Developing and Appraising a Toolbox of Numerical Models to Quantify Global Blockage Effects

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Overview

- Objective
  - To explore the need and potential for developing a toolbox of methods to quantify blockage effects
- Contents
  - Refresher on blockage
  - Why develop a toolbox?
  - A need for coupling
  - A candidate model ensemble and initial observations
  - Coupling test case and results
  - Summary and forward outlook

- Co-author Acknowledgements
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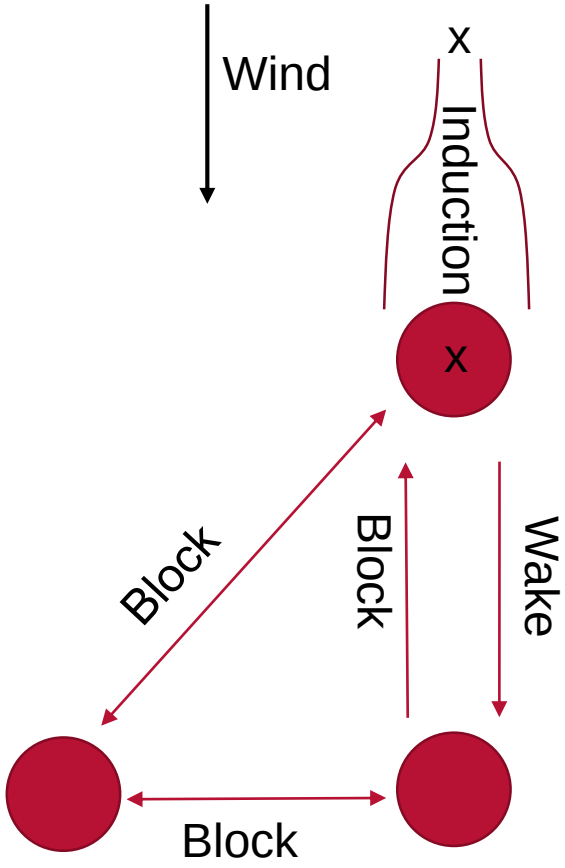
Refresher on Blockage

- Basic induction effect of a single turbine
  - Theory describes existence of upstream influence (but not extent or magnitude)
  - Tacitly ignored in power performance assessments
- Conventional wake loss assessment
  - Windward WTGs see the freestream, form wakes which impact other WTGs
  - Convenient streamwise workflow - Not a bad approximation
- In an array upstream influences start to interact
  - Change inflow, power production and wake behaviour
  - Complex coupled wake-blockage system (elliptic)
- Physics or Accountancy?
  - Most noticeable on windward power asymmetry/deficit and upstream deceleration
  - But is it a “loss”, a “power correction” or a “redistribution of production”?



Why develop a toolbox?: A Wake Loss Analogy

- Usage of wake loss model ensembles is common
  - Confidence weighted ensembles help us to manage model uncertainty
  - Engineering models: N.O. Jensen, Ainslie, Larsen etc
  - Higher fidelity models: Fuga, CFD
  - Both types of model have their place in wake loss assessment

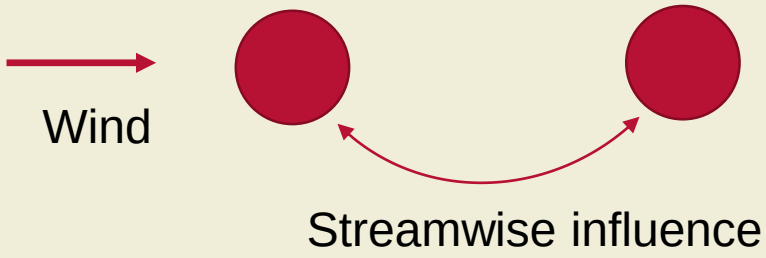
- Engineering models
  - Industry wants these! Run quickly and afford optimisation
  - Requires few inputs and avoids need for data we often do not know

- Higher fidelity models
  - Fundamental approach with fewer assumptions – potential for extrapolation
  - Offer physical insight in addition to raw answers
  - Are computationally intensive and precision places demands on quality of inputs/assumptions

Blockage Tools: A Need for Coupling?

