single turbine or small wind farms and the atmospheric boundary layer [1]. With the increasing importance of wind energy and the planning of large-scale offshore wind farms, the first studies of large wind farms and their influence on the atmospheric boundary layer were carried out. It has been shown by Maas, 2023 [2] that above a certain wind farm size, mesoscale effects occur in the atmospheric boundary layer that are not observable for smaller wind farms. Recently, in the ocean Reynolds-Averaged Navier-Stokes (RANS) simulations by Christiansen, et. al, 2023 [3] indicated that the additional drag of the foundation of wind turbines has an impact on the far wake field in the ocean. So far, these numerical studies have focused either on the atmosphere or the ocean. As this field of research is still at an early stage, the impact of large offshore wind farms on atmospheric and ocean currents as a coupled system is still unexplored.

Applying Large Eddy Simulations (LES) to carry out high-resolution, coupled atmosphere and oceanic would allow a more accurate study on the influence of the individual turbines and inner wind farm wakes and provide an insight into the combined effects of wind turbine structures above and below the sea surface. In the proposed study we focus on the following research questions:

- At what wind farm size do mesoscale atmospheric effects lead to relevant changes that must be taken into account in wind farm planning?
- How large is the effect of wind farms substructures on the ocean currents?
- Which effects can be observed interacting between the atmosphere and the ocean within and in the wake of a large wind farm?

For this we will use the LES Model System PALM. PALM is an advanced meteorological LES model for atmospheric and oceanic boundary layer flows with an embedded rotating actuator disc method that allows direct feedback on the flow [4].

At first the isolated effects on atmosphere and ocean will be investigated by running uncoupled simulations under different meteorological conditions. The first atmospheric setup will focus on a multi gigawatt wind farm in conventionally neutral boundary layer, i.e. with a neutral stratification and a capping inversion at 700 m, driven by a geostrophic wind. The second consists a convective boundary layer by heating the surface. To quantify the mesoscale effects, the incoming wind and the wind turbine placements will be varied and compared with previous work of Maas, 2023 [2]. After that a reference wind farm, located in the german bight at (55.25 °N, 4.75 °E), will be simulated. Next, PALM will be run in ocean mode to simulate the

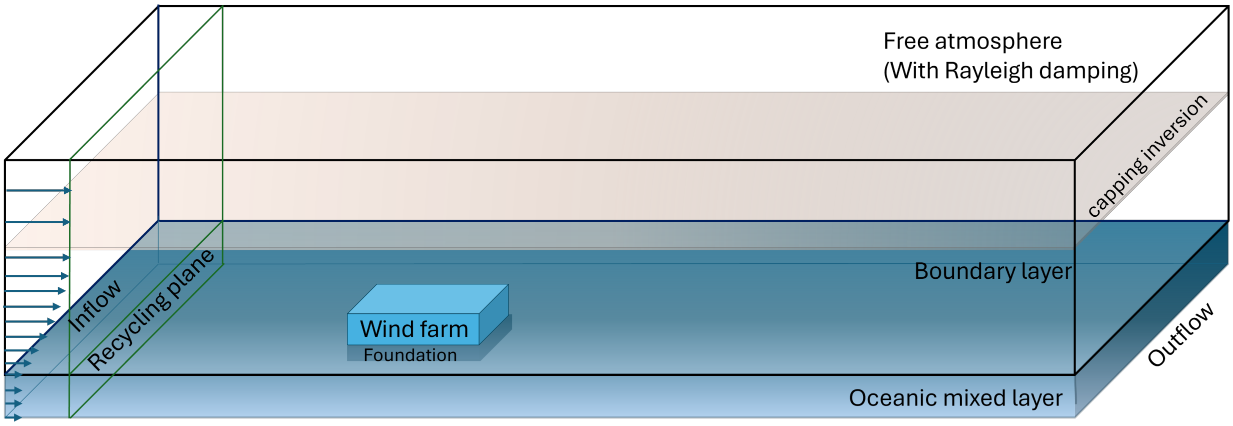

Figure 1: *Setup of the coupled atmospheric-ocean mode. It includes the inflow on the left as well as a turbulence recycling plane. The height is zero at sea surface. Negative values indicate the depth in the ocean layer. There is a capping inversion to limit the boundary layer height. To avoid reflection of gravity waves at the domain top, there is a Rayleigh damping layer above in the free atmosphere. The domain size is variable for each specific setup. Note that the horizontal area of the atmosphere and the ocean has to be equal.*

wake flow of the substructures of the wind turbines. Stokes drift and wave breaking will be considered. Moreover the wave model SWAN is coupled to have more realistic results. The horizontal area of the ocean will be the same as the atmospheric setup. The results will be evaluated regarding wake effects found in literature, such as changes in temperature and salinity distribution and impacts on hydrodynamic.

The last setup will combine the atmospheric and oceanic flow systems via the two-way coupling mode in PALM (see Figure 1). This means that wake effects from the atmosphere (e.g. flow deceleration and deflection inside the wind farm) can propagate into the ocean and vice versa. The planned simulation require a large amount of computational resources. Due to the fact that turbulent eddies in the ocean are smaller than in the atmosphere, the resolution of the ocean must be high enough to resolve the mixing flow and the turbulent fluxes accurately. For this purpose, a large amount of processor cores, memory and computing time is required, which can only be realized by the NHR-system.

WWW

https://www.meteo.uni-hannover.de/en/

More Information

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[3] N. Christiansen, et. al, *Frontiers in Marine Science* **10**, 2296-7745 (2023). doi: 10.3389/fmars.2023.1178330

[4] B. Maronga, et. al, *Geoscientific Model Development.* **13**, (2020). doi:10.5194/gmd-13-1335-2020

[5] Model description https://palm.muk.uni-hannover.de or https://docs.palm-model.org

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