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The effects of boundary layer height and Ekman Spiral on wakes within CFD simulations of offshore wind farms

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Abstract

Computational Fluid Dynamics (CFD) simulations are made of the Nysted offshore wind farm using a transient Unsteady Reynolds-Averaged Navier-Stokes (URANS) model. A thermally stratified capping boundary layer is included, with its height varied between simulations. Each URANS simulation is compared to an identical simulation which also incorporates the Ekman Spiral via a Coriolis parameter. Comparisons against field data show including the Coriolis parameter increases simulation accuracy and deep array effects, whilst the inclusion of the thermal capping layer highlights the need to measure atmospheric parameters above the turbine heights.

Objectives

The objective of this study was to asses the significance to which the Coriolis effect and the height of a stably stratified thermal capping layer effect turbine wakes and their dissipation behaviour within CFD simulations of large offshore wind farms.

Methods

Using the software package Ansys CFX, driven by the Windmodeller set of tools, a number of URANS simulations of the Nysted offshore wind farm were conducted using standard values for constants in the k-ε turbulence equations. Actuator discs represented each of the 72 wind turbines. Measured power production and SCADA data from the farm were available for validation, corresponding to the dates December 2006 to November 2007. To ensure significant wake losses were observed, this investigation only considered events corresponding to high values of turbine thrust coefficient directly along a line of turbines. Thus wind speeds and directions of 8 ± 0.5m/s and $278\pm2.5^{\circ}$ were used. Each row of 8 turbines was considered independently from the rest of the farm with 10-minute events removed if any turbines appeared to be stationary during that period. The most northerly and southerly rows were also ignored to mitigate any bias from possible farm edge effects. The farm layout can be seen in figure 1 below.

Three scenarios with different capping layer heights were simulated. Case A had no capping layer, simulating a neutral stratification in the lowest 1km of the atmosphere, and the most analogous to more traditional RANS simulations. Case B calculated the capping layer height using techniques developed by reference [1] which roughly equates to 300m. Case C incorporated the capping layer at half the height used in Case B and is roughly 150m above the domain floor. The three thermal profiles simulated in this study are shown below in figure 2.

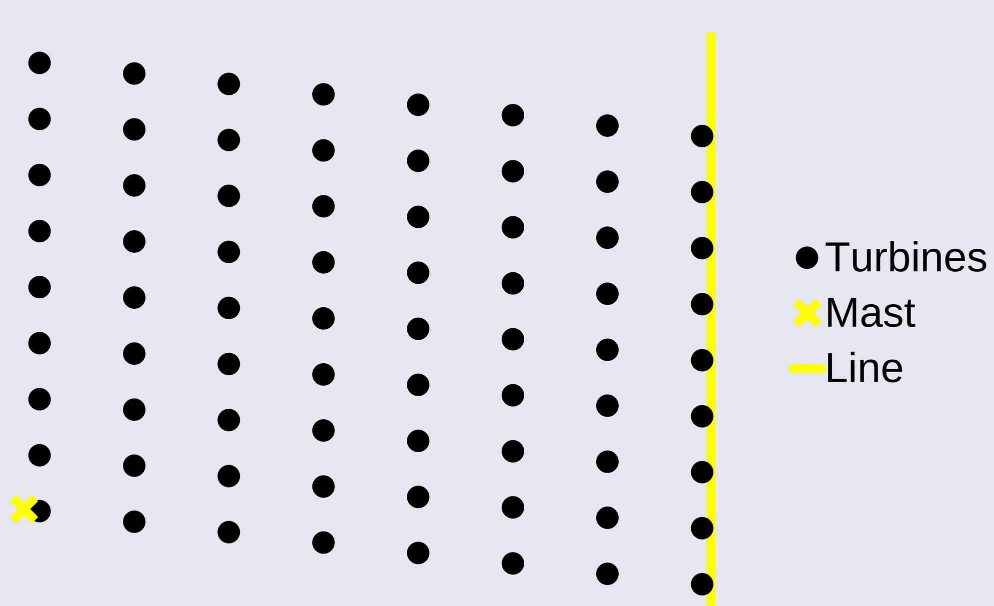

Figure 1: Locations of wind turbines (black dots), the upstream met mast (yellow cross) and wake measurement line (yellow line).

