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Long Range Wake Calculations Sensitive To Surface Layer Stability

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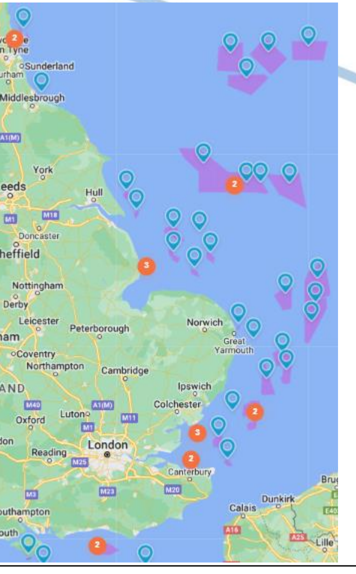
The Challenge

- Current offshore wind farm map for UK →
- Not shown:
  - Other Countries
  - New Wind Farms
- Very crowded and will get more so!
- We need models to accurately predict yields, and to understand that accuracy
  - Familiar wind farm wake models are not applicable for long range wakes
- (The industry would prefer an <u>ensemble</u> of <u>rapid</u> models)



The Crown Estate Asset Map
https://www.thecrownestate.co.uk/en-gb/what-we-do/asset-map/

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Motivation and Approach

- At long range, we know that wakes merge
  - Individual wake resolution less important
- Long been postulated in Top-Down models that
  - For very long length scales, energy exchange with the atmosphere is what matters
  - This is sensitive to surface layer stability
- R B Smith formulation
  - Is very fast
  - Provides a link between turbine level, farm level and atmospheric processes
  - Can be made sensitive to surface layer stability
- Other rapid models
  - Have made really significant progress in past two years
  - May have some limitations due to not directly modelling ABL height and stability

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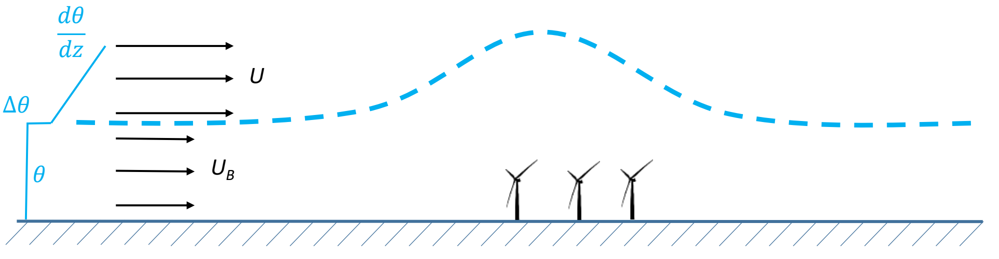
RB Smith Formulation

- 'Slab' model of Atmospheric Boundary Layer
  - Depth-averaged quantities



- Analytical solution for horizontal pressure field set up by ABL displacement
- Coupled to conservation of mass and momentum within ABL
- Closed equation set
- Linearisation around undisturbed condition permits very fast FFT solution

