

## SUMMARY

Newer, taller, wind turbines are now able to interact with the geostrophic layers of wind triggering Atmospheric Gravity Waves (AGWs). Using Large Eddy Simulations (LES) of 15MW turbines based in the North Sea, the impact of these waves was evaluated on the turbine scale. It was found that the waves could be triggered under a simplified setup where only one infinitely wide row was simulated. The waves were found to alter the shape of the turbine wake and the rate of wake recovery. Increasing the lateral spacing of a turbine row was found to impact the wave strength and wave effects. In addition, by altering the position of a second downstream turbine to be inline with either a wave peak or trough, the triggered AGW and the power and blade loading of the second turbine was found to vary.

## INTRODUCTION

Offshore wind turbines sit in a turbulent boundary layer (Fig 1) with layers of laminar flow and strong temperature gradients above. The newer 15MW turbines interact with the upper stratified layers [1].

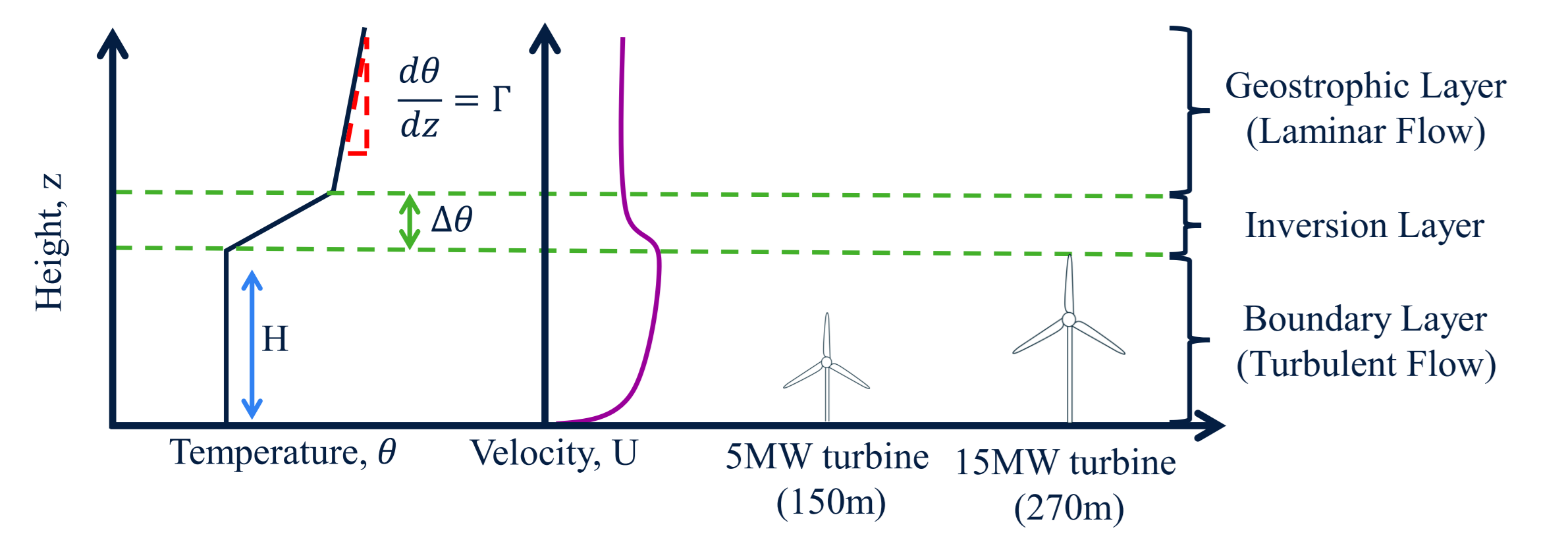


Figure 1: Illustrations of the typical offshore wind and temperature profiles relative to the turbine heights.

Mountains trigger Atmospheric Gravity Waves (AGWs) by vertically displacing stratified geostrophic winds (Fig 2) [2]. Similarly, the low-lying inversion layer offshore and increased turbine reach, mean wind farms are predicted to initiate these same buoyancy driven AGWs [3].