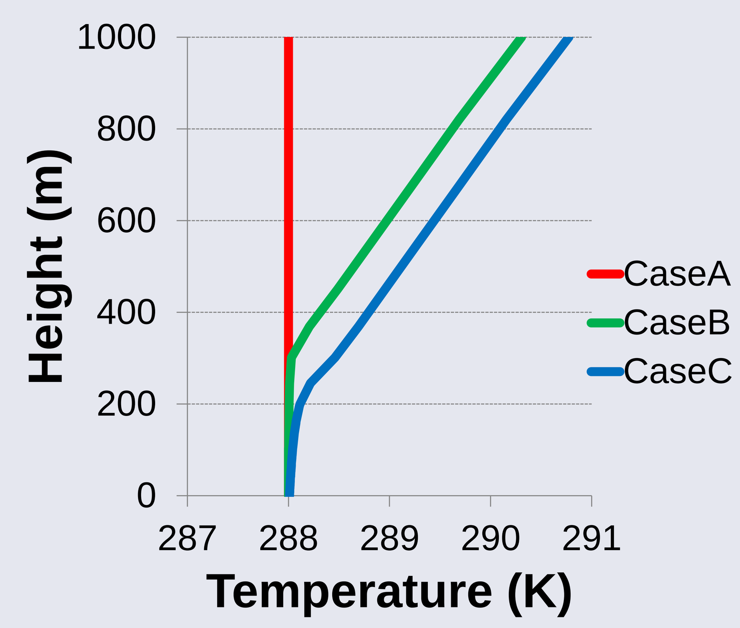

Figure 2: Temperature profiles through the simulation domain at the met mast's location for each Case.

To show how the varying the thermal profiles effect turbine wakes, figure 3 below shows the horizontal flow velocity as it passes the distance of one diameter downstream of the rear turbines, indicated by the yellow line in figure 1. The figure shows that wakes in simulations incorporating a thermal capping layer exhibit greater horizontal expansion at the edges of the wind farm, especially along the south edge. The farm also displays heightened blockage effects on the flow.