Add Horizontal Eddy Viscosity

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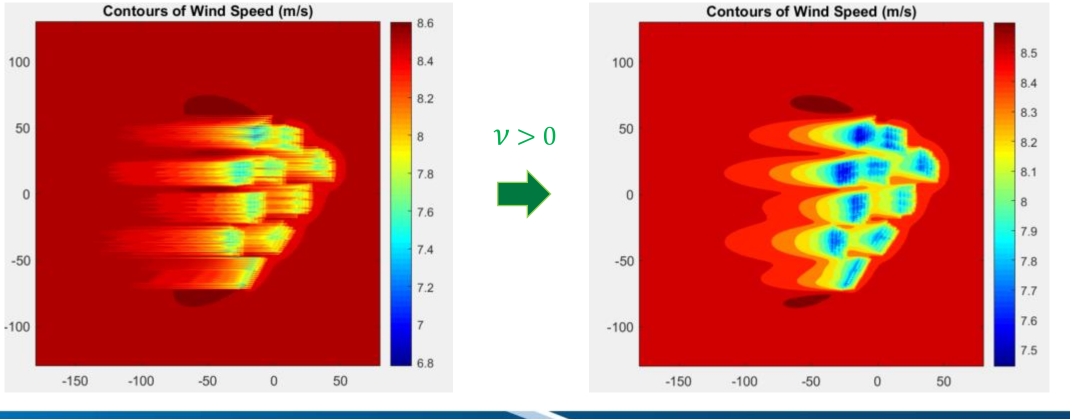
$$u_{B,0}\frac{\partial u'_B}{\partial x} + v_{B,0}\frac{\partial u'_B}{\partial y} = -\frac{1}{\rho_B}\frac{\partial p'_B}{\partial x} + \nu\frac{\partial^2 u'_B}{\partial y^2} + F_x - C_T u'_B - C_B u'_B$$

$$u_{B,0}\frac{\partial v'_B}{\partial x} + v_{B,0}\frac{\partial v'_B}{\partial y} = -\frac{1}{\rho_B}\frac{\partial p'_B}{\partial y} + \nu\frac{\partial^2 v'_B}{\partial x^2} + F_y - C_T v'_B - C_B v'_B$$



Space-Marching, Non-linear Solver

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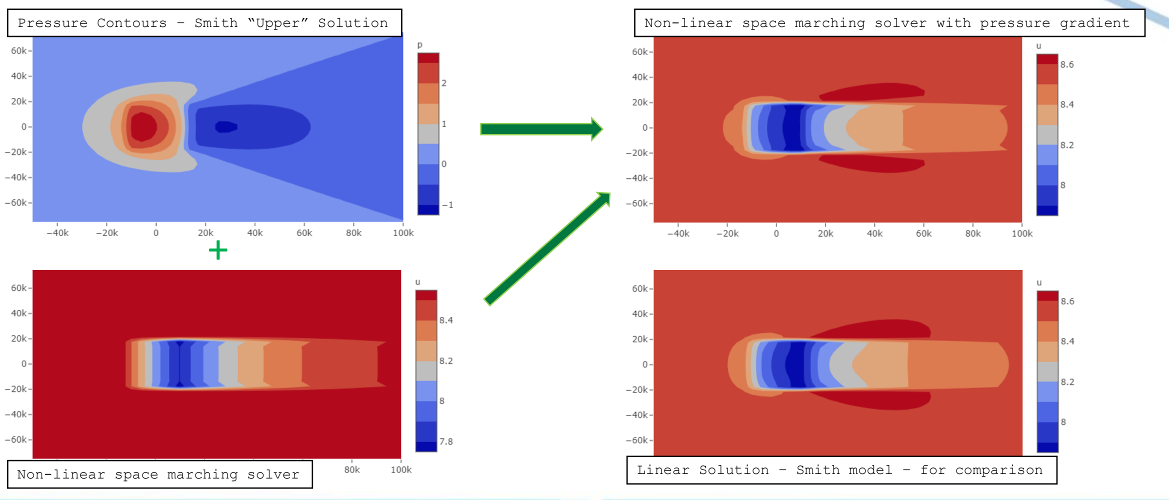
$$u_B \frac{\partial u_B}{\partial x} + v_B \frac{\partial u_B}{\partial y} = -\frac{1}{\rho_B}\frac{\partial p_B}{\partial x} + F_x + C_T(U - u_B) - C_B u_B$$



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Side note : Influence of Pressure Feedback On Wind Speed