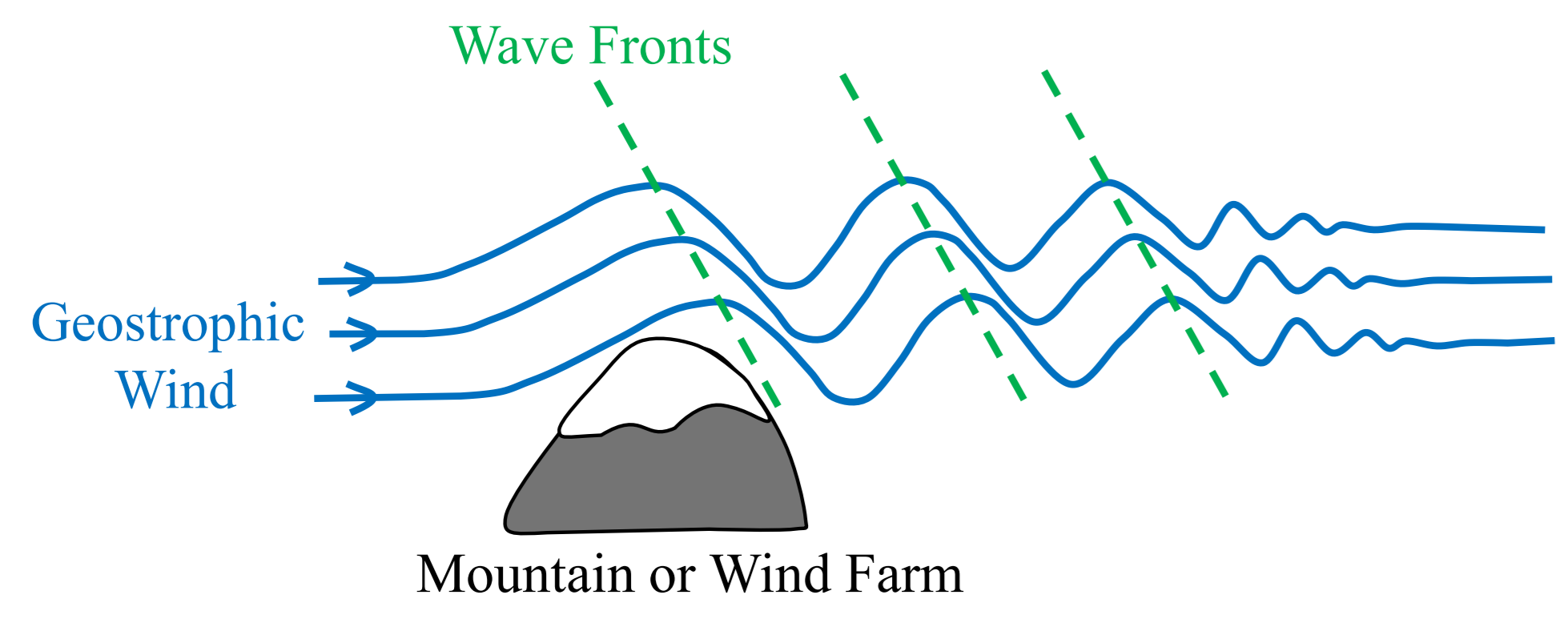


Figure 2: Illustration of how a resistance to the flow can displace wind triggering Atmospheric Gravity Waves (AGWs).

So far only wind farm scale flows have been simulated using low fidelity turbine models, consequently, little is known about the impact of AGWs on the turbine scale [4]. This work aimed to investigate:

1. The AGW impact on turbine scale flows and wakes.
2. If changing wind turbine layouts will impact the AGW produced.
3. If its is possible to optimise power production through an AGW wind turbine interaction.

## METHODOLOGY

Large Eddy Simulations (LES) of wind turbines in a stratified atmospheric flow were carried out using Open FOAM with a precursor-successor methodology (Fig 3). Cyclic lateral boundaries were used in the successor, so the turbines represent the middle of an infinitely wide row.

