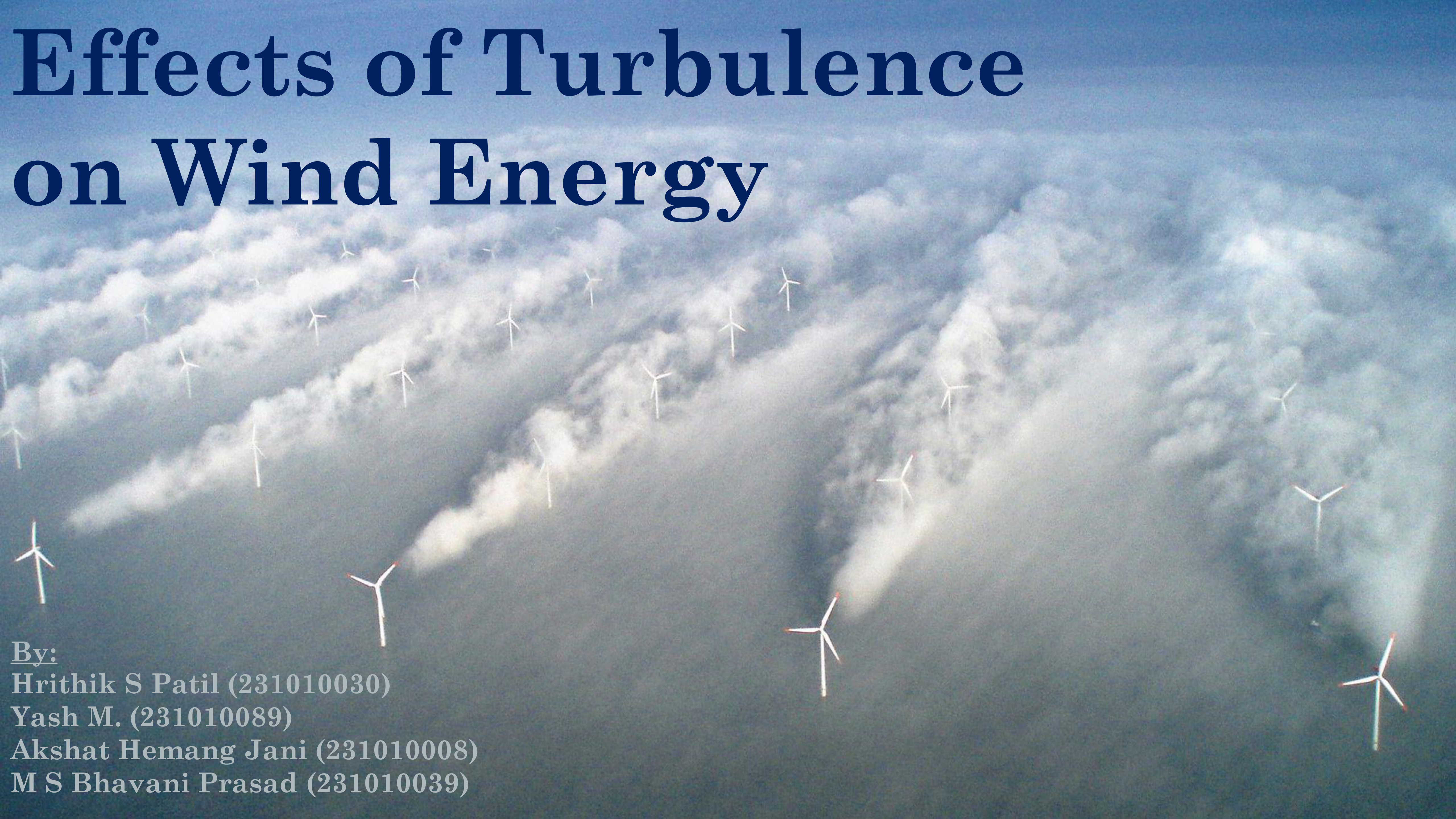

Effects of Turbulence on Wind Energy

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Important Definitions

$$C_p = \frac{P_{extracted}}{P_{available}} = \frac{P}{\frac{1}{2}\rho A U^3}$$

$$C_T = \frac{T}{\frac{1}{2}\rho A U^2}$$

$$\text{Tip Speed Ratio}(\lambda) = \frac{\Omega \mathrm{R}}{\mathrm{U}}$$

$$\text{Turbulence Intensity}(\mathrm{Ti}) = \frac{\sigma_u}{\mathrm{U}}$$

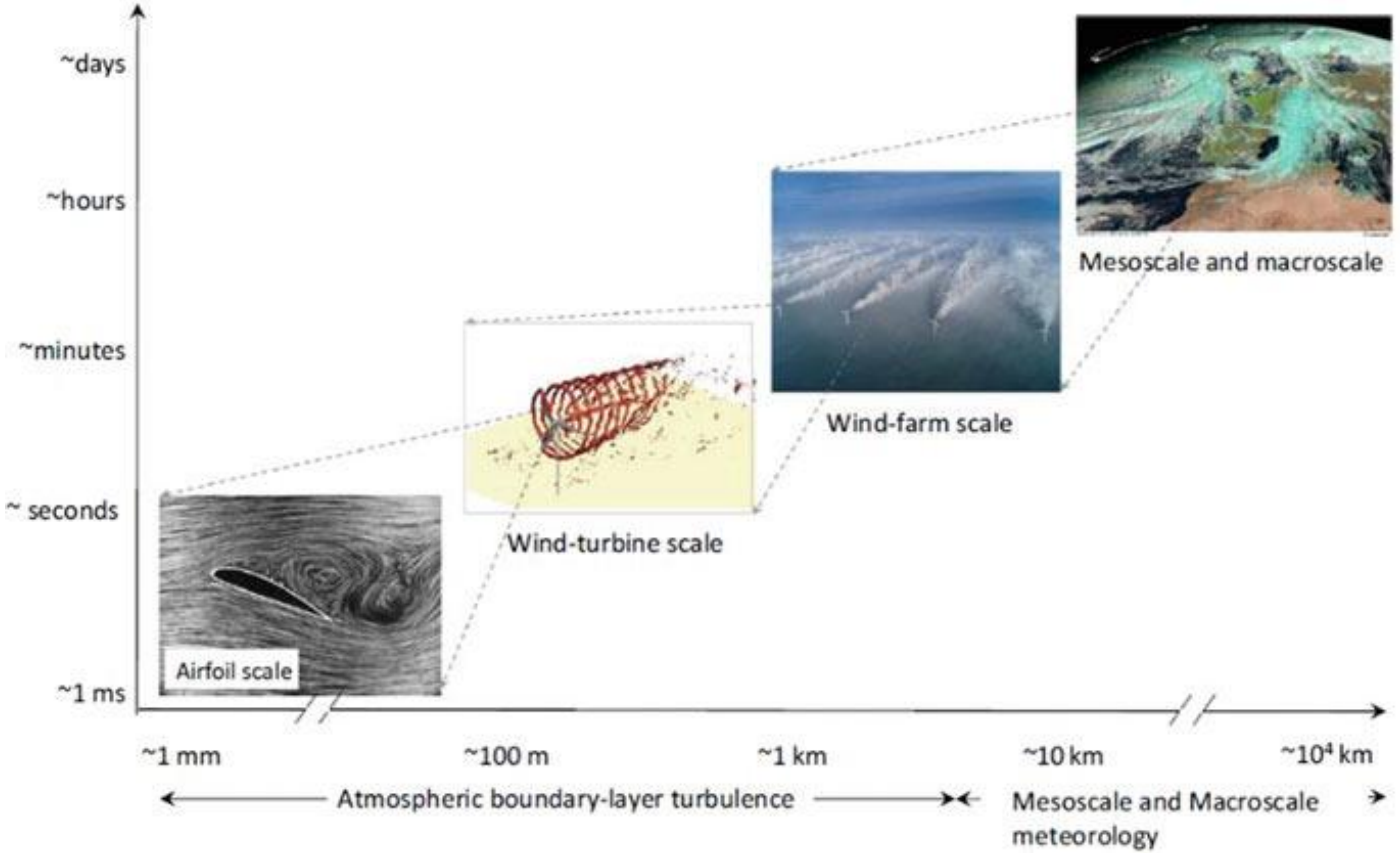
$$\text{Tip Reynolds Number}(\mathrm{Re}) = \frac{\rho \Omega \mathrm{Rc}}{\mu}$$

$$a = \frac{U_1 - U_2}{U_1}$$

Where

Ω= angular velocity
R= Rotor radius
U= free stream Velocity

Introduction



BASIC MODEL EQUATIONS (KERMANI, N. A., ANDERSEN, S. J., SØRENSEN, J. N., & SHEN, W. Z. (2013))

To make theoretical approach, the wake behind a wind turbine is assumed to be incompressible, steady and fully turbulent. In addition the inflow is assumed to be uniform and stationary with time, and the ground effects and pressure gradient outside the wake are negligible.

The wake is described in cylindrical coordinates with the axial and radial velocity components respectively as;

$$\frac{\partial(\bar{u})}{\partial x}+\frac{1}{r}\frac{\partial(r\bar{v})}{\partial r}=0 \quad ; \quad \frac{\partial(u')}{\partial x}+\frac{1}{r}\frac{\partial(rv')}{\partial r}=0 \qquad (1)$$

$$\left(\bar{u}\frac{\partial\bar{u}}{\partial x}+\bar{v}\frac{\partial\bar{u}}{\partial r}\right)=-\frac{1}{r}\frac{\partial(r\overline{u'v'})}{\partial r}-\frac{\partial\left(\overline{u'^2}\right)}{\partial x}+\nu_s\left(\frac{\partial}{\partial x}\frac{\partial\bar{u}}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\bar{u}}{\partial r}\right)\right)-\frac{1}{\rho}\frac{\partial\bar{p}}{\partial x} \qquad (2)$$