- Do we separate blockage and wakes or predict the total interaction in a single model?
  - Blockage interactions in an array are complex. A viable tool needs to appraise 2 basic scenarios
  - Inherent wakes-blockage interaction suggests a coupled approach to predict interaction
  - Physically correct, safest (yield accountancy) and could be integrated alongside existing wake models

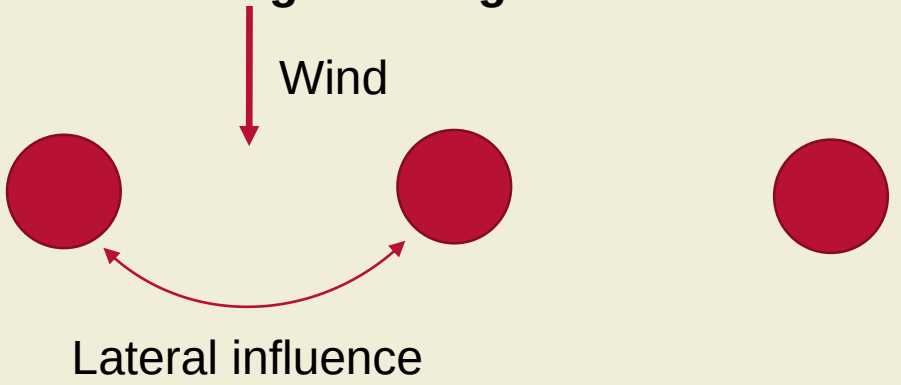
Scenario 1: Streamwise aligned WTGs



Relative to wakes only approach, blockage …

1) decreases the output of the upstream WTG
2) increases the output of the downstream WTG

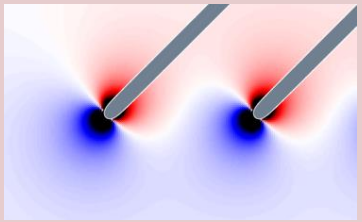
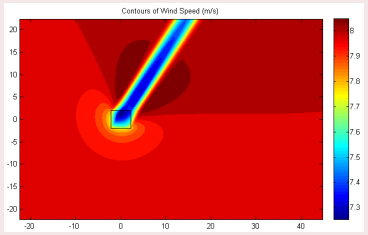
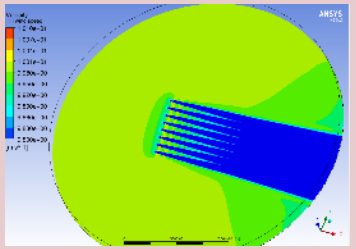
Scenario 2: 3 neighbouring WTGs



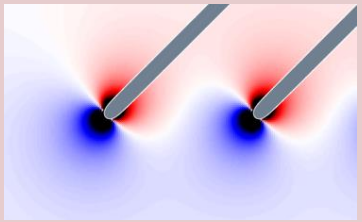
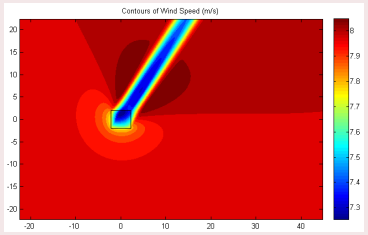
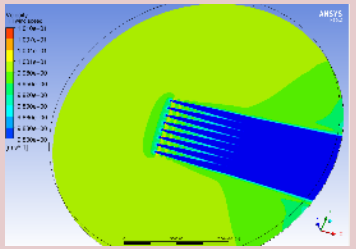
Relative to wakes only approach, blockage …