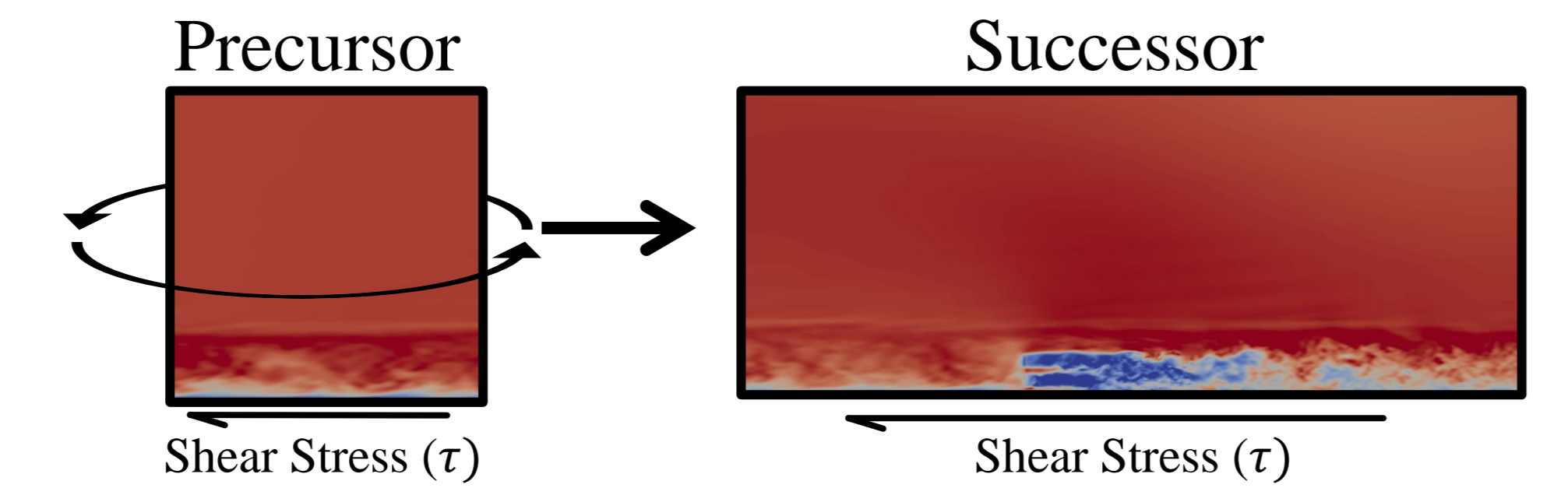


Figure 3: The precursor successor setup with a wind turbine included in the successor.

The solver includes the Coriolis force and captures buoyancy effects through a Boussinesq approximation. The key atmospheric parameters of the simulations are given in table 1.

Table 1: Key simulation wind and temperature profile parameters

Velocity at hub height (m/s)	$\Gamma$ (K/km)	H (m)	$\Delta\theta$ (K)	Inversion Layer Thickness (m)	Surface roughness, $z_0$ (m)
8	5	350	5	100	0.001

To test the impact of farm layout (Fig 4) the simulation setup was varied in two ways:

1. The domain width was varied to achieve different lateral spacings.
2. A second turbine was added and its downstream position varied to evaluate the impact of streamwise spacing