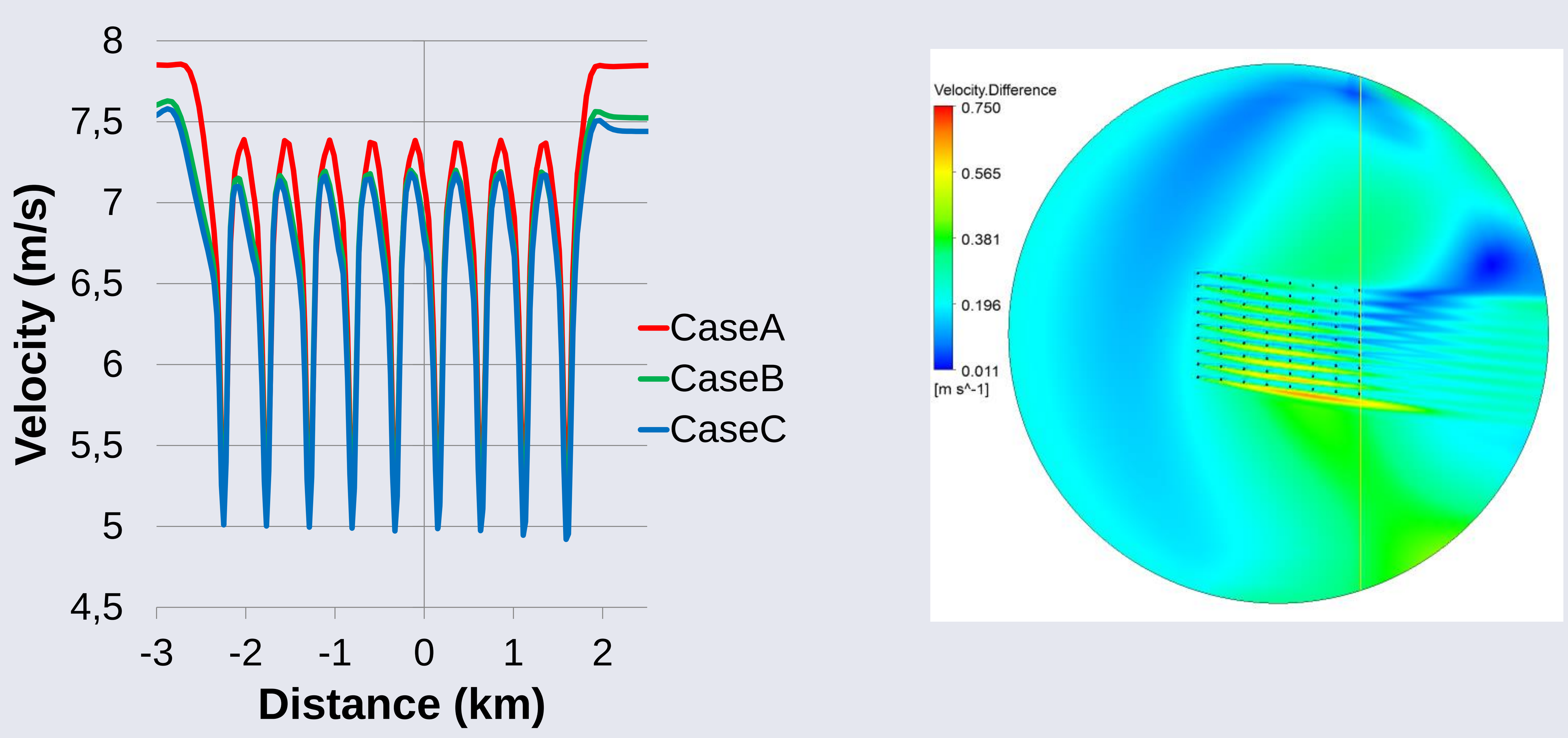

Figure 3: Left: Horizontal velocity one diameter downstream from the farm, across the yellow line in Figure 1. Right: Difference in wind speed velocity at hub height (CaseA minus CaseB).

Results

Simulated power production from each turbine in the three URANS case studies were normalized by the corresponding free-stream turbine's production and plotted against both the measured power output from the wind farm as well as results from a standard RANS k-ε simulation. Results from URANS simulations which did not include a Coriolis parameter are shown in figure 4 whilst results from the URANS models incorporating a Coriolis parameter are shown in figure 5 below.

