The analytical wind farm efficiency and wake model EFFWAKE

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EFFWAKE

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Introduction

Analytical models are needed for rapid assessment of major features of planned wind farms

There are two types of analytical wind farm models:

(1) bottom-up models: superposition of multiple wakes, suitable for small farms

(2) top-down models: wind farm is seen as one homogeneous entity which contributes to momentum dissipation, suitable for large farms

Short Characterization

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EFFWAKE is a top-down analytical wind farm efficiency and wake model for an indefinitely large wind farm

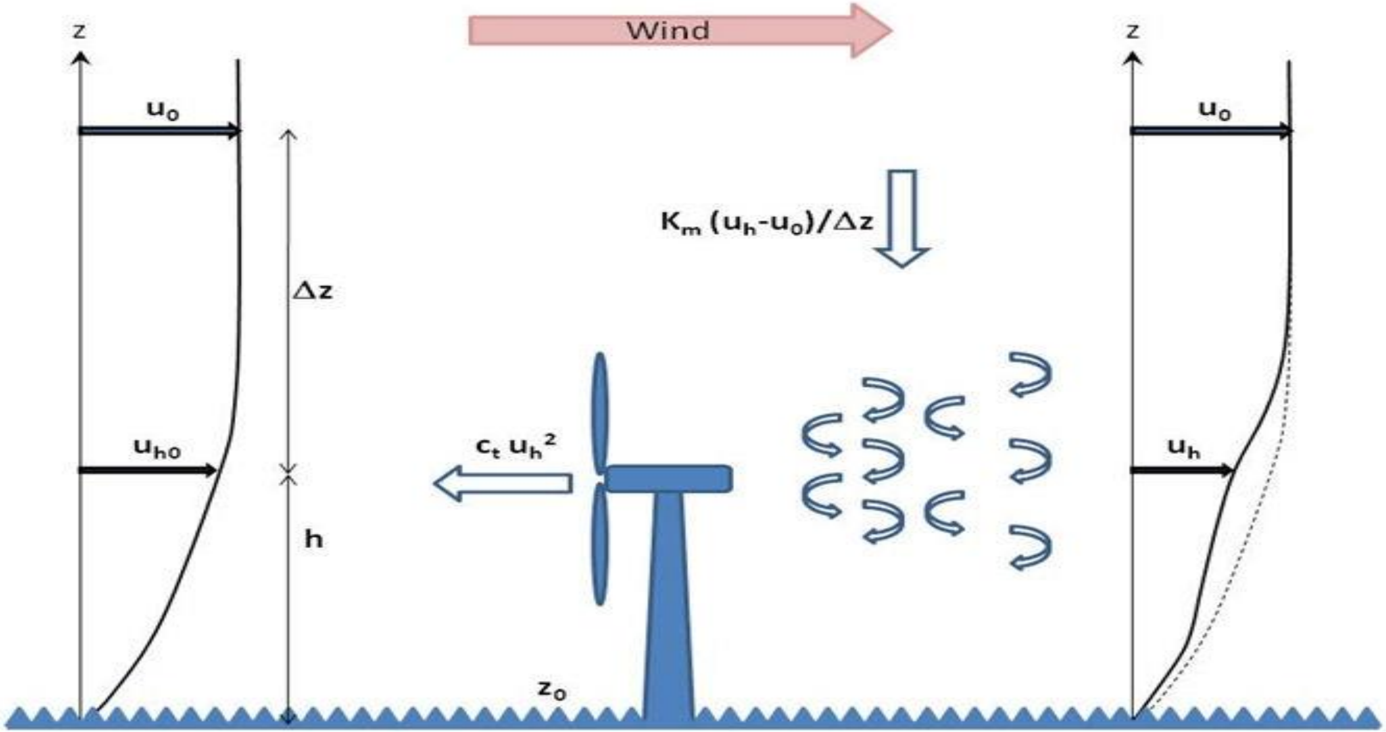
EFFWAKE is based on an equilibrium between momentum dissipation by WEA and re-supply by vertical turbulent fluxes from above