1) decreases the output of the centre WTG relative to those on the edge

Our Candidate Model Ensemble

Model	Images	Comments
Inviscid **Runs <1min**		▸ Vortex/potential representations of WTGs, coupled to conventional wake models ▸ Blockage outside of wake zones, ground constraint modelled using method of images ▸ **Sensitive to:** WTG parameters, layout, wind direction and speed ▸ **Insensitive to:** viscous effects, turbulence, ABL properties, coriolis, gravity waves
Combined Shallow Layer **Runs <1min**		▸ Based on the separate work of Smith and Hunt. Single layer with farm as a drag patch ▸ Potential to couple to wake model via bespoke drag distribution ▸ **Sensitive to:** WTG parameters, layout bounds, wind direction and speed, thermal ABL properties, coriolis, gravity waves ▸ **Insensitive to:** Detailed layout, ABL velocity profile
CFD **Runs > 1hr**		▸ Solution of RANS closed Navier-Stokes equations ▸ Elliptic nature of equations provides upstream influence as required ▸ **Sensitive to:** Has all the physics necessary to address blockage within RANS closure limits ▸ **Challenges:** Sensitivity to AD implementation, WTG mesh, ABL definition/preservation

Our Candidate Model Ensemble: Initial Observations of Performance

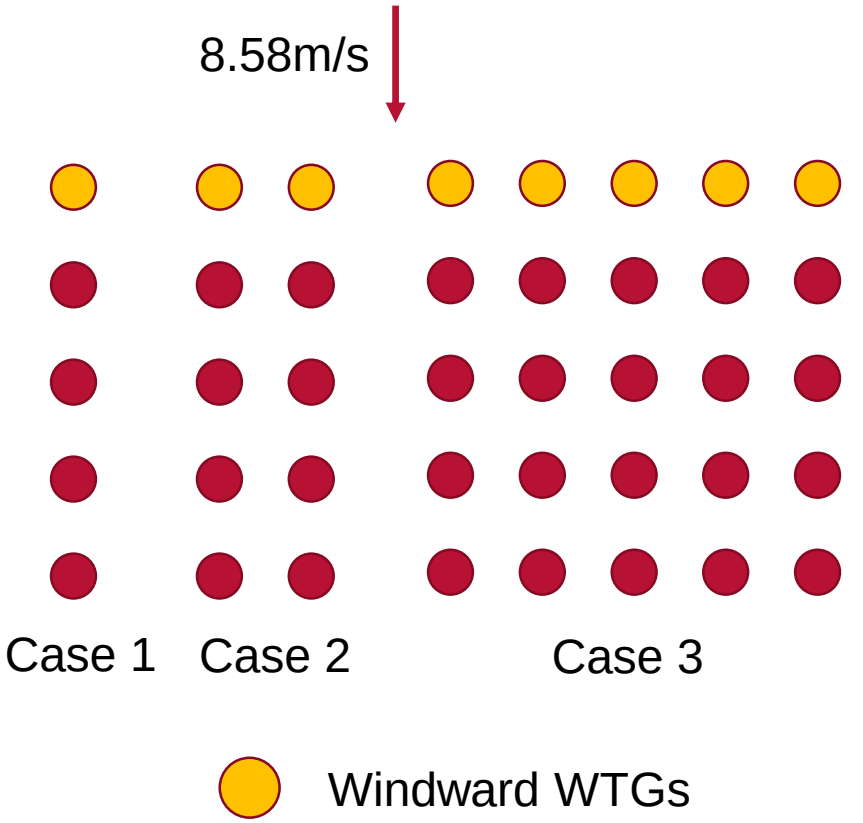
Model	Images
Inviscid **Runs <1min**	
Combined Shallow Layer **Runs <1min**	
CFD **Runs > 1hr**	