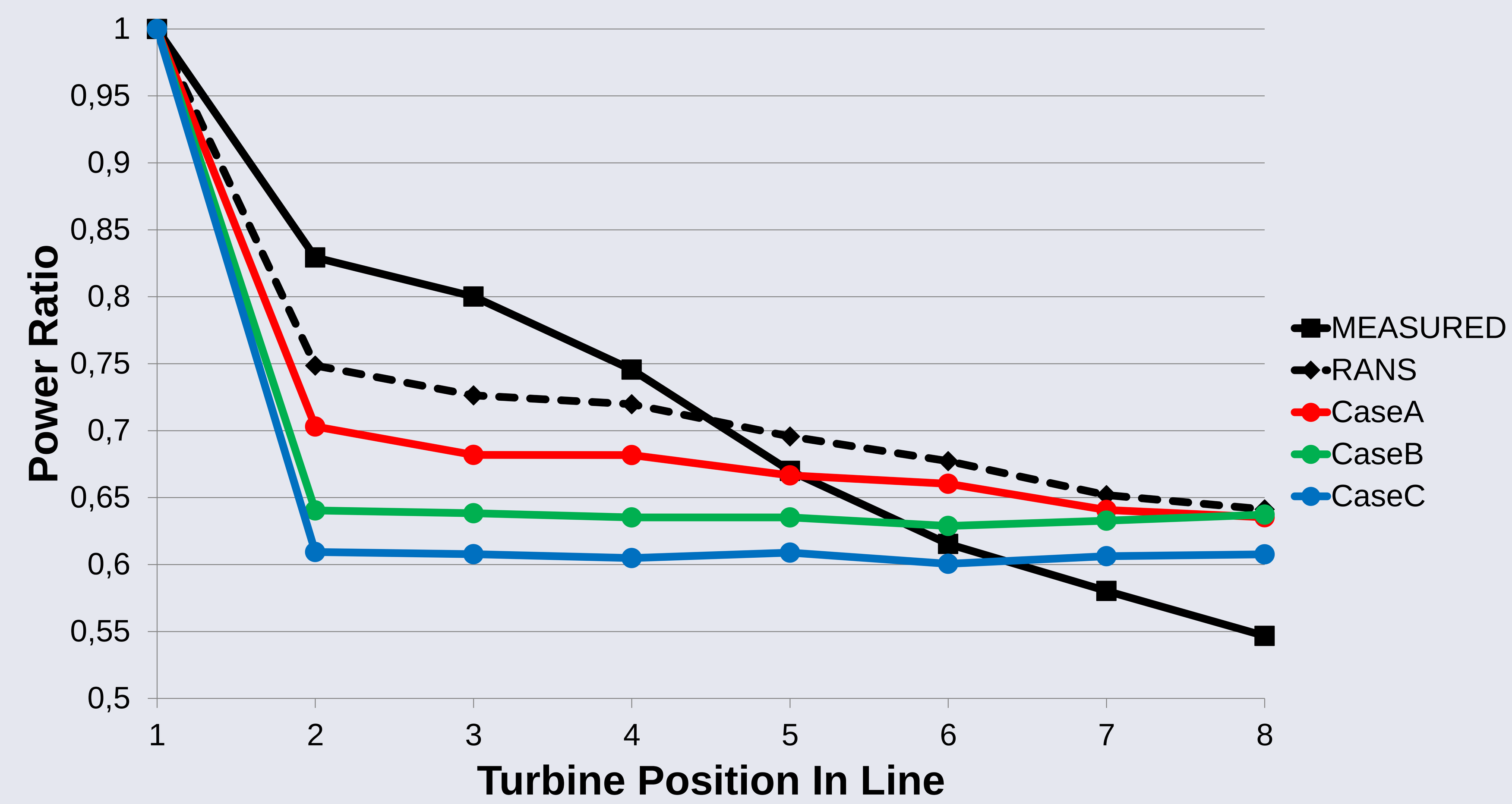

Figure 4: Results from the URANS simulations which did not incorporate the Coriolis parameter.