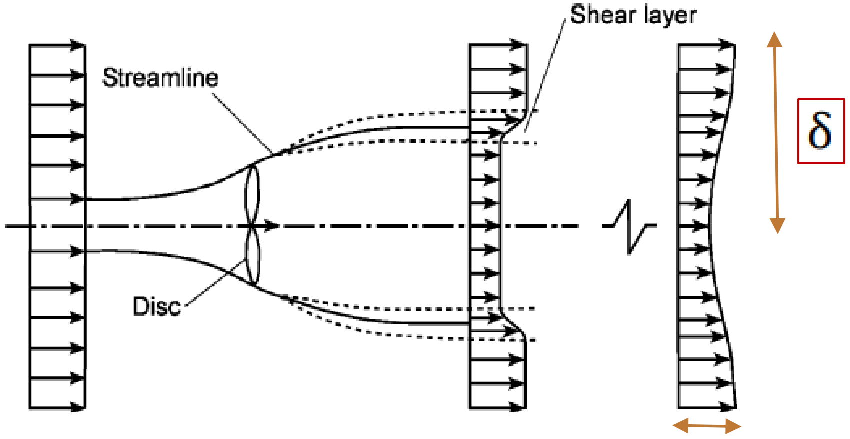
Viscous Terms

Pressure Term

where u' and v' are the fluctuating parts of u and v, and a bar over the quantities denotes time average.

In far wake region,

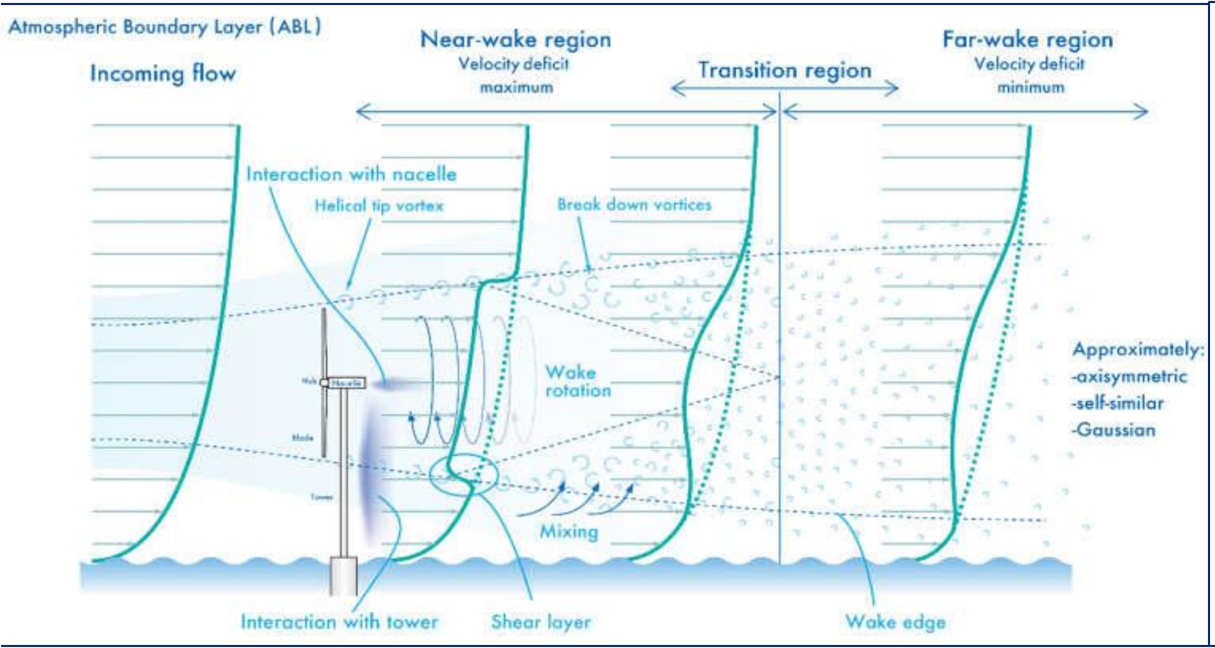
$\boxed{\overline{u_s}} = \boxed{U_\infty - \bar{u}}$: cross-sectional wake velocity deficit

