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Wind Energy Advisory

WakeBlaster

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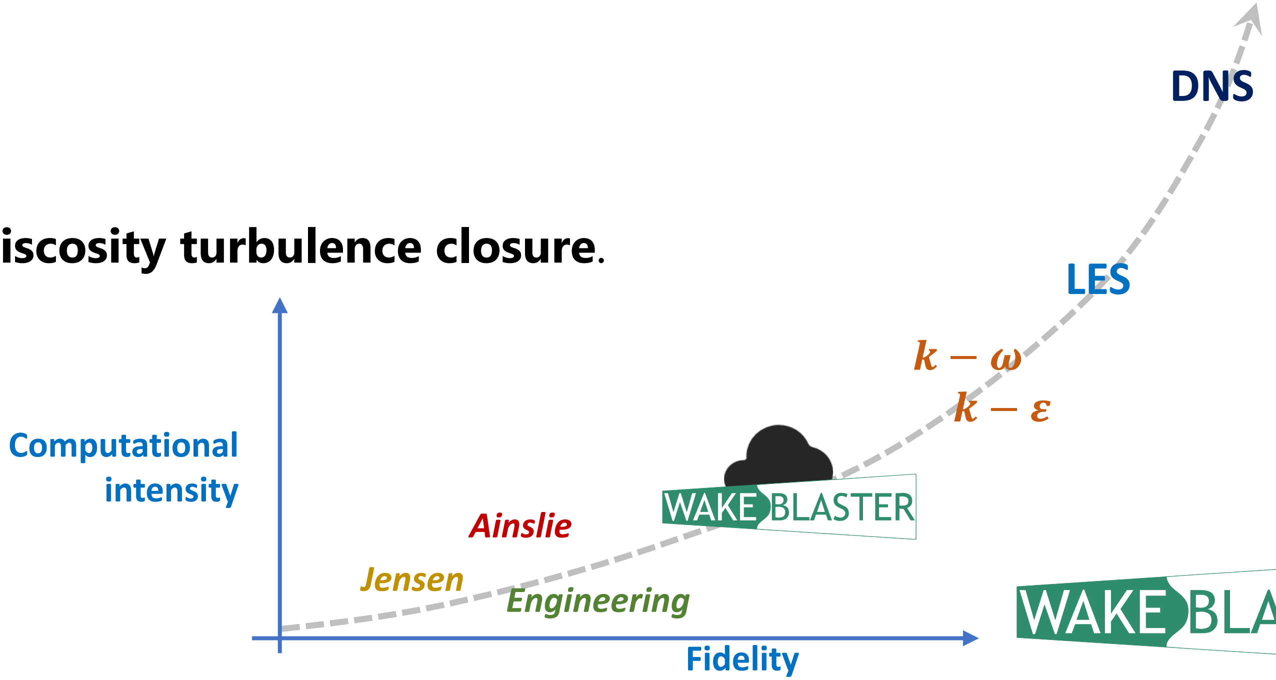
WAKE BLASTER

WakeBlaster Theory

CFD Model

- WakeBlaster is a Reynolds-Averaged Navier-Stokes (**RANS**) model
  - Solved in **3D Cartesian** coordinates
  - Parabolic solver using Alternating Direction Implicit (ADI) method

- Assumptions:
  - Fluctuations separated from mean conditions (Reynolds averaging)
  - Stationary conditions
  - Thin shear layer approximation
  - Ignore pressure terms
  - Incompressible flow
  - Fluctuations represented by **eddy-viscosity turbulence closure**.



RANS Equations

Momentum conservation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}+\frac{\partial\overline{u'v'}}{\partial y}+\frac{\partial\overline{u'w'}}{\partial z}=0$$

$$\Rightarrow \boxed{u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-\varepsilon\frac{\partial^2 u}{\partial y^2}-\varepsilon\frac{\partial^2 u}{\partial z^2}=0}$$

Solved by Alternating Direction Implicit (ADI) method

Displacement: $\vec{\boldsymbol{x}}=\begin{bmatrix}x\\y\\z\end{bmatrix}$

Velocity: $\vec{\boldsymbol{u}}=\begin{bmatrix}u\\v\\w\end{bmatrix}$

ε = eddy viscosity

v and w determined by mass flow conservation:

ξ = radial velocity damping coefficient

$$w(Z)=\int_0^Z\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}-\xi w\right)dz$$

$$v(Y)=\frac{\Upsilon(Y_{max})-\Upsilon(Y_{min})}{2}\quad \text{where}\quad \Upsilon(\Upsilon_0)=\int_{\Upsilon_0}^{Y}\left(\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}-\xi v\right)dy$$