- Magnitude and shape
  - All models return “few percent” power reduction on lead row
  - General U-shape power trends as expected
- Symmetry
  - Analytical forms in Inviscid/CSL return symmetric U-shapes
  - Some asymmetry in CFD: residual ABL development, Mesh variation noise, Actuator disk assumption
- Parametric variation
  - Inviscid models invariant with lapse rate – gives lowest blockage
  - CSL/CFD show lower lead row power with increasing lapse rate/reducing BL height (consistent with Wu & Porté-Agel [2017])
- Outlook
  - Looks promising, but formal validation required

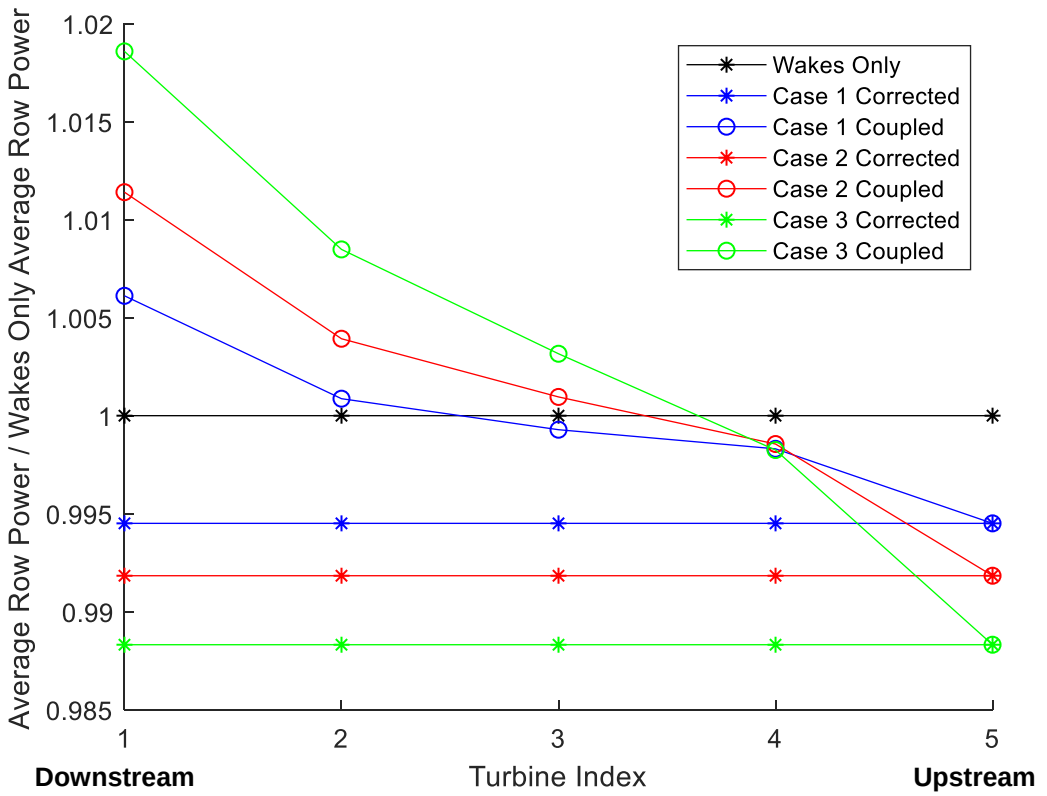
Example Coupling Test Case: Description

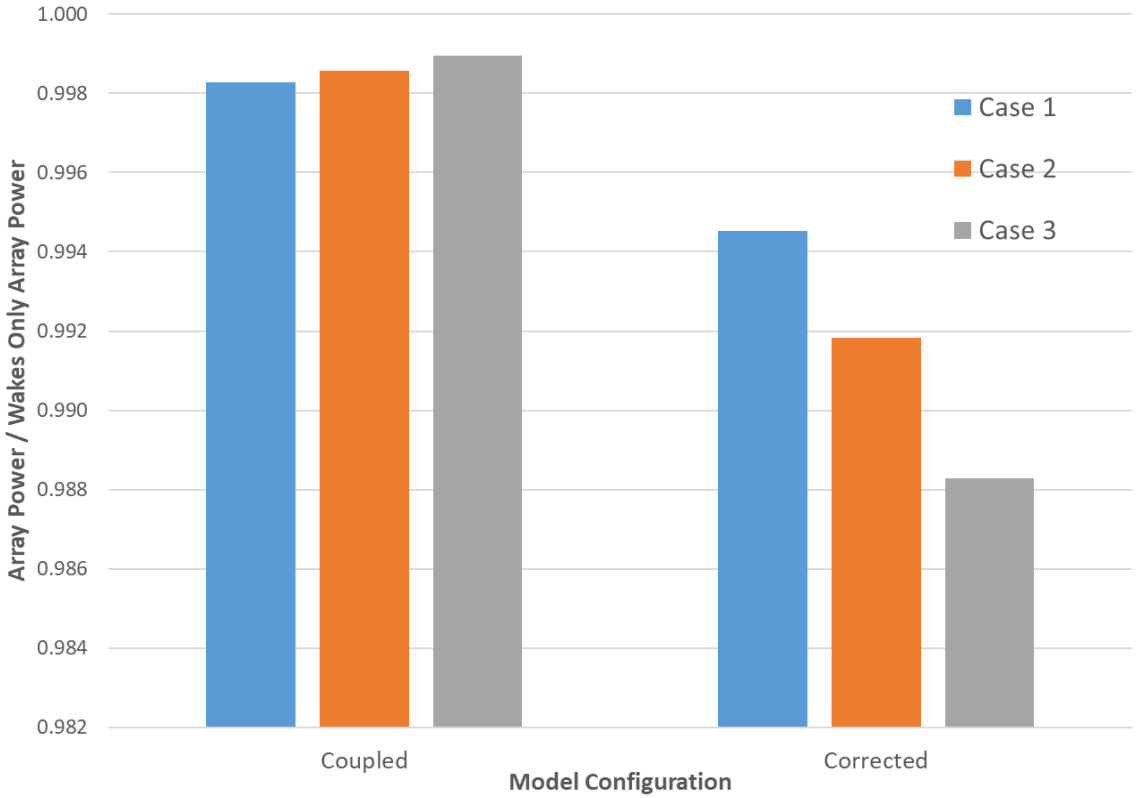
- Consider 1, 2 and 5 columns of turbines, each 5 rows deep
- Using Coupled Inviscid-Wake model
  - Quick, can turn on/off both wakes and blockage independently
  - Mirror turbines for blockage and wake (ground constraint)
  - Probably lower bound blockage estimate
- Do 3 sets of calculations for each site
  1. **Wakes Only** calculations N.O Jensen model ("today's practice")
  2. **Coupled** inviscid-wakes calculations
  3. **Corrected** Wakes only multiplied by lead row power correction from coupled model
- Outputs
  - Power variation on through rows and total farm output

Small hypothetical offshore wind farms



Example Coupling Test Case: Results





- Data show power reduction at lead row but coupled model suggests this is partially compensated for by power uplift at later rows
  - Why … blockage-induced acceleration field outside of wake, unwinding of blockage through array

Summary and Forward Outlook

- The nature of blockage
  - We see blockage in data and mass/momentum conserving analytical codes
  - Is it always a loss? Perhaps, although there is evidence that blockage also redistributes power offtake

- Blockage accountancy
  - Accountancy by a lead row correction may be possible, but it doesn't represent the physics of blockage
  - We believe blockage should be handled in a coupled model to predict turbine interaction losses
    - This might need some retuning of historical wake loss models (correction requires blockage to be "baked in")

- Blockage models
  - We've introduced the basic capabilities of a family of models that could couple blockage/wakes
  - Development/validation is needed – but currently they suggest that power redistribution could be important

- But there is still more to do! Work continues on:
  - CFD good practice, rapid model development/enhancement and validation against real wind farm data