EFFWAKE is based on Prandtl-layer relations for the full WEA layer

EFFWAKE is layout-independent and wind direction-independent

EFFWAKE considers thermal stability of Prandtl layer and turbine-generated turbulence

Short Characterization



Short Characterization

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farm efficiency (in terms of power)

$$R_p = R_t^3 = \frac{\left(\frac{\phi_m c_{s,h}}{\kappa^2} + f_z I_{ueff}\right)^3}{\left(\frac{\phi_m c_{teff}}{\kappa^2} + f_z I_{ueff}\right)^3}$$

recovery of wind speed in the wake

$$R_n(t) = \frac{u_{hn}(t)}{u_0} = 1 + \left(\frac{u_{uhn0}}{u_0} - 1\right)\exp(-\alpha t)$$

(temporal ➔ spatial domain)

$$R_{np} = R_n^3(x) = R_n^3(t u_{h0}) = 0.95$$

History

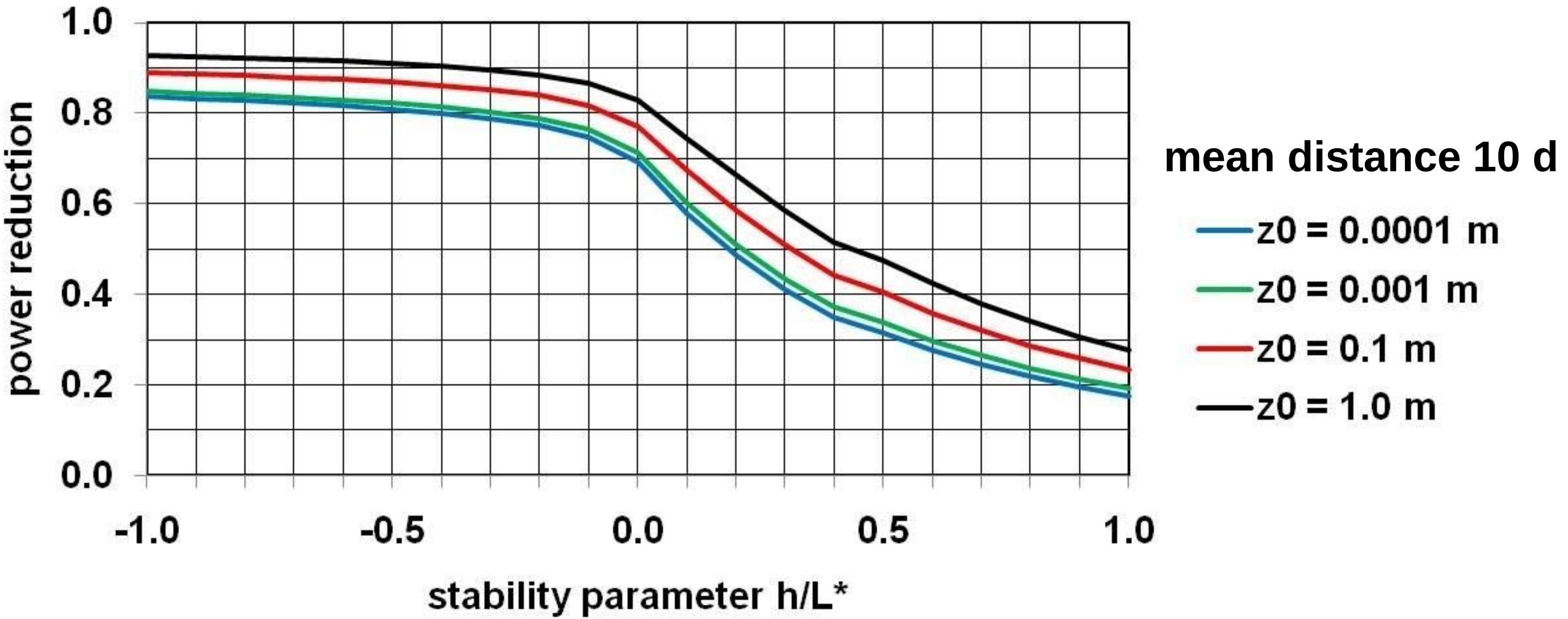
- **Newman (1977)**, wind speed at hub height as function of turbine density, wind farm considered as additional roughness
- **Bossanyi et al. (1980)**, extensive review on previous approaches, wind farm efficiency, wind speed-dependent turbine drag, assumptions on replenishment from above using a logarithmic profile, basis of all top-down models
- **Jensen (1983)**, redistribution of momentum in a single wake, basis of all bottom-up wake models
- **Frandsen (1992)**, first idea for this farm efficiency top-down model, two-layer model with geostrophic drag law in the outer layer used for the determination of the friction velocity