Solved by iteration

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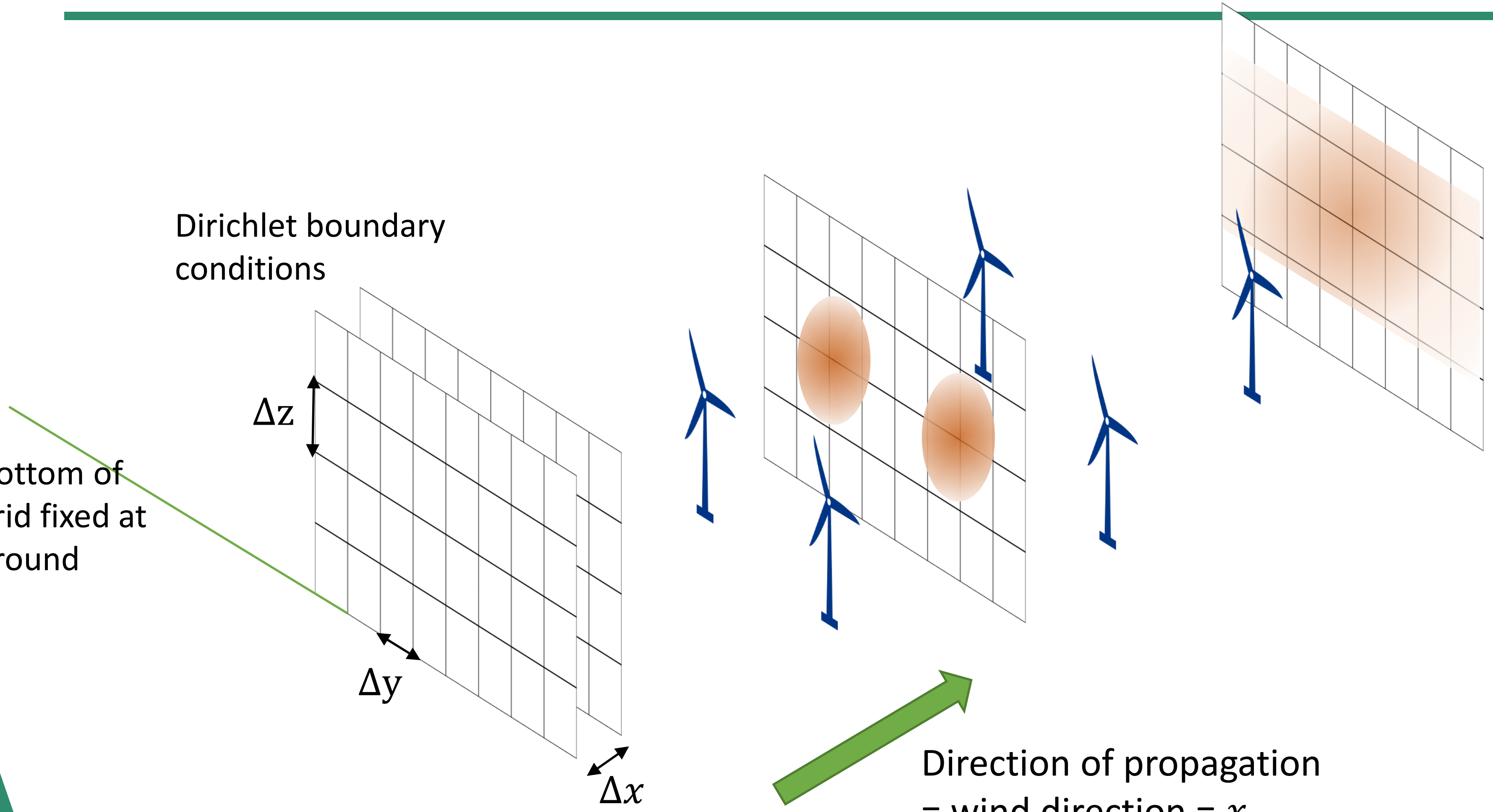
Flow Plane Propagation