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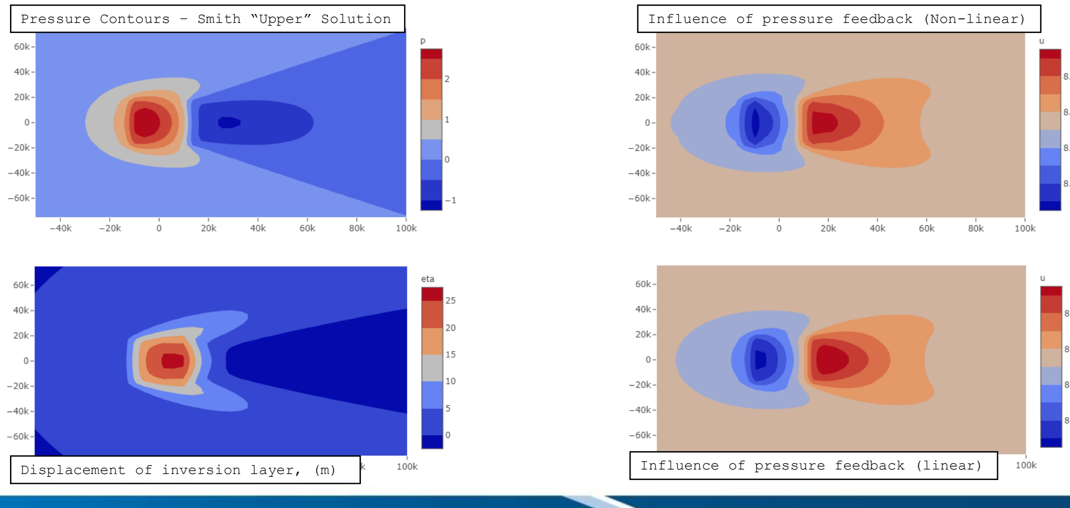
$$u_B \frac{\partial u_B}{\partial x} + v_B \frac{\partial u_B}{\partial y} = -\frac{1}{\rho_B}\frac{\partial p_B}{\partial x} + \cancelto{0}{F_x} + C_T(U - u_B) - C_B u_B$$



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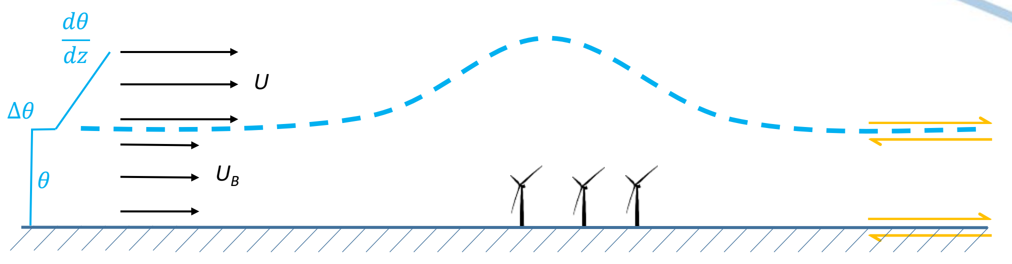
Rayleigh Friction Coefficient



$$u_B \frac{\partial u_B}{\partial x} + v_B \frac{\partial u_B}{\partial y} = -\frac{1}{\rho_B}\frac{\partial p_B}{\partial x} + \nu \frac{\partial^2 u_B}{\partial y^2} + F_x + C_T(U - u_B) - C_B u_B$$

$$u_{B,0}\frac{\partial u_B'}{\partial x} + v_{B,0}\frac{\partial u_B'}{\partial y} = -\frac{1}{\rho_B}\frac{\partial p_B'}{\partial x} + \nu\frac{\partial^2 u_B'}{\partial y^2} + F_x - C_T u_B' - C_B u_B'$$

$C_T = C_T$ (MOL)?
$C_B = C_B$ (MOL)?