History

- **Emeis und Frandsen (1993)**, equations for farm efficiency for neutral stratification with no wind profile assumptions, ratio of mixing length to vertical distance to undisturbed flow is the only tuneable parameter (core idea of EFFWAKE)
- **Rooijmans (2004)**, enhancement of the E&F93 model for thermal stratification by making the mixing length stability-dependent using André (1978), comparison with MM5 shows very similar results
- **Emeis (2010)**, EFFWAKE, inspired by Rooijmans (2004) extension of the E&F93 model with surface drag and vertical exchange coefficient (instead of mixing length) stability-dependent, computes farm efficiency and wake length, without turbine-generated turbulence
- **Emeis (2018)**, EFFWAKE, second version with turbine-generated turbulence added

Sample Results

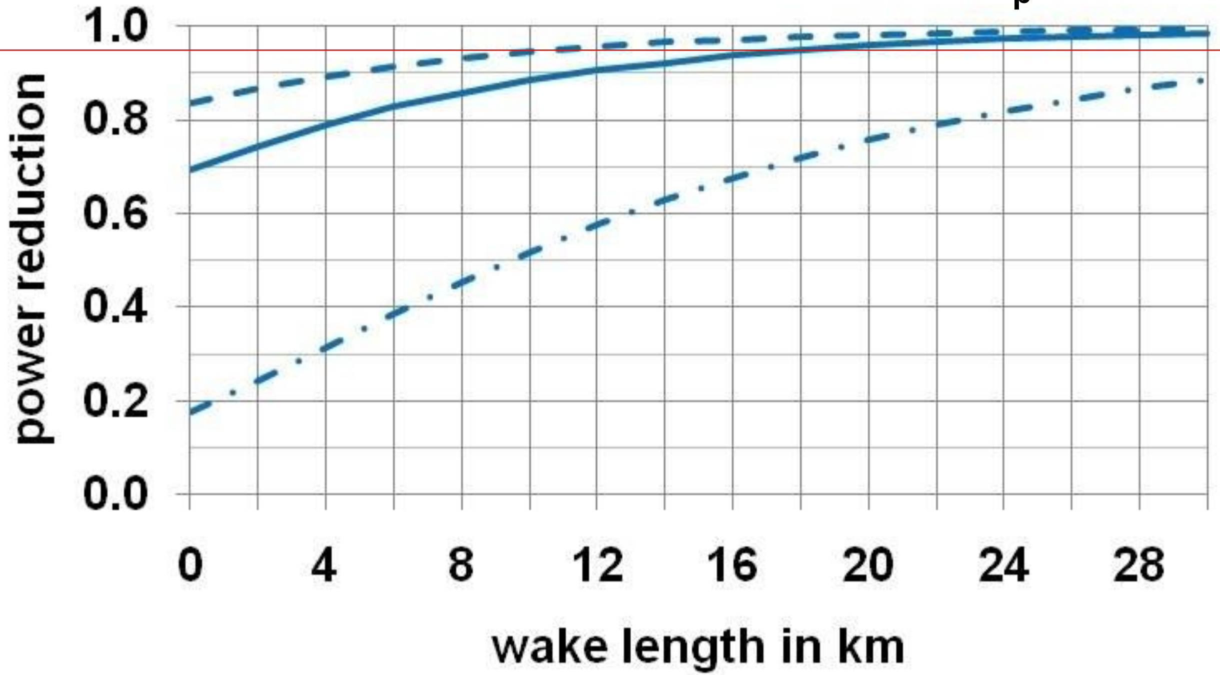
farm efficiency



Sample Results

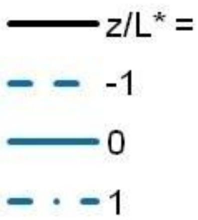
wake length

definition: $R_p < 0.95$



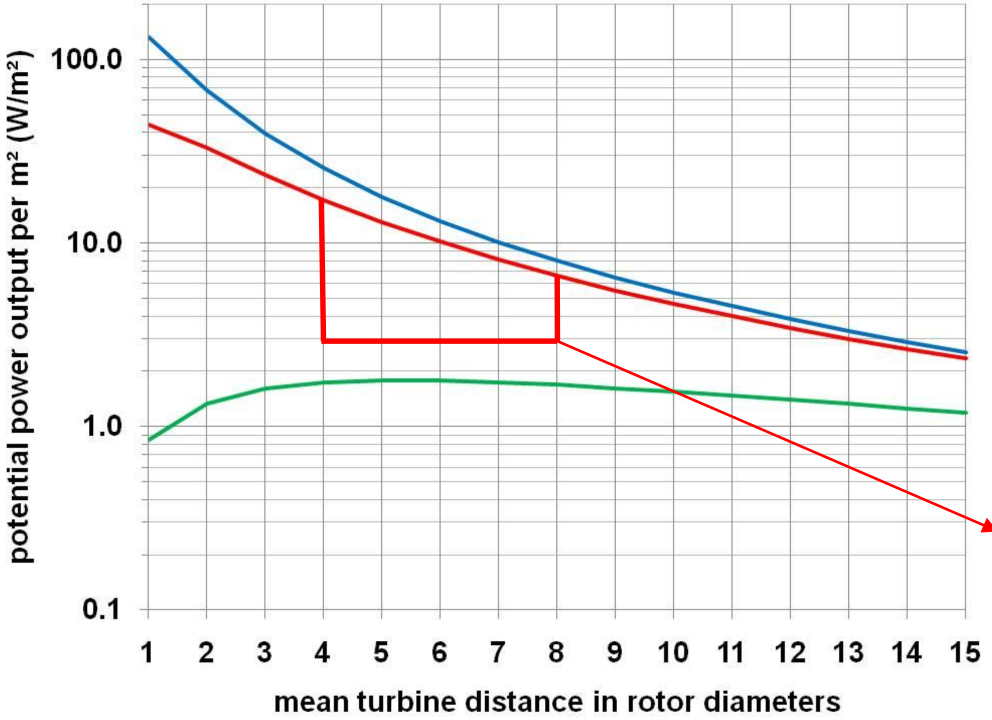
mean distance 10 d

offshore (z_0 = 0.0001 m)



Sample Results

optimum turbine density

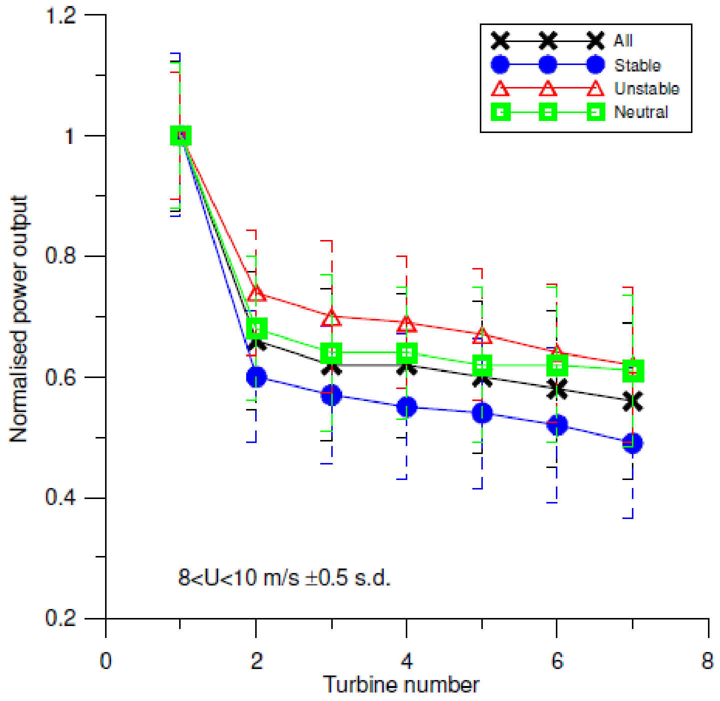


offshore (z_0 = 0.0001 m)

unstable (h/L* = -1)
neutral
stable (h/L* = 1)

halving the mean distance
➔ four times as much turbines
➔ yield increases by ~2.5