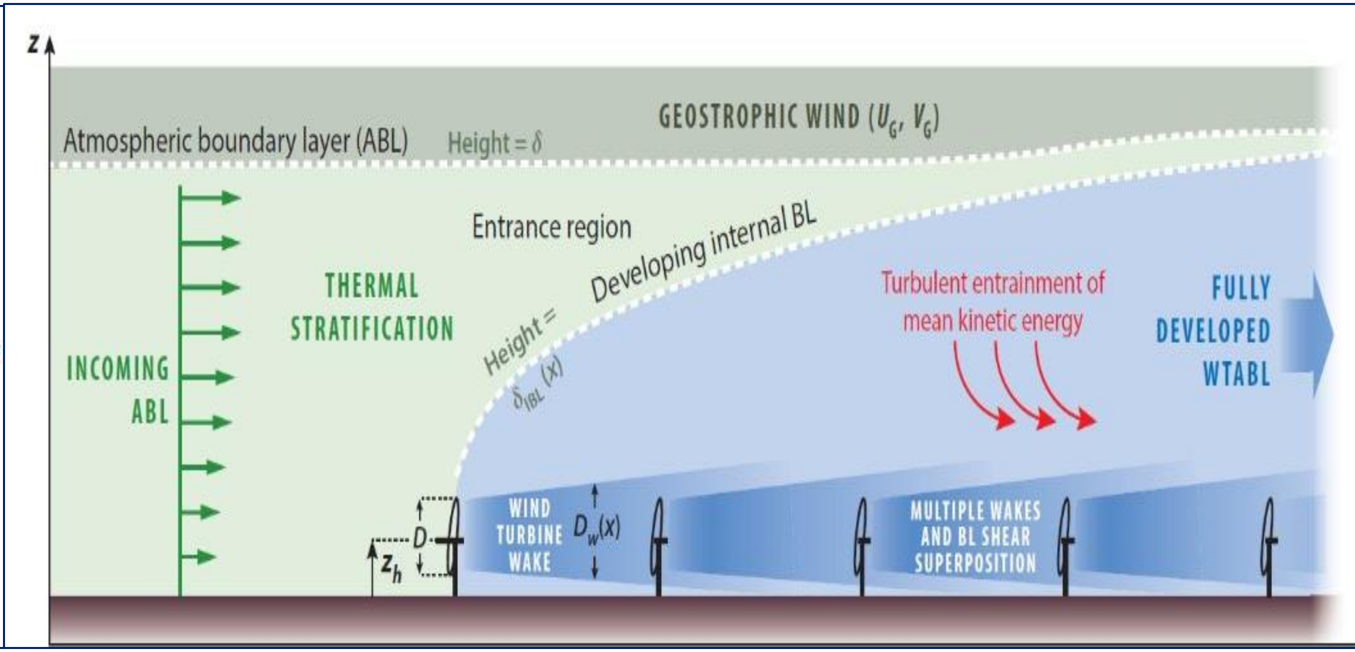


For a fully turbulent axisymmetric wake, using order or magnitude analysis eqn (2) can be simplified as:

$$(U_\infty)\frac{\partial}{\partial x}(\overline{u_s})=-\frac{1}{r}\frac{\partial(r\overline{u'v'})}{\partial r}+\nu_s\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\overline{u_s}\right)$$

WAKE DESCRIPTION





- A classic turbulent axisymmetric wake in a laminar inflow is expected to grow far downstream following a 1/3 power law (Tennekes & Lumley 1972, Larsen 1988).

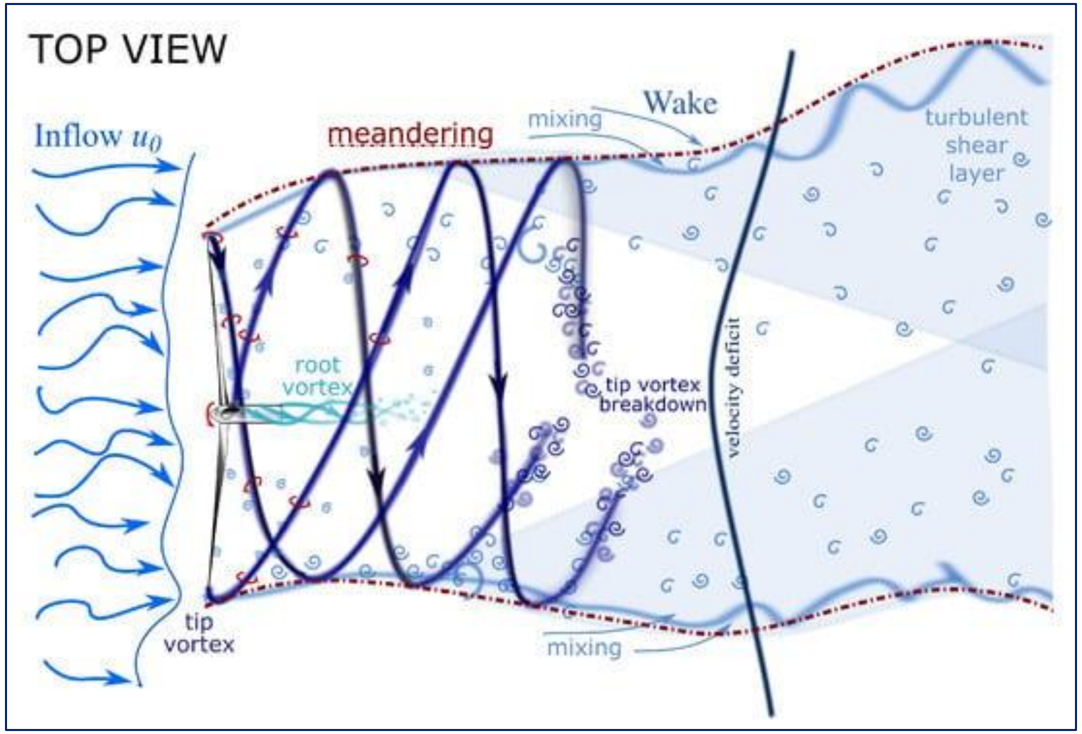
- Specifically, if Dw(x) is the wake diameter as a function of downstream distance x and D the turbine diameter, one expects $D_w(x)/D \sim (x/D)^{1/3}$