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Rayleigh Friction Coefficient

$$C_B = 2\,(u^*)^2/(H u_B)$$

- **RB Smith 2007**
- **Also, similar magnitudes by**
  - **Algebraic treatment of log law profile**
  - **Numerical treatment of 'tall' wind profile**

$$C_T = C_B u_B/(U - u_B)$$

- **RB Smith 2007 (shape function arguments)**
- **Also, same result from assuming top and bottom friction forces balance approximately**

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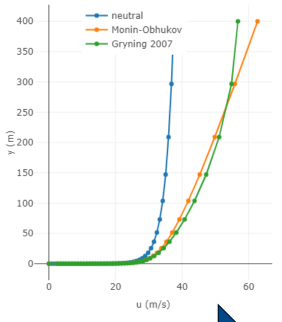
Calculation Process

Wind Speed (h.h.)
Wind Direction

Surface Layer
Temperature Gradient

ABL height
Inversion Strength
Lapse Rate Aloft



'Tall' Wind Profile

Depth-averaged wind speed
Geostrophic wind speed
Friction velocity
M.O. Length

$C_B = 2\,(u^*)^2/(Hu_B)$

$C_T = C_B u_B/(U - u_B)$

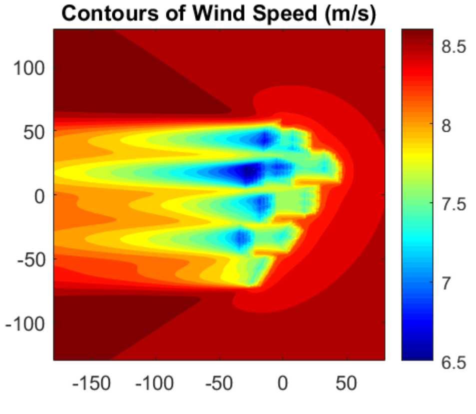
Rayleigh
Friction
Relations

Friction coefficients C_B, C_T

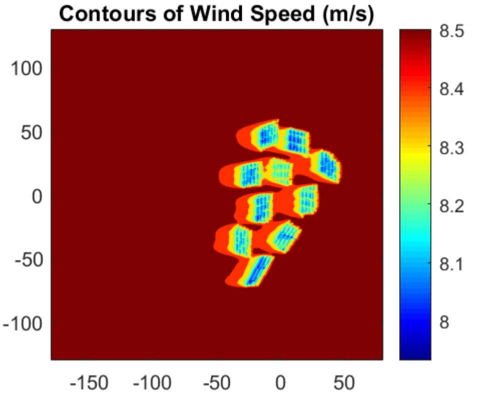
Model Ready

Example : Danish Energy Island Concept

STABLE: M.O.L. = + 50



UNSTABLE: M.O.L. = - 100



Validation

- **Alpha Ventus wind farm wake length estimated via SAR**
- **Simultaneous measurement of wind speed and temperature gradient *in situ***
  - *'Impact of atmospheric stability on X-band and C-band synthetic aperture radar imagery of offshore windpark wakes', B. Djath, J. Schulz-Stellenfleth and B. Cañadillas. J. Renewable Sustainable Energy 10, 043301 (2018).*
- **Pioneering observational data set**
- **Rare opportunity for model validation**

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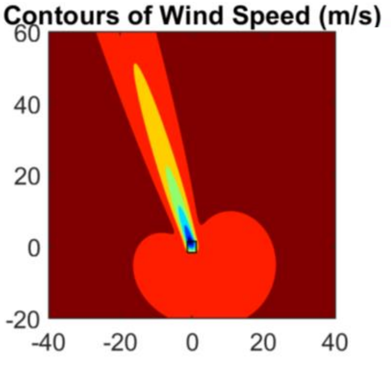
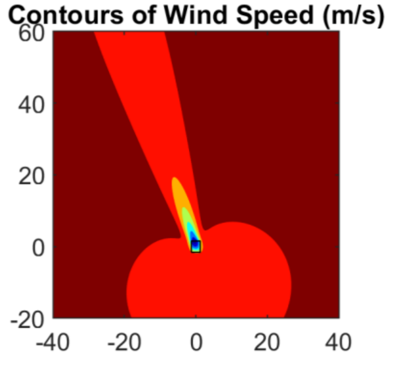
Results