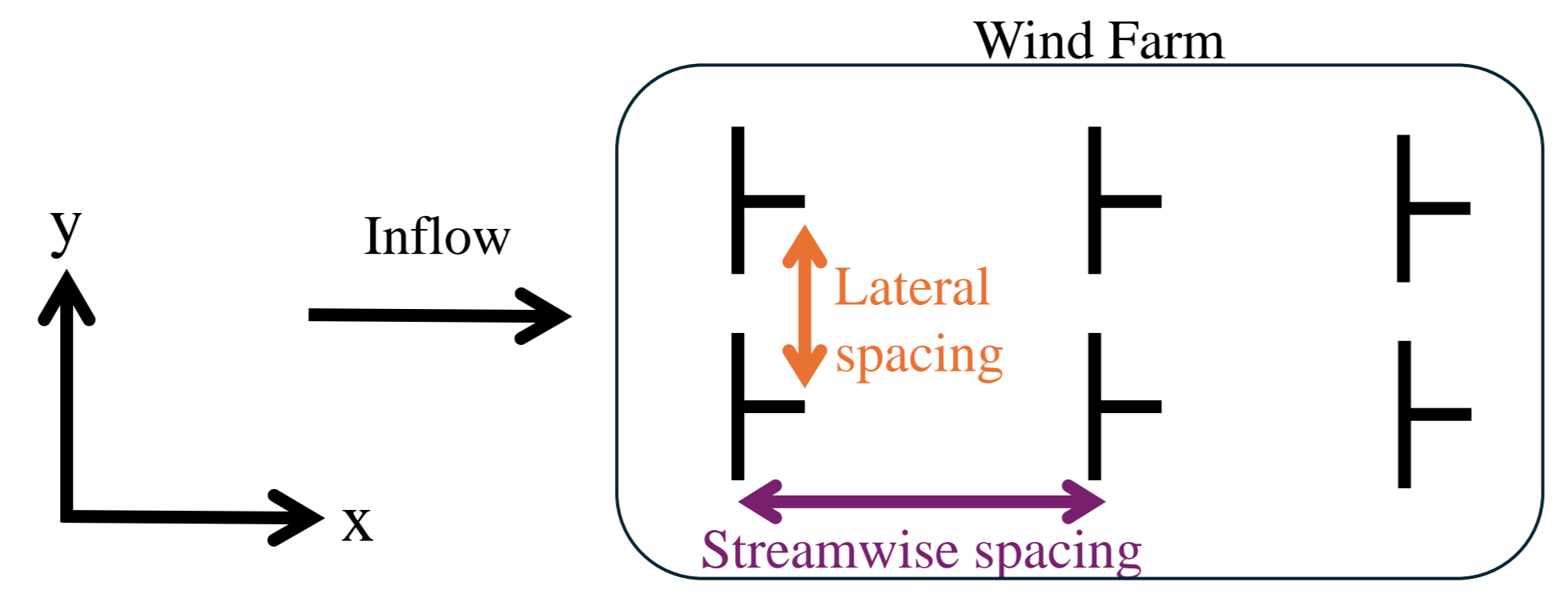


Figure 4: The two key farm layout parameters tested in this research.

## RESULTS

The turbine simulations with AGWs produce a different wake to the equivalent wave free case (Fig 5) in three key ways:

1. There are pockets of accelerated bypass flow above the wake.
2. The wake height sinusoidally varies along the streamwise direction.
3. The rate of wake recovery is non monotonic in the streamwise direction.

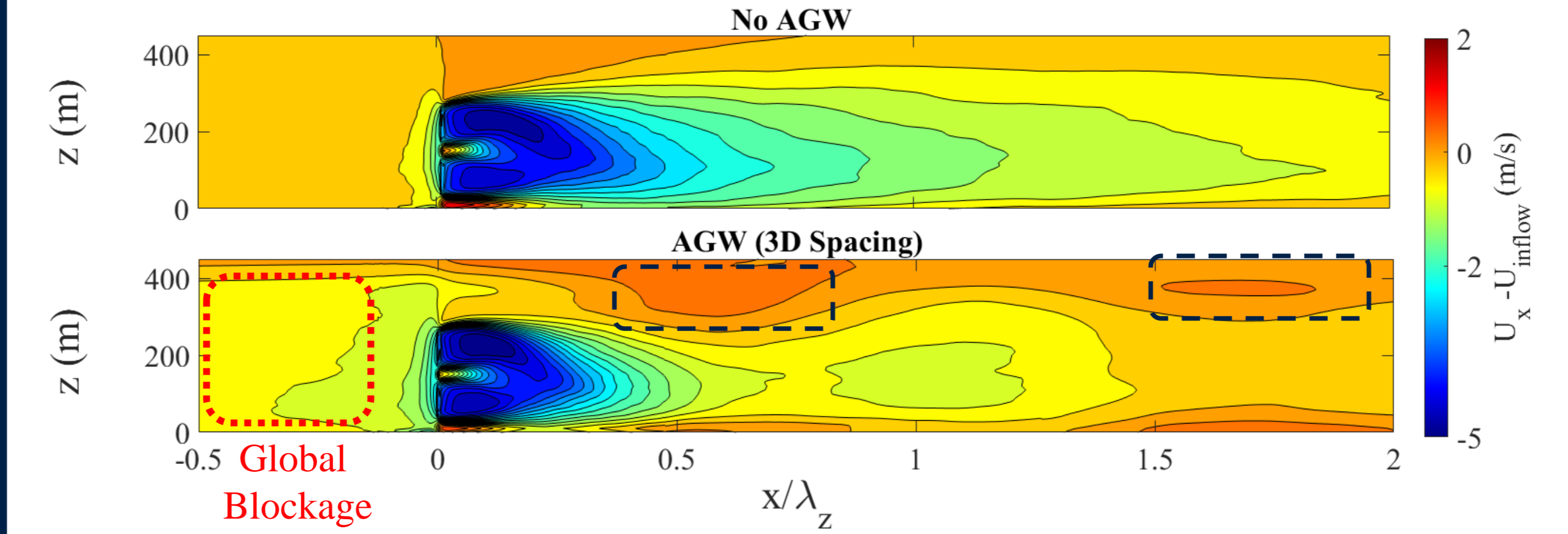


Figure 5: The time averaged turbine wake velocity relative to the inflow, with black dashed boxes indicating pockets of accelerated bypass flow. The x-axis is taken relative to the turbine position.