- Directly behind the wind turbine, a strong velocity deficit is created that slowly recovers with increasing downstream distance

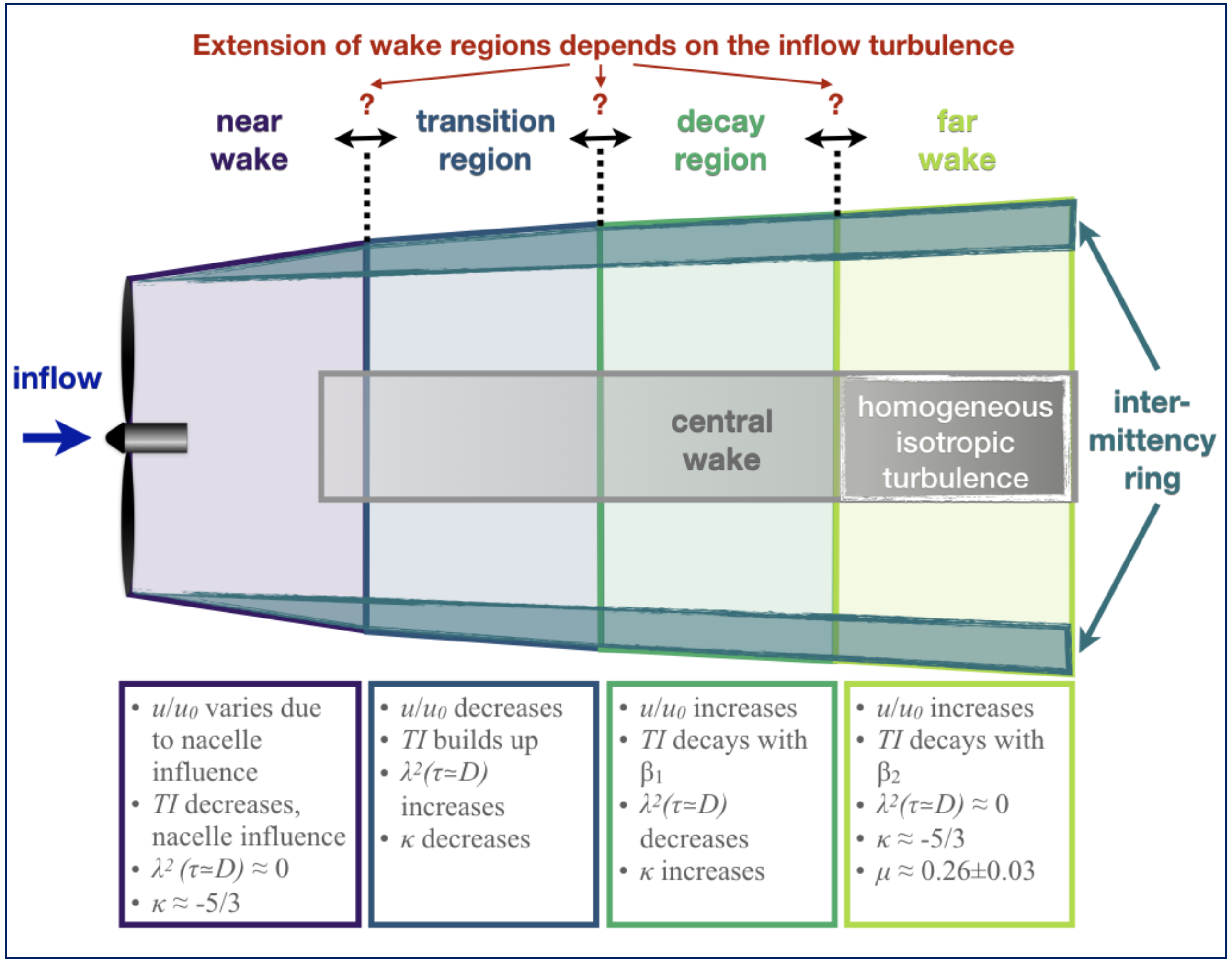
- Wind turbine wakes are mostly viewed in an average sense: the flow at any point is treated as an ensemble average over many blade revolutions

