Mesh resolution effects in Large Eddy simulations of atmospheric boundary layers in various stratifications and terrains

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High fidelity modeling...

Just another buzz word? (...and what does it mean to the turbine?)

Validation vs verification

And what about accuracy and robustness...?
WHY LES of the ABL – and what about resolution?

Resolved turbulence in time and space

time series, covariance functions and coherence

fatigue loads estimations
WHY LES of the ABL – and what about resolution?

So by definition – LES is Mesh size dependent (in contrast to RANS?)
Critical areas: surface layers, stable layers, entrainment layer and in complex terrain; in principle everywhere...

Critical scales: small scales inside the inertial range (non-Gaussian scales)
Current setup

- Pseudo spectral LES developed at NCAR
  - (Sullivan & Patton JAS 68, p.2395, 2011 and Sullivan et et. JAS 71, p.4001, 2014 etc )

- Pseudo spectral means explicit filter in horizontal directions (2. order FD in vertical)
  - in contrast to explicit filter in FV

- Deardorff SGS model with stability corrections

- Flat or curvy bottom (inhomogeneous terrain)

- Boussinesq approximation for buoyancy

- Radiation BC at top

Remember: non neutral stratified flows are non-stationary
Why LES works in shear produced boundary layers

\[ C_{uu} (k) \sim k_i^{-7/3} \]

\[ q^w \]

\[ \Delta = \{ 128, 23, 12, 6, 3 \} \]

\[ 128^3 \quad A \quad (\text{coarse}) \quad B \quad C \quad D \quad (\text{fine}) \quad 1024^3 \]
Conditional neutral boundary layer

Mesh size independence not yet achieved of TKE budget at 1024^3!
Conditional neutral boundary layer

\[
\frac{d}{dt} TKE = SP + PT + TT + BP + \epsilon
\]
Conditional neutral boundary layer

\[ \phi_m = \frac{dS}{dz} \frac{\kappa z}{u_*} \]
Conditional neutral boundary layer

SO, ~TI seems invariant cross resolutions – but resolved is not!
Conditional neutral boundary layer
Conditional neutral boundary layer

- Structure functions and the small scales (perhaps not turbine relevant... ??? )

Fine resolution (D) in agreement with generalized log-law of order $O(8)$ ($k^{-1}$ scaling regime)
Conditional neutral boundary layer

Spectral tensor in height, $z$:

$$
\Phi_{ij}(k_x, k_y, z) = \frac{1}{(2\pi)^2} \int \int R_{ij}(r_x, r_y, z)e^{-i(k_x r_x + k_y r_y)} dr_x dr_y
$$

Coarse

Fine
Conditional neutral boundary layer

\[ E_h(k_h) = \frac{1}{2} \int_0^{2\pi} (\Phi_{11}(k_h, \theta) + \Phi_{22}(k_h, \theta)) k_h d\theta \]

\[ E_w(k_h) = \int_0^{2\pi} (\Phi_{33}(k_h, \theta)) k_h d\theta \]
Convective and stable stratification

Convective

Stable (GABL1 @ Δ = 0.4m!)

(Sullivan & Patton JAS 68, p.2395, 2011)

(Sullivan et al. JAS 73, p.1815, 2016)
Complex terrain at Perdigao

Technique: Terrain following