The rotor causes an internal AGW to propagate through the geostrophic layer and a trapped AGW along the inversion layer (Fig 6). Through changing the lateral spacing from 3 turbine Diameters (D) to 6D the strength of the AGWs reduces.

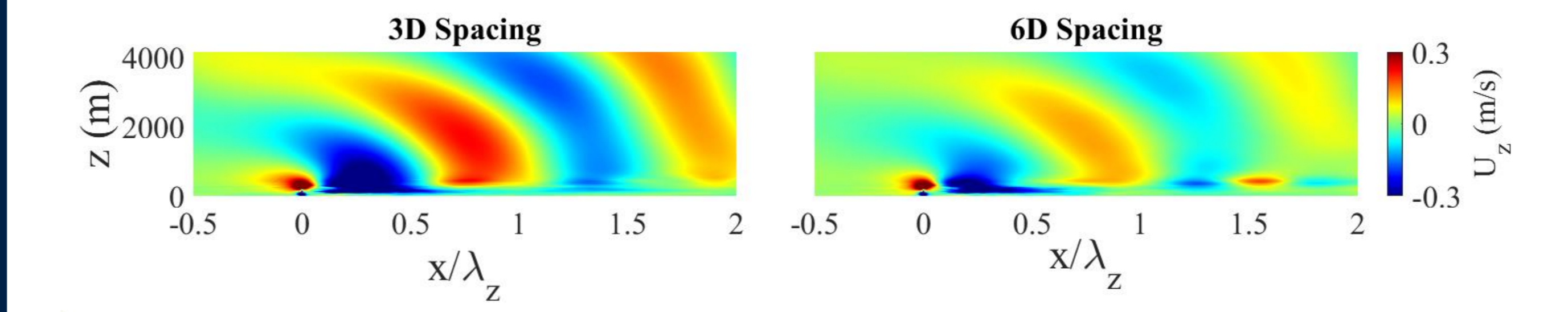


Figure 6: The perturbation to the vertical velocity field for different turbine spacings. The x axis is taken about the turbine position and non dimensionalised by the vertical AGW wavelength.

Adding in a second downstream turbine and varying its position (Fig 7) leads to a sinusoidal variation in the second turbines power (Fig 8). At  $1.5 \lambda_z$  the second turbine unconventionally outperforms the first despite being in its wake.

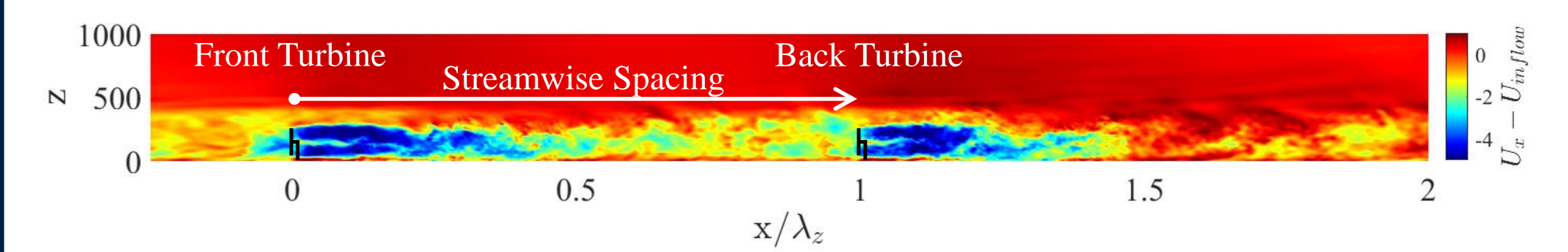


Figure 7: Instantaneous flow field of the two-row turbine set up

By changing the position of the second turbine the AGW strength, shape and phase also varied (Fig 9). At a spacing of  $0.5 \lambda_z$  the AGW is damped and at  $1 \lambda_z$  it is amplified.