Direction of propagation = wind direction = x

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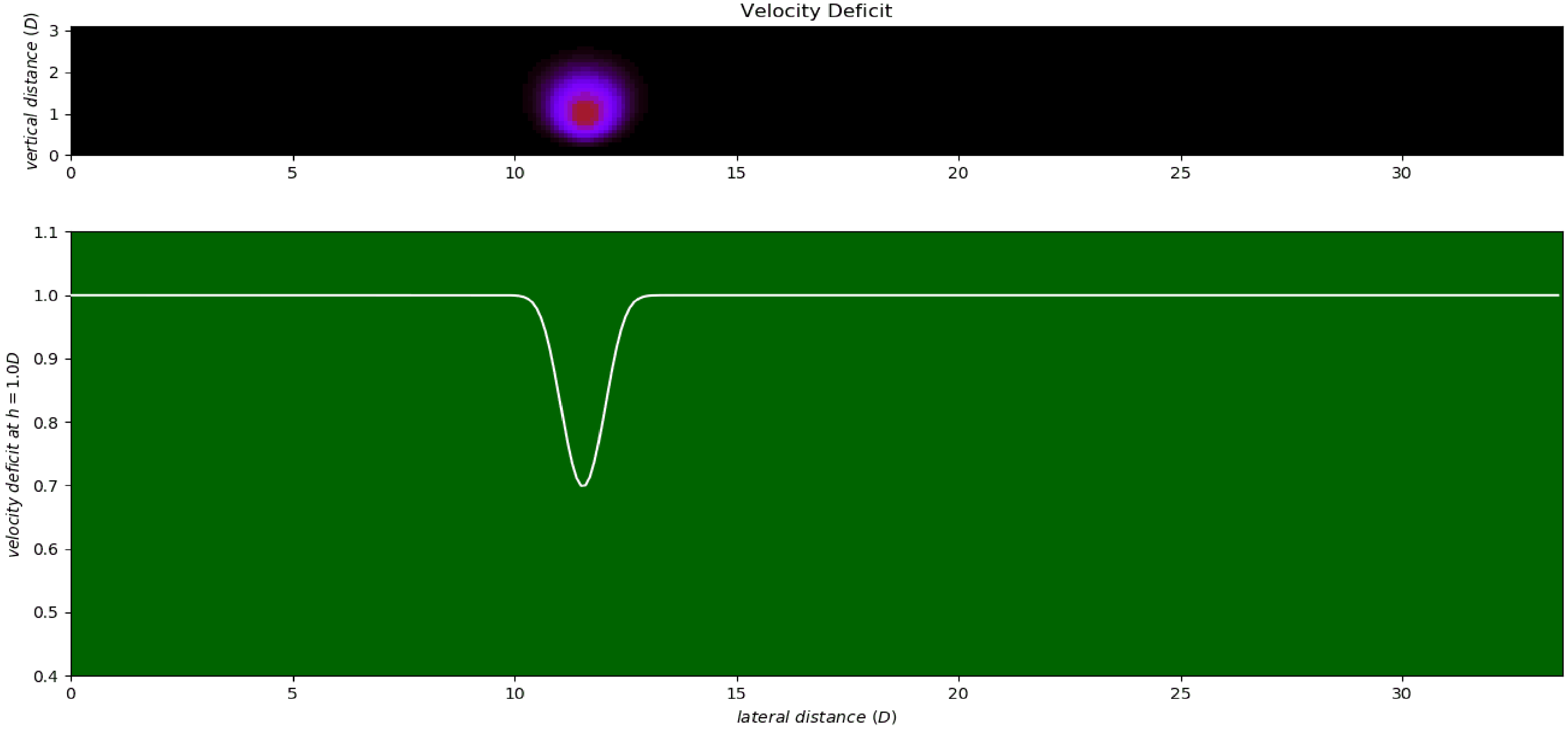
Flow Plane Propagation in Action!



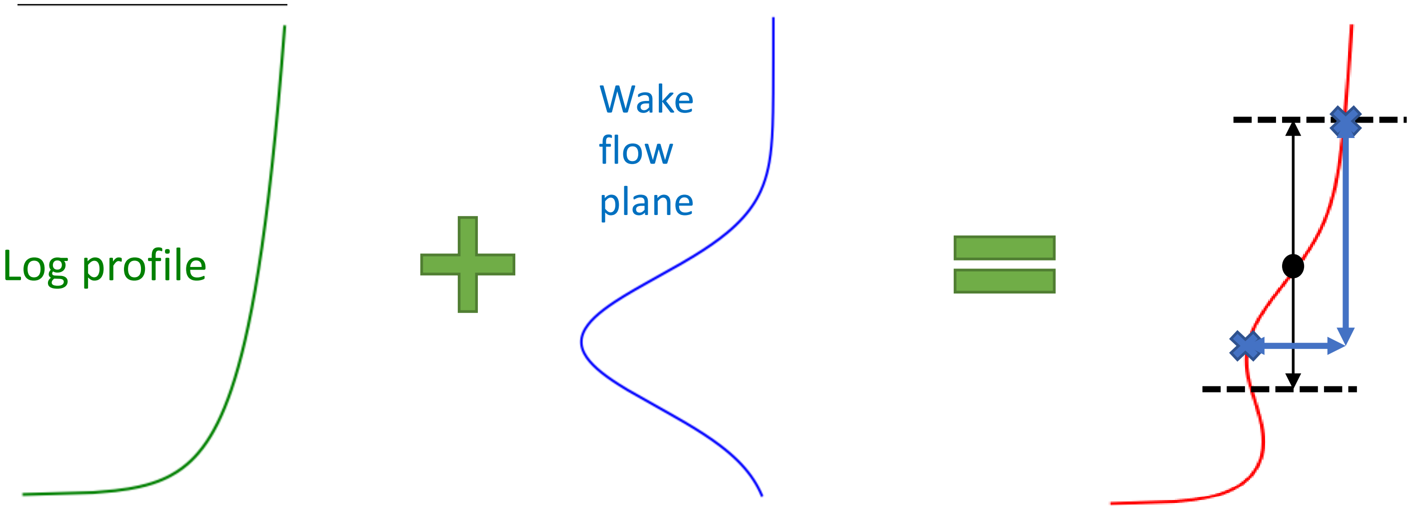
Eddy Viscosity Model

- Eddy viscosity (units = m^2s^{-1}) calculated from wind shear profile

$$\varepsilon_i = \Delta u_{\mathrm{i}}\Lambda_i$$

$$\bar{\varepsilon} = k\sqrt{\varepsilon_y^2 + \varepsilon_z^2}$$

k = calibration factor
Δu_i = velocity range in window
Λ_i = distance between min & max velocities