- As the shear layer reaches the wake axis, near wake region ends, after which there is a transition region leading to the far wake region, where the wake is completely developed

EVOLUTION OF WAKE

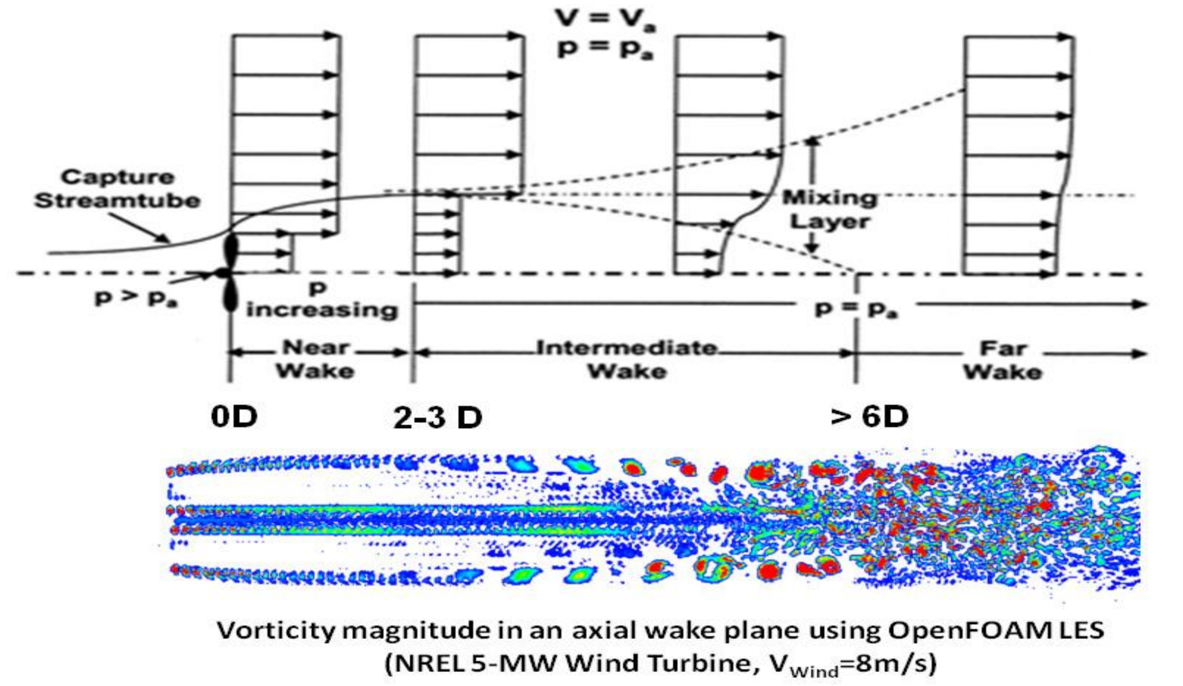


D = Diameter of Rotor



- In the case of **laminar inflow**, the near wake extends to roughly 3D, the transition region extends approximately between 3D and 6D, the decay region is found between 6D and 9D, and the far wake starts around 9D.
- In the case of **turbulent inflow**, the near wake extends to approximately 1D, the transition region is found between 1D and 2D, the decay region between 2D and 2.5D, and the far wake from approximately 2.5D.

CFD RESULTS FOR WIND TURBINE WAKE



Vorticity magnitude in an axial wake plane using OpenFOAM LES (NREL 5-MW Wind Turbine, V_{Wind}=8m/s)

Fig.1 The Wake of Wind Turbine (D = Rotor Diameter)