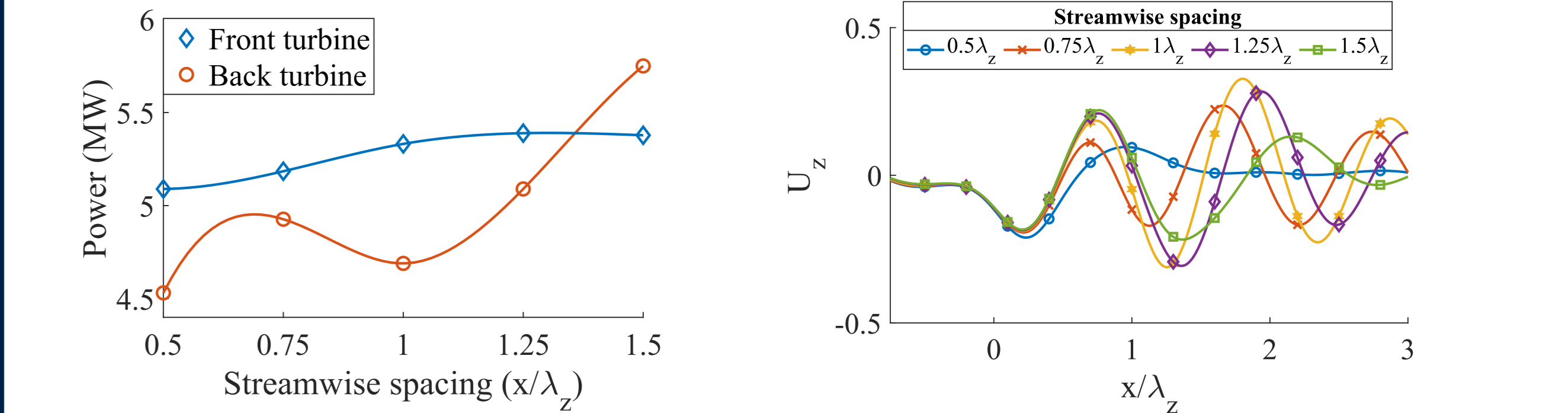


Figure 8: Turbine power for varying second turbine positions

Whilst positioning the second turbine at  $0.75 \lambda_z$  will lead to more power than at  $1 \lambda_z$  it comes at the cost of higher cyclic and mean loading (Fig 10). This is because the rotor at  $0.75 \lambda_z$  interacts with the pockets of acceleration identified in figure 7.

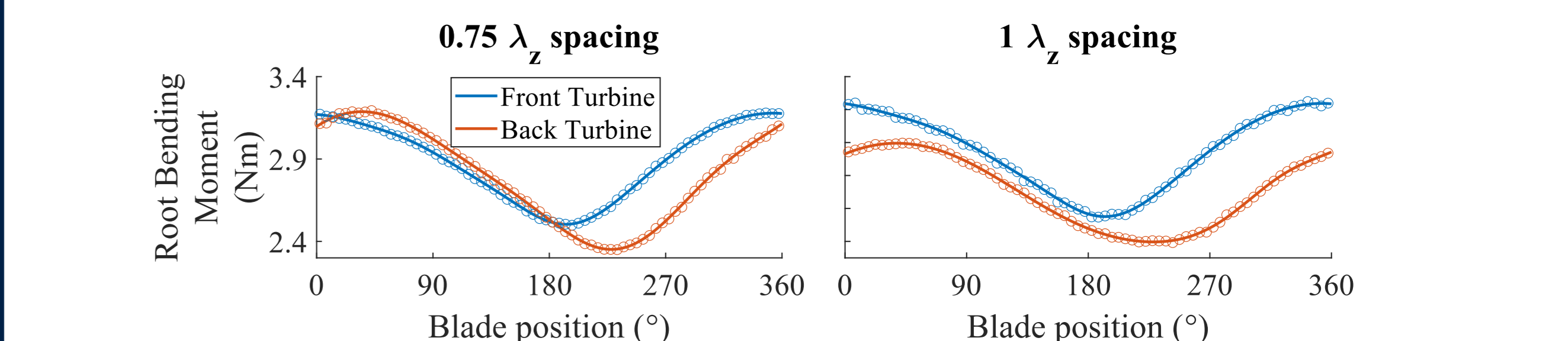


Figure 10: Variation in the root bending momentum of a blade over a rotor sweep for different spacings

## CONCLUSIONS

- **AGW interaction:** AGWs do impact the flows on the turbine scale creating significantly different wake dynamics.
- **Lateral Spacing:** By altering turbine lateral spacing, it is possible to control the wave strength and its impacts.
- **Streamwise Spacing:** Clever positioning of downstream turbines could take advantage of an AGW induced sinusoidal variation in power, however, this may come at the cost of more extreme blade loading. Streamwise spacing also impacts the AGW wave strength, shape and phase, meaning farm design could be used to control them.

## ACKNOWLEDGEMENTS

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## REFERENCES

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