Eddy Viscosity Lag Model

- Generation of shear-generated turbulence (eddy-viscosity) considered to **not** be instantaneous.
- Reduces wake dissipation in near-far wake – well supported by measured data

Fixed lag-length:

$$\eta\Lambda\frac{d\epsilon}{dx}+\epsilon=\bar{\epsilon}$$

$\Lambda=\frac{\bar{\epsilon}}{\sqrt{\Delta u_x^2+\Delta u_y^2}}$ = mixing length

η = relative lag length

Turbulence dependent:

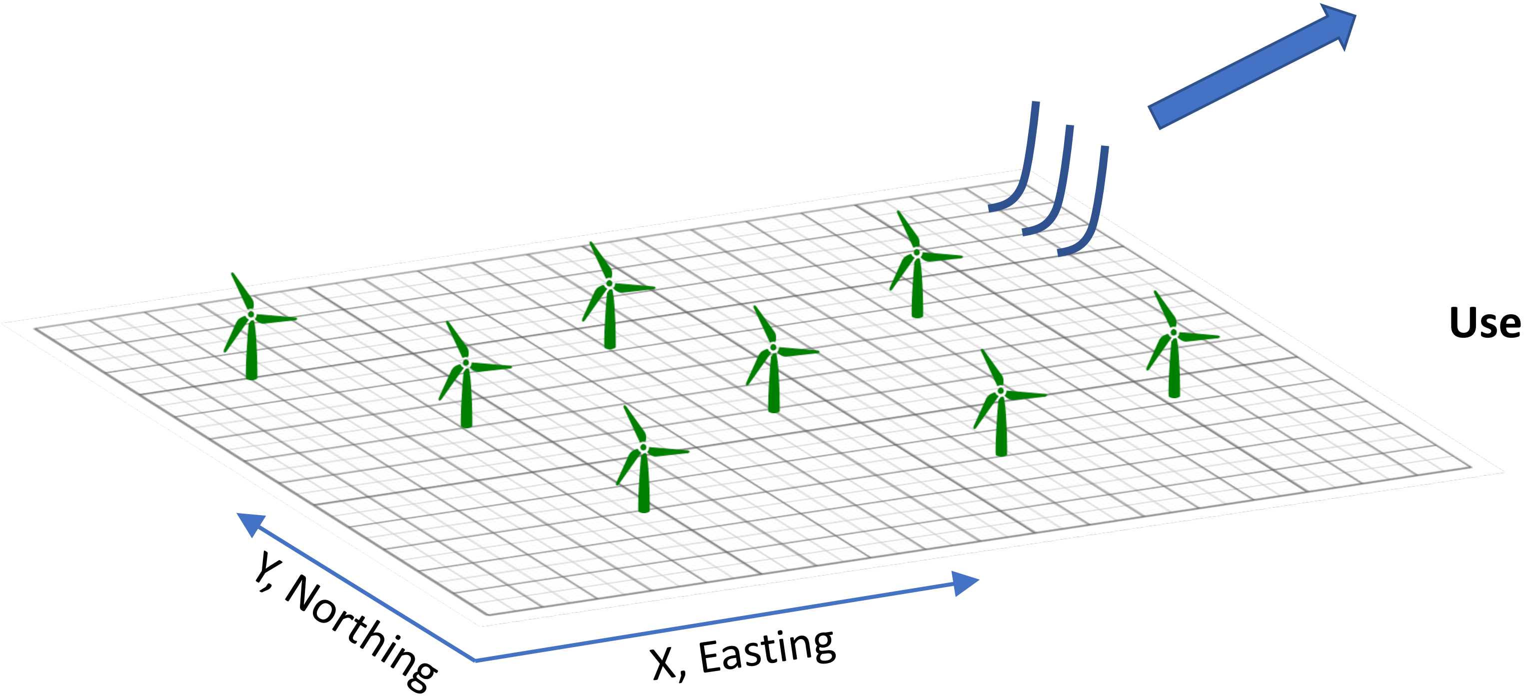
$$\frac{\Lambda}{\phi\frac{\epsilon}{kz}+\frac{\Lambda}{\lambda_{max}}}*\frac{d\epsilon}{dx}+\epsilon=\bar{\epsilon}$$

ϕ = turbulence scale parameter

Basic idea => lower turbulence means longer eddy viscosity lag!

Terrain Model

- Geographical relative ambient wind speed, $u_{amb} = f(X,Y)$
- Accepts WAsP-style *.wrg/rsf
- $\sigma_u \approx$ constant $\therefore I_{amb} = f(X,Y)$



Log wind profile at each grid point:

$$z_0 = h_{ref} \exp\left(\frac{-u_{ref}}{\sigma_u}\right)$$

$$u = \frac{u^*}{\kappa} \ln \frac{z}{z_0}$$

Used in eddy viscosity model at every geographical point!