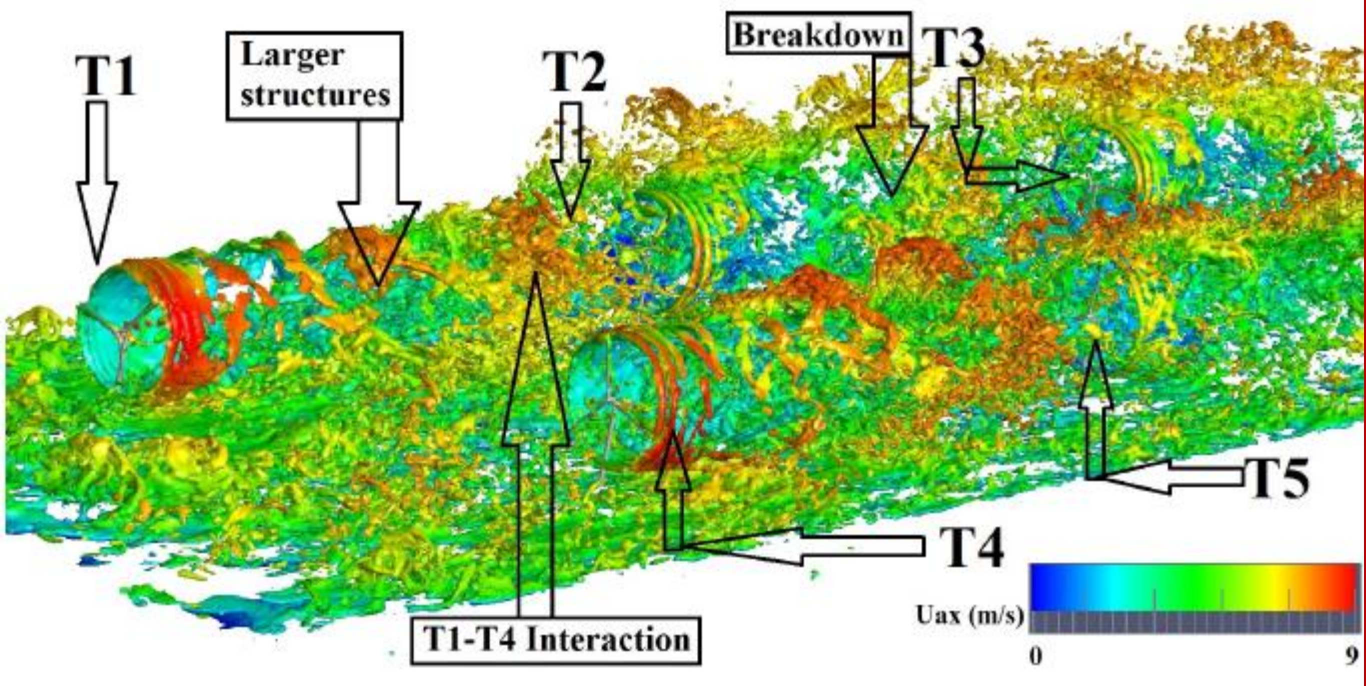


Fig.2 iso-surface of vorticity magnitude equal to 0.5 (1/s) colored by streamwise velocity