Validation

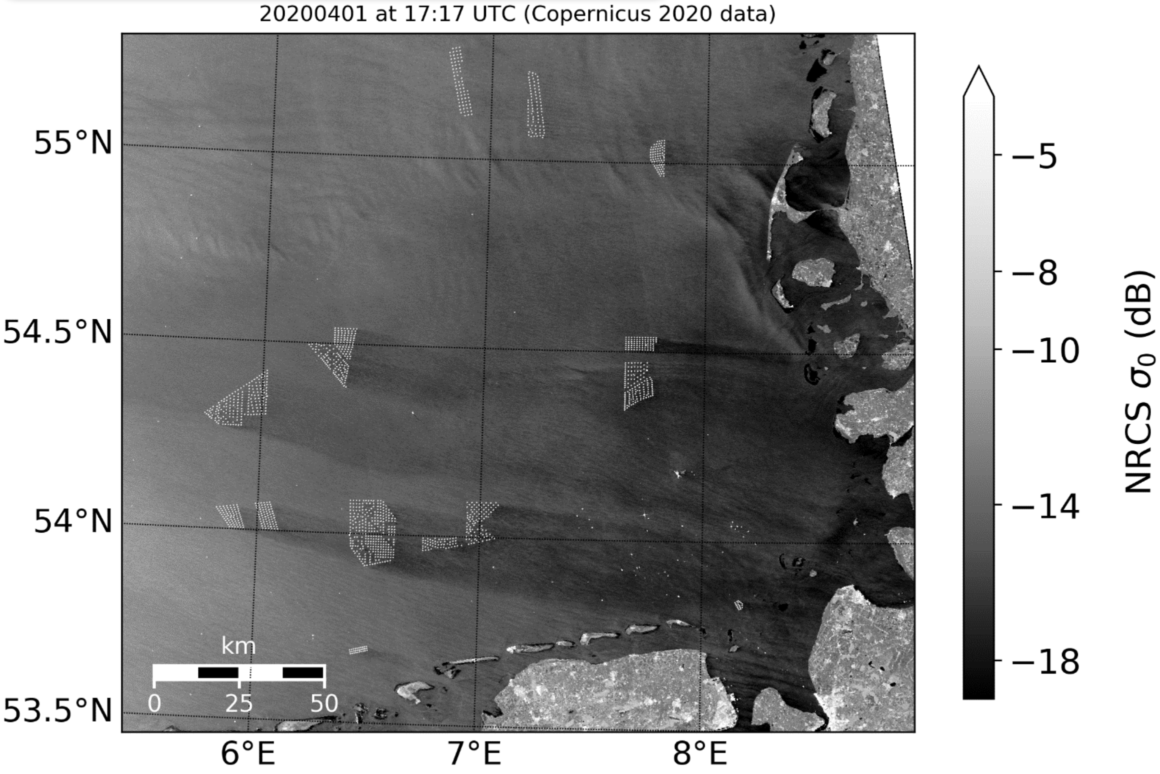


farm efficiency (in terms of power)

order of magnitude is correct even for rather small wind farms (Nysted: 7 by 7 turbines)

Barthelmie R, Frandsen ST, Rethore PE, Jensen L., 2007: Analysis of atmospheric impacts on the development of wind turbine wakes at the Nysted wind farm. Proceedings of the European Offshore Wind Conference, Berlin 4.-6.12.2007.