Stability - Beta

Modified log profile:

$$u = \frac{u^*}{\kappa} \ln\left(\frac{z}{z_0} - \psi_m\right)$$

Modified vertical component of eddy viscosity:

$$\varepsilon_z = \frac{\Delta u_{\mathrm{z}} \Delta \Lambda_z}{\phi_m}$$

ϕ_m = non-dimensional wind shear

$\psi_m = \int_{\frac{z_0}{L}}^{\zeta} [1 - \psi_m(\zeta)] \frac{d\zeta}{\zeta}$ where $\zeta = \frac{z}{L}$

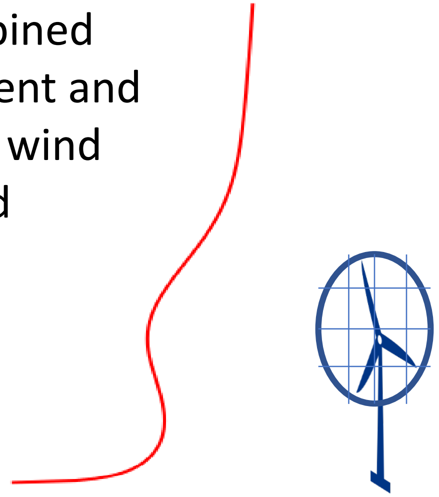
L = Monin-Obukhov length

Businger-Dyer Relationship:

$$\phi_m = \begin{cases} 1 + 5\zeta & \text{stable} \\ 0 & \text{neutral} \\ (1 - 16\zeta)^{-0.25} & \text{unstable} \end{cases}$$

Power Capture – Rotor Integration

- Waked flow plane is integrated (2D) across the rotor



Combined ambient and wake wind speed

$$u_{rotor} = \sqrt[n]{\int_{A_{rotor}} u^n \, dA}$$

$$n = \begin{cases} \boxed{1 \quad \text{RAWS(linear average)}} \\ 3 \quad \text{REWS(sum of cubes)} \end{cases}$$

Power Capture – Other Effects

- Additional power adjustments considered
  - Turbulence correction to the power curve (IEC)
  - Air density correction (IEC)

$$u_\rho = \left(\frac{\rho}{\rho_{ref}}\right)^{-\frac{1}{3}} u_{ref}$$

  - Yaw Misalignment:

$$\mathrm{P}_\theta = P_0 \cos^3\theta\,,\ \theta = \text{yaw misalignment}$$

WakeBlaster Verification & Validation

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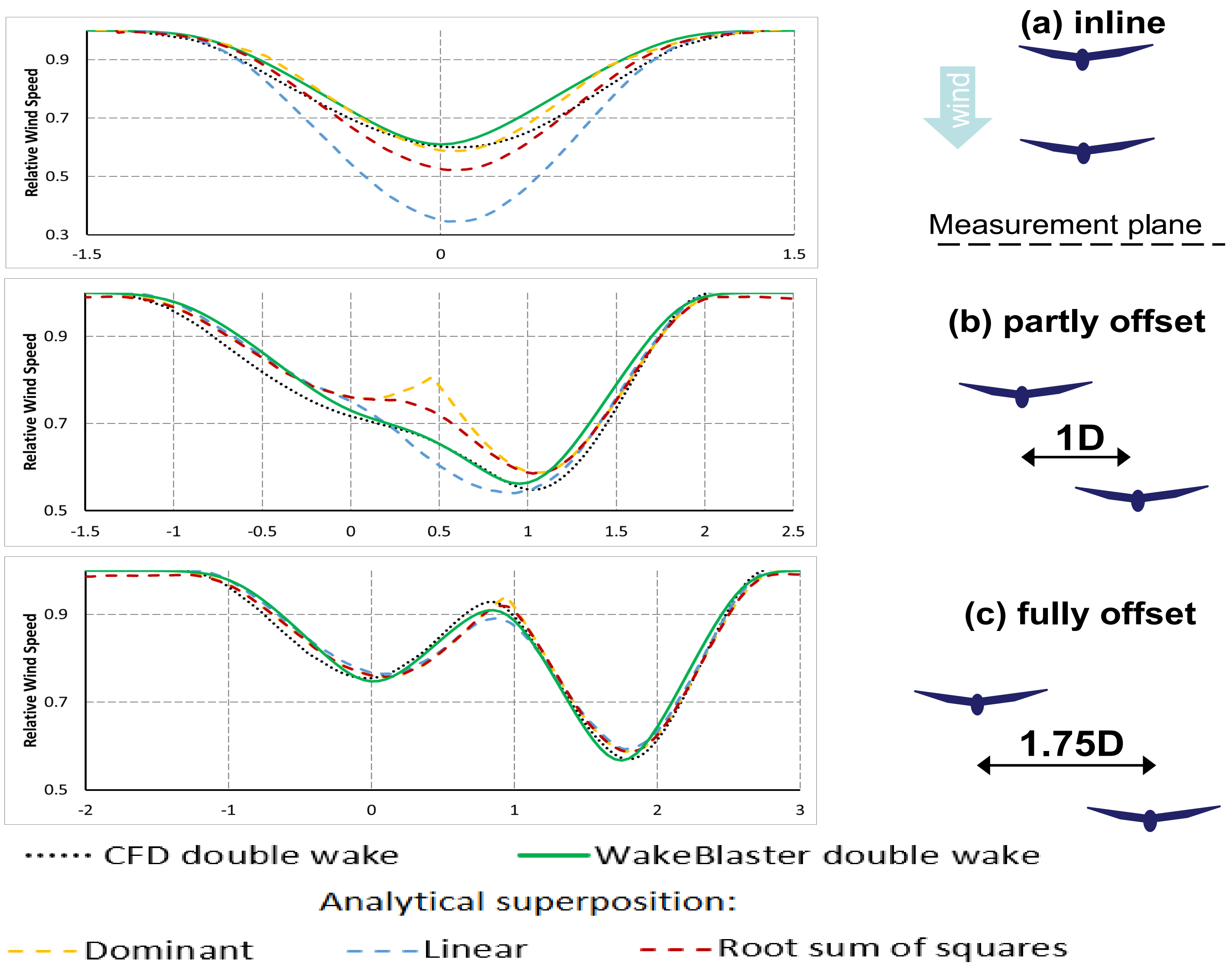
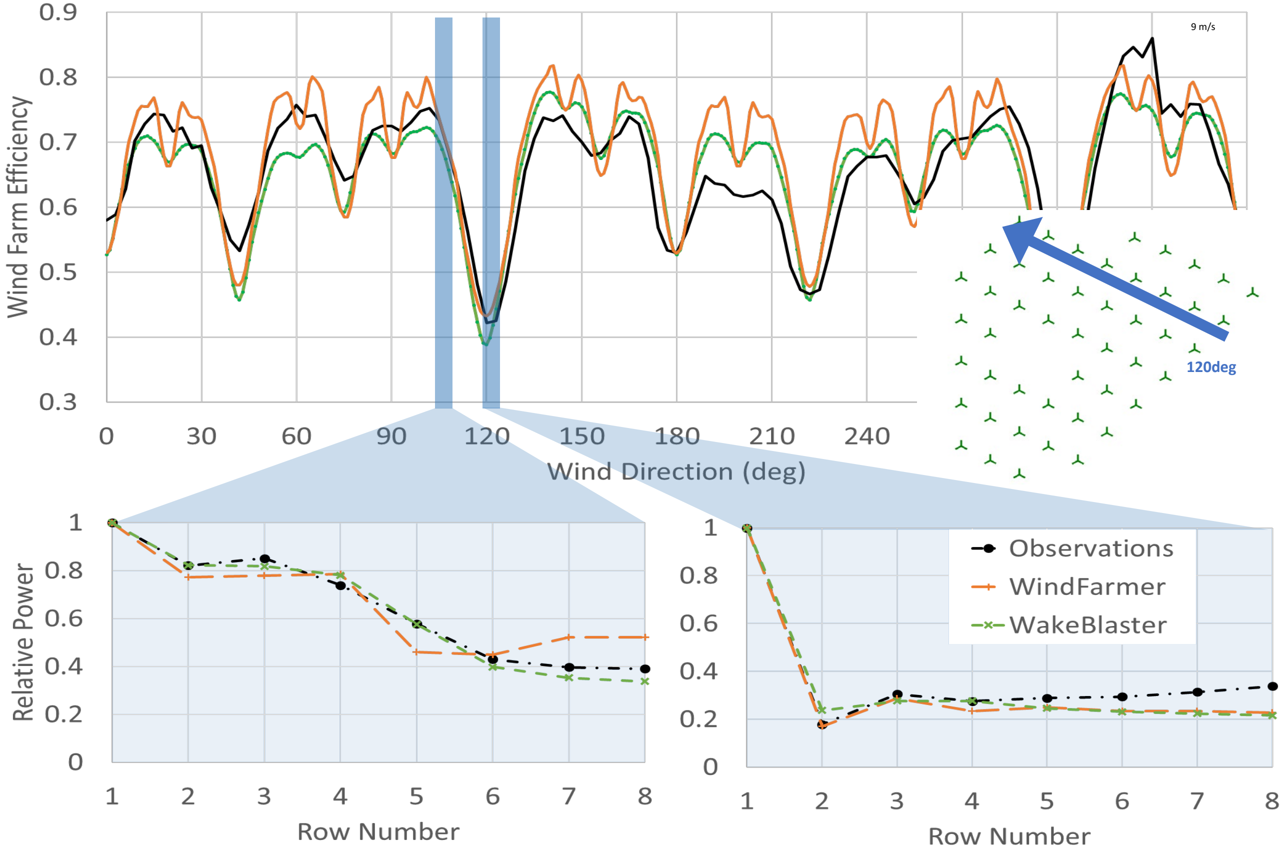
Verification – wake superposition