STABLE: M.O.L. = + 50



UNSTABLE: M.O.L. = - 50



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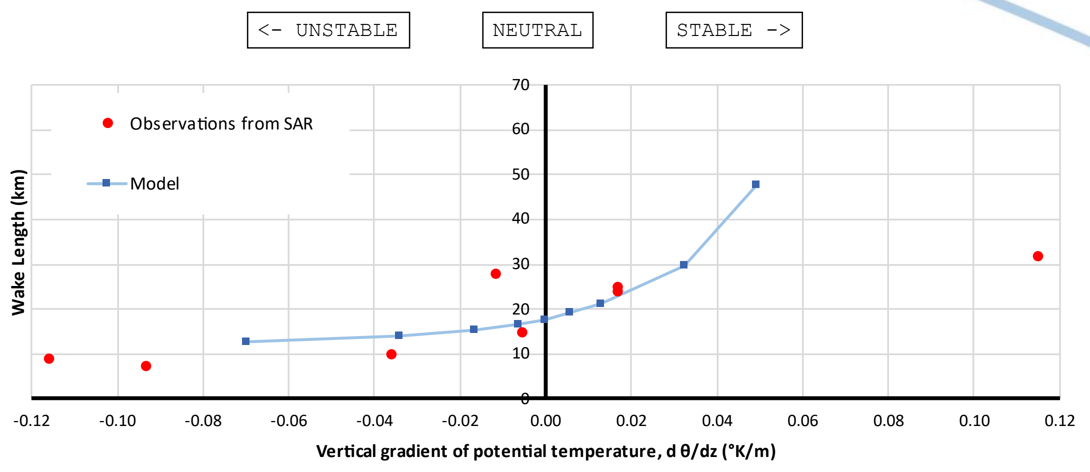
Results



Linear model results shown – Non-linear results very similar

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Results & Findings

- R B Smith ‘shallow layer’ model applied to long range wakes problem
  - Rational and workable approach to surface layer sensitivity
  - Effective viscosity in horizontal plane added
  - Feasibility confirmed
  - Initial validation promising
- Strengths:
  - Directly represents stability on wake recovery
  - Very quick to run
  - Can use turbine thrust from standard models
  - Pressure field and non-linearity investigation
- Weakness:
  - Demands ABL/thermal profile data
  - Relies on ‘Tall Wind Profile’
    - Hard to trust above 160m
- Thank you RAVE for pioneering measurement campaigns

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References and Related Work

1. "Gravity Wave Effects on Wind Farm Efficiency", R.B. Smith, Wind Energy 2009.
2. 'Interacting mountain waves and boundary layers', R B Smith. Journal of the Atmospheric Sciences, Vol. 64, 2007.
3. "Analysis of Some Major Limitations of Analytical Top-Down Wind-Farm Models", Stefan Emeis, Boundary-Layer Meteorology, January 2022.
4. "Benchmarking results from multiple wake models on operational data from offshore wind farms", Ewa Johansson, Wind Europe Tech. Workshop, June 2023.
5. "Multi-fidelity wake model benchmark of external wake effects from the X-Wakes research project", Lukas Vollmer, Wind Europe Tech. Workshop, June 2023.
6. "Impact of long-distance wakes between offshore wind farms assessed using operational data", Nicolai Gayle Nygaard, Wind Europe Tech. Workshop, June 2023.
7. 'On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer', S-E Gryning, E Batchvarova, B Brümmer, H Jørgensen and S Larsen. Boundary-Layer Meteorology, Volume 124, March 2007.
8. 'The wind profile up to 300 meters over flat terrain', S-E Gryning, H Jørgensen, S Larsen and E Batchvarova. Journal of Physics: Conference Series 75 (2007) 012066.
9. 'Impact of atmospheric stability on X-band and C-band synthetic aperture radar imagery of offshore windpark wakes', B. Djath, J. Schulz-Stellenfleth and B. Cañadillas. J. Renewable Sustainable Energy 10, 043301 (2018).

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