Validation



farm wakes in SAR satellite data

April 2020 , **produced by Bughsin Djath (Hereon) from Copernicus remote sensing data**

(@) European Space Agency – ESA

Validation

Cañadillas et al. 2020, Wind Energy
DOI: 10.1002/we.2484

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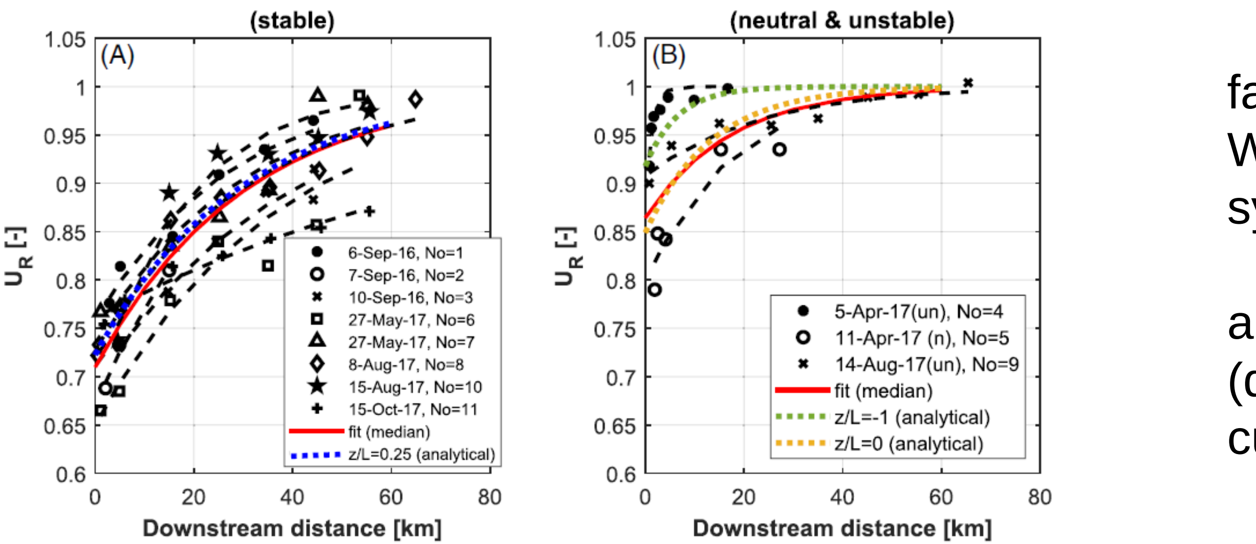

FIGURE 7 The wind speed recovery $U_R(x)$ as a function of the downstream distance x. Each data point indicates the wind speed recovery U_R (Equation 5) at the minimum wake wind speed U_{min} for each wake traversal at hub height ($h \approx 100$ m) for stable A, and unstable/neutral B, stratification based on the stability criteria presented in Table 2. The black dashed curves are exponential fits to each case based on Equation (5), red curves correspond to the exponential function applied to the median values of the stable A, and unstable B, cases, and the dashed colored curves are calculated from the analytical model introduced in Section 2 for $z/L = 0.25$ (A) and $z/L = 0, -1$ (B) [Colour figure can be viewed at wileyonlinelibrary.com]

farm wakes from WIPAFF data (black symbols)

and EFFWAKE (dashed coloured curves)