Validation – compact offshore wind farm



Target: reproduce directional wind farm production

Target: reproduce partial wake superposition at each turbine

Target: reproduce wakes turbine to turbine for linear arrangement

Method: data processed to power matrix and flow case extracted. Model calculation for average ambient inflow conditions. Example: Lillgrund wind farm in Sweden[1]

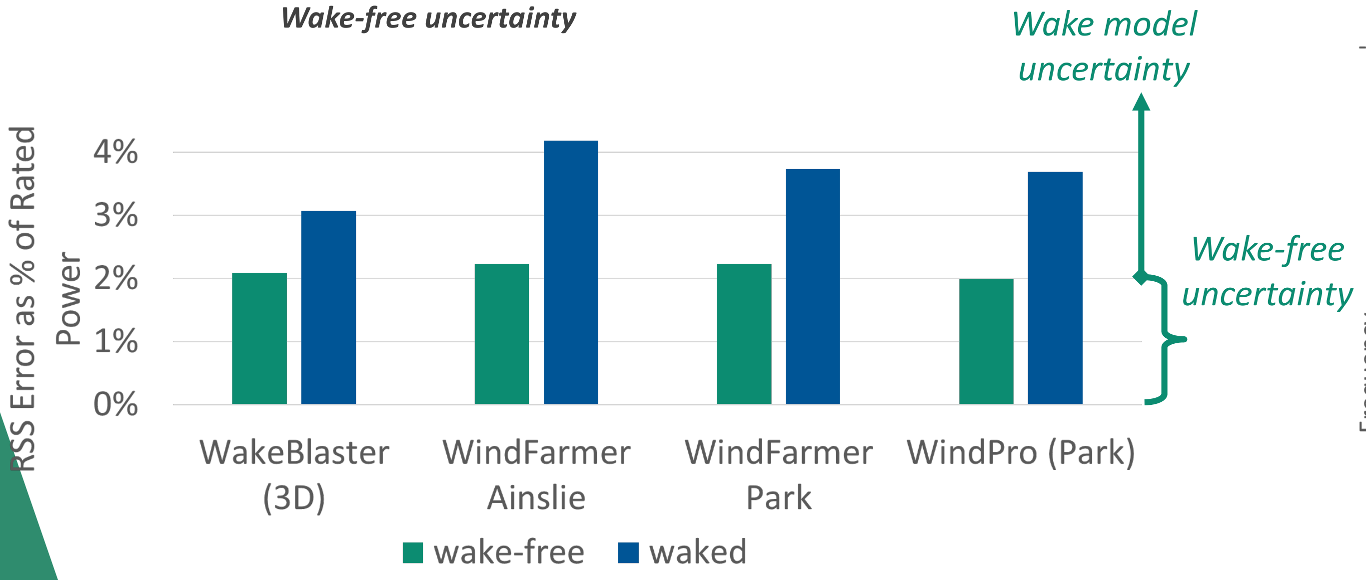
Solution: Match with full scale data achieved

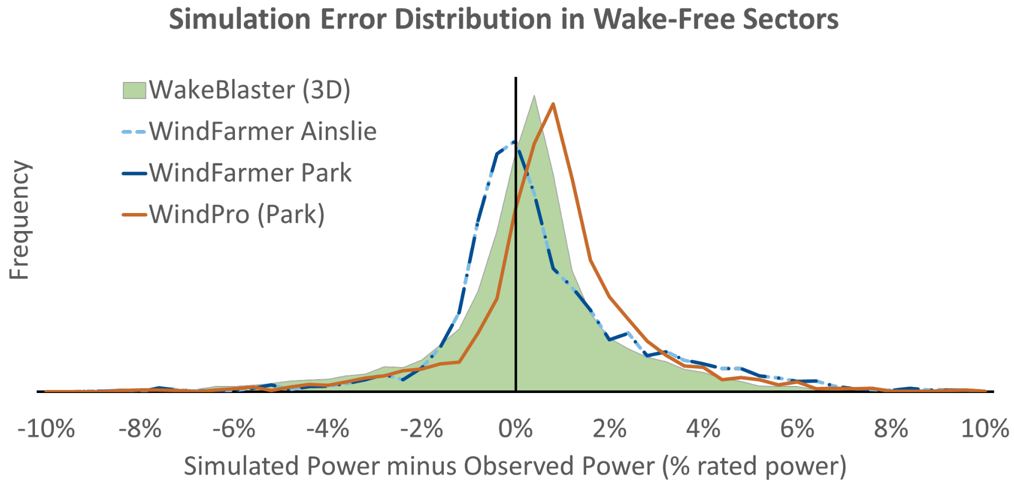
Validation – Onshore – Error Distribution

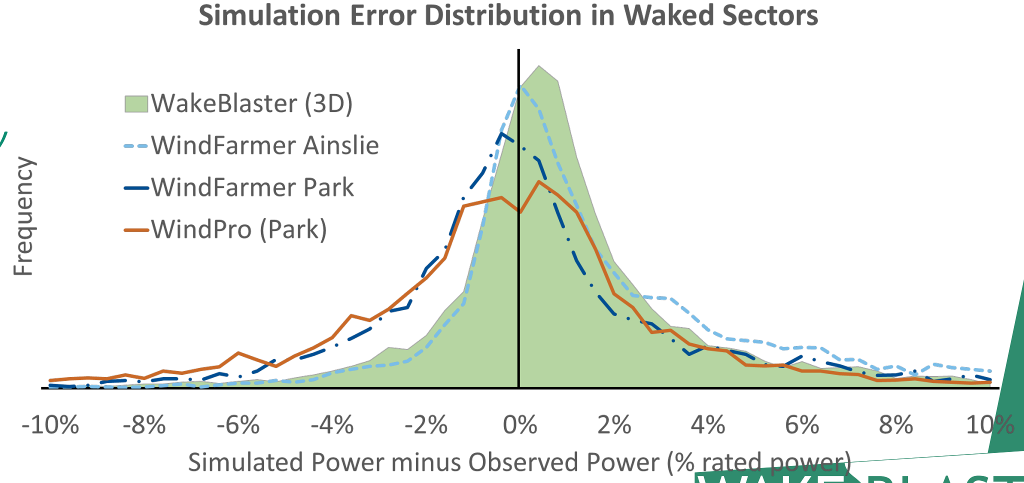
Calculate error (simulated – observed) in every wind speed and direction bin and do some stats!

Terrain & flow uncertainty + *Power curve uncertainty* + *Observational uncertainty* + *Wake model uncertainty* = *Total uncertainty*

Wake-free uncertainty

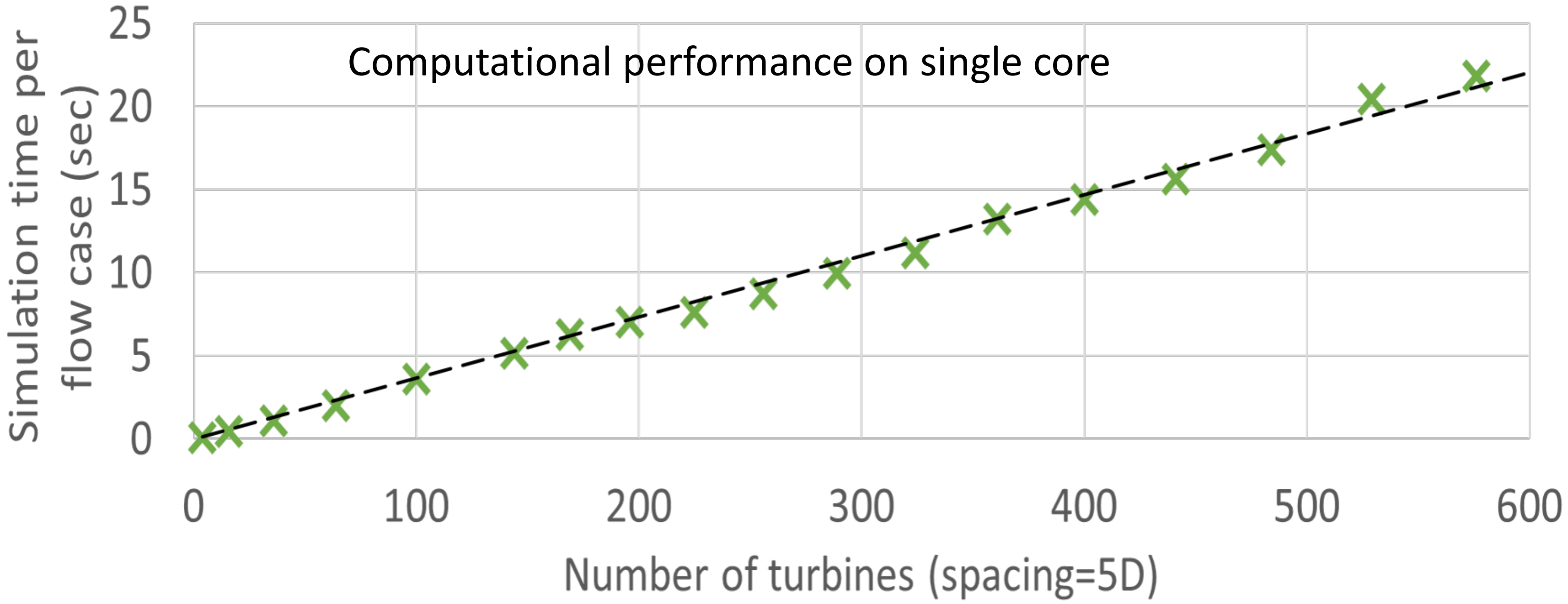






Verification - Scalability

- Can calculate wind farm AEP in minutes
- Practical for wind farms with up to 10,000 wind turbine



Any Questions?

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