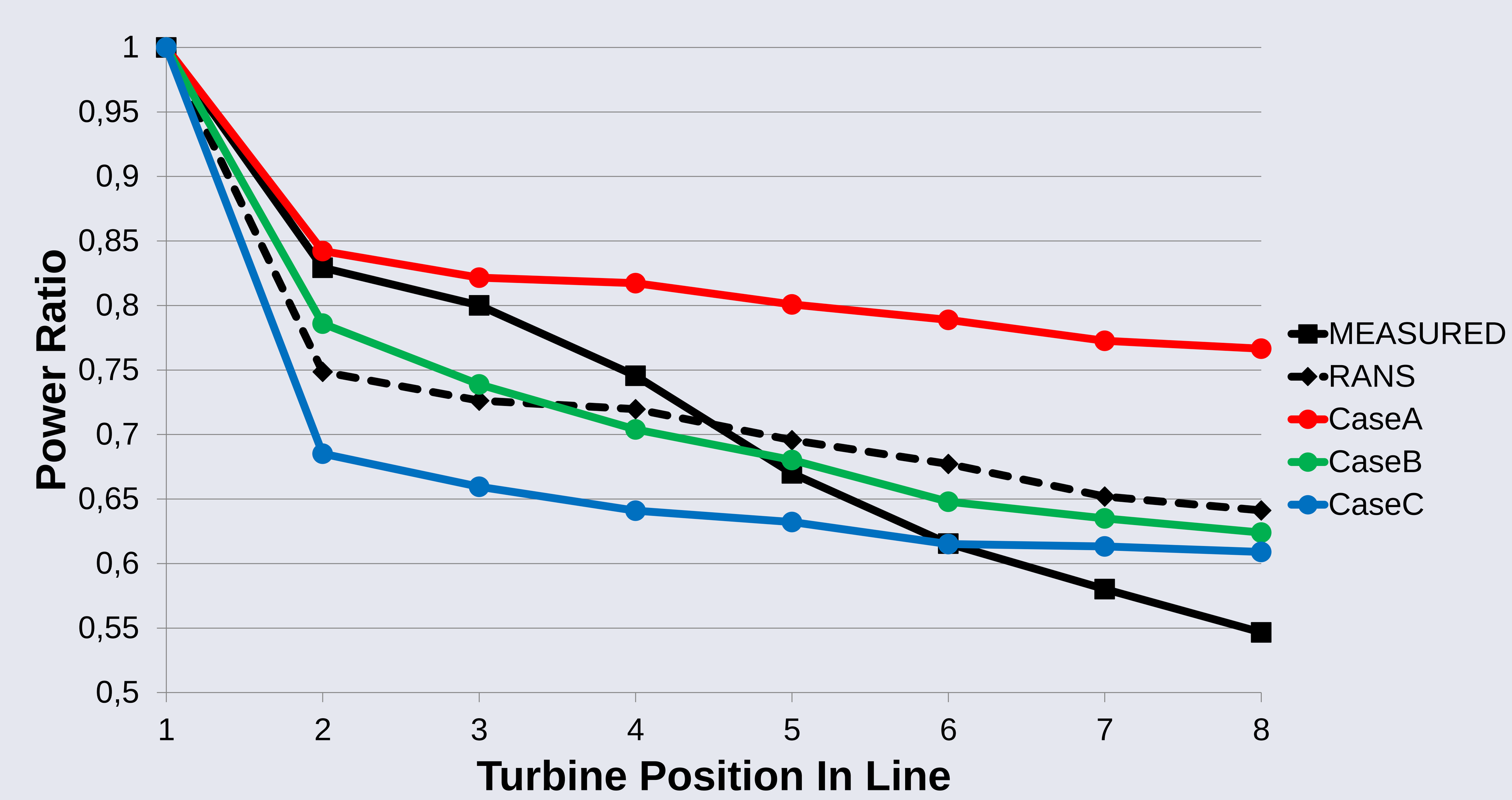

Figure 5: Results from the URANS simulations which did incorporate the Coriolis parameter.

Comparing the results shown in figures 4 and 5, it is clear that simply incorporating the Coriolis parameter significantly decreases the simulated wake losses, especially for the second turbine in the line, the first to encounter wake effected wind resource. This difference is significant enough that Case A reports power ratios at turbine positions 2 and 3 of within 2.5% of the measured values from Nysted, compared to a difference of over 10% without considering the Coriolis effect. The higher power ratios among the first 4 turbine positions in figure 5 also results in an enhanced deep array effect, especially for Cases B and C.

Varying the height of the thermal capping layer significantly alters the simulated productivity of the wind farm. This is seen in both figures 4 and 5. This may be considered a result of the wakes being restricted by buoyancy from expanding vertically and mixing with flow with higher velocities.

Conclusions

- Incorporating a thermal capping layer increases horizontal wake expansion.
- Wake losses increase as the capping layer's height approaches turbine heights.
- The Coriolis effect reduces simulated wake losses along lines of turbines.
- The Coriolis effect enhances the observed deep-array effect.
- In order to more accurately predict wake expansion and related losses within large offshore wind farms, measurements of temperature and velocity profiles need to be made above the turbine heights during resource assessments.

References

1. Simulation of Atmospheric Flows Over Complex Terrain for Wind Power Potential Assessment, *PhD Thesis, Ecole Polytechnique Federale de Lausanne:* C. Montavon 1998.