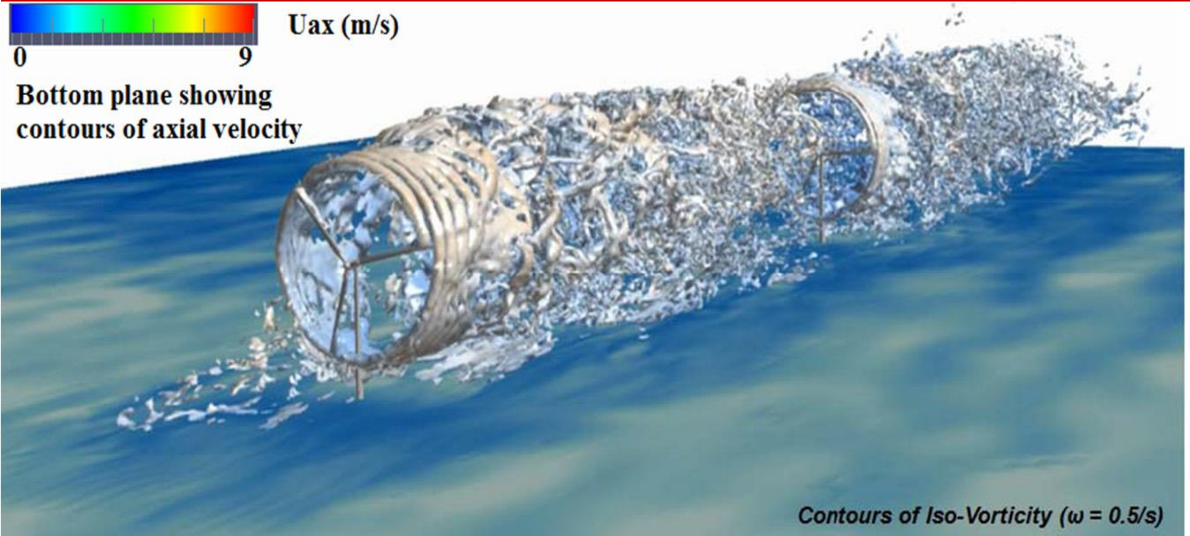


Fig.4 Turbine Turbine Interaction in NBL flow

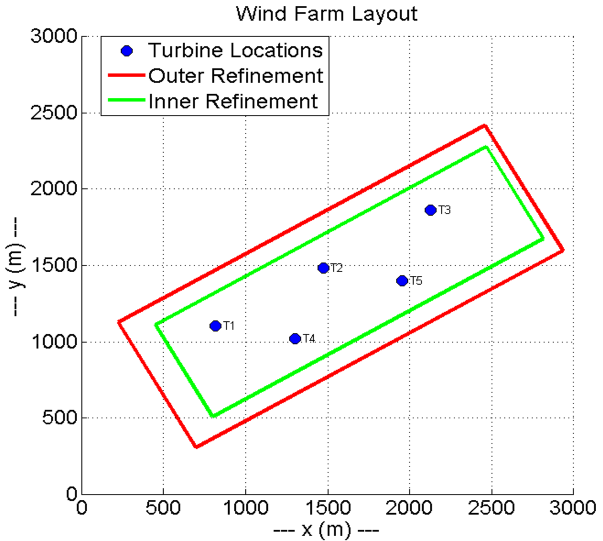


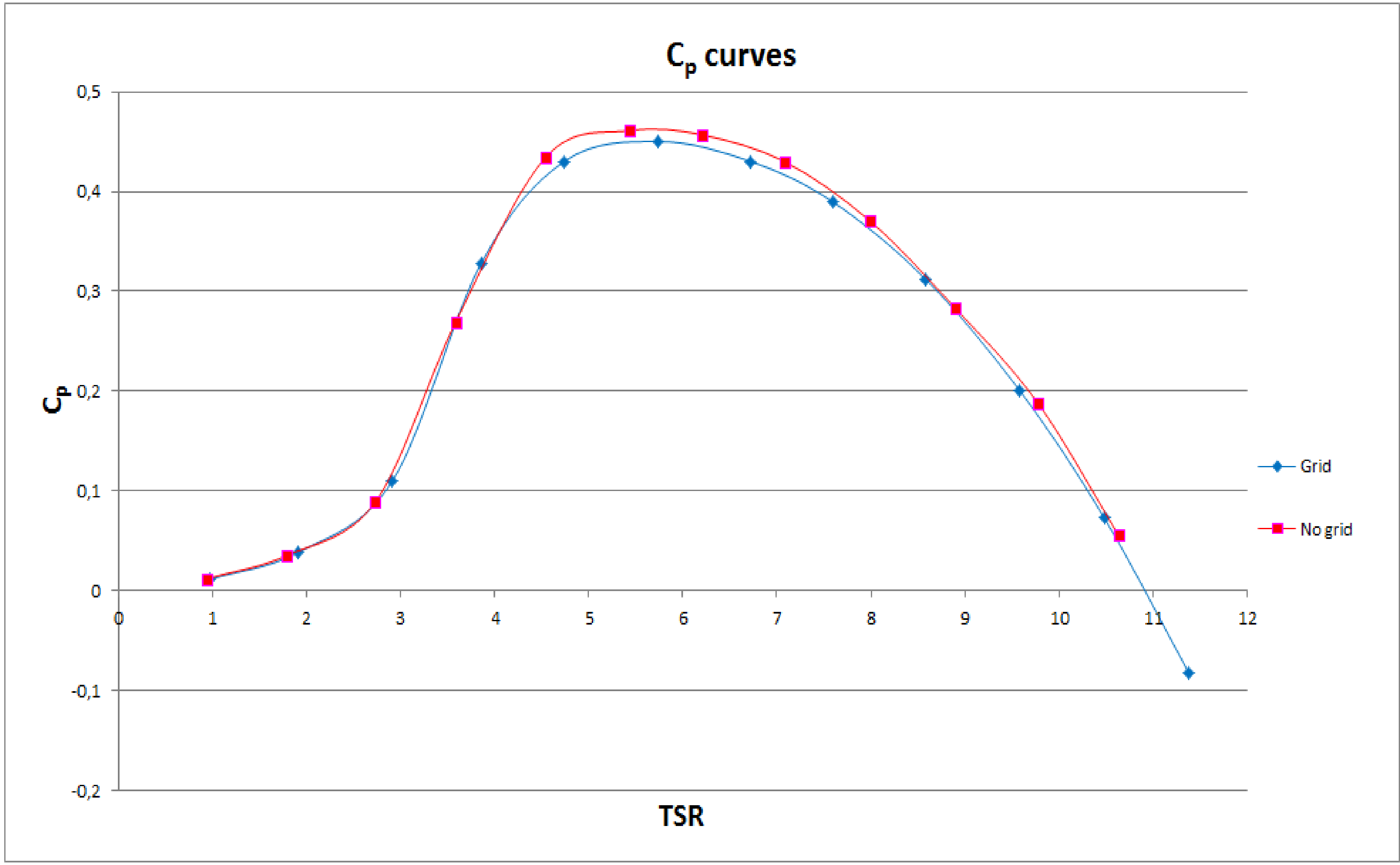
Fig.3 Nested Grid used for simulations

RESULTS

- The experiments show that the power coefficient without free stream turbulence is slightly higher compared to the results with a free stream turbulence intensity of 5.5 %, except at low tip speed ratios where the effect of stall dominates.
- The largest difference in the power coefficients is found at 6, the wind TSR, which is where turbine operates most efficiently.
- For offshore wind farms the ambient turbulence is often lower than on shore, leading to more persistent wakes. Hence, the total power losses in a wind farm due to wind turbine wakes may be higher offshore than on shore because of lower levels of turbulence.

RESULTS

- As turbulence increases, it delays stall,
- Hence wind turbine can be operated at higher velocity leading to higher power produced.
- At low TSR Cp is low due to stall effects.



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THANK YOU