Validation

Platis et al. 2021, Wind Energy
DOI: 10.1002/we.2568

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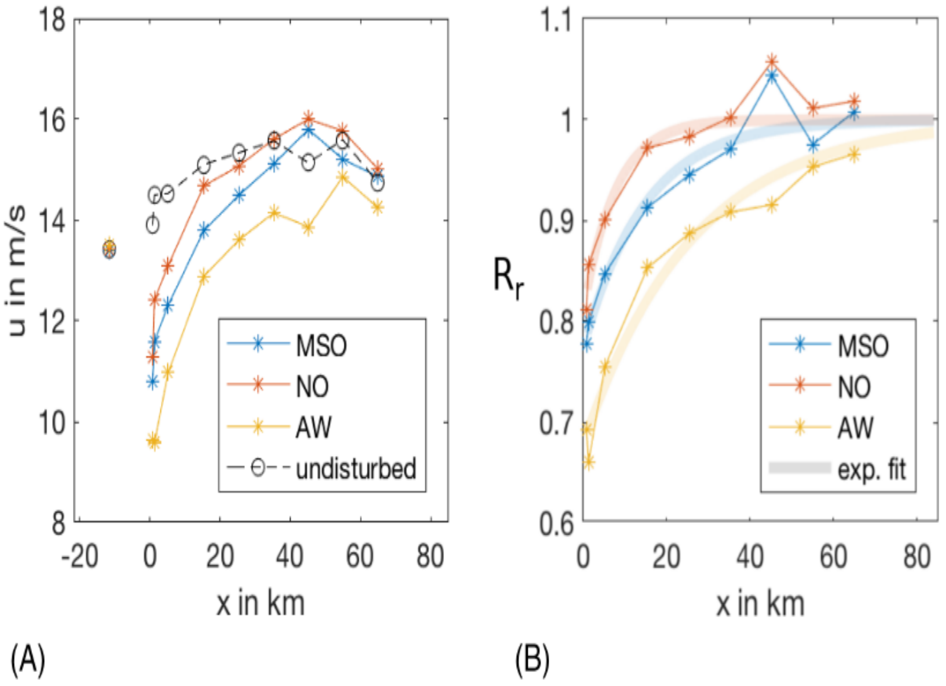
FIGURE 5 (A) Wind speed in the wake and undisturbed zone of Flight 31. The blue line indicates the wind speed in the wake downstream of the wind farm MSO, the red NO and the yellow one AW. The dashed black line indicates the wind speed of the undisturbed flow aside of the wake. (B) Relative wind speed deficit of Flight 31 [Colour figure can be viewed at wileyonlinelibrary.com]



farm wakes from WIPAFF data (lines and symbols)

and EFFWAKE (shaded curves)

Outlook

EFFWAKE is a rapid assessment tool. Suitable chains of numerical models at different scales can yield higher precision (if sufficient input data is available).

(Financially) Optimum density of turbines in a large farm can be easily estimated with EFFWAKE when adding price tags to the turbines.

Turbines get larger which violates the assumption that wind turbines are fully immersed in the Prandtl layer.

Upstream blocking of larger farms is not (yet) considered.

Coastal effects (internal boundary layers) are not considered. Issue in the currently running project X-Wakes.

Acknowledgements

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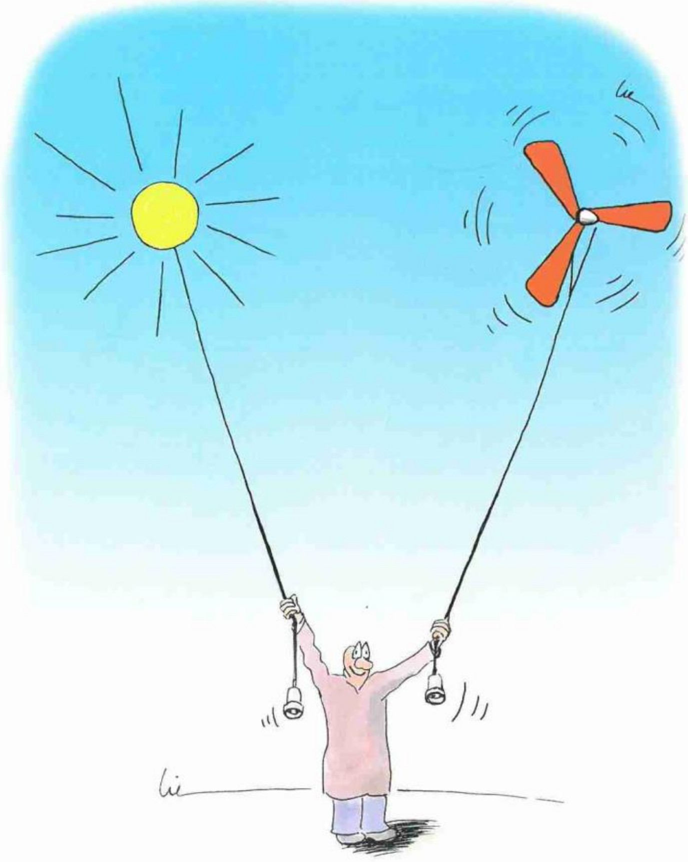
on the basis of a decision by the German Bundestag

Thank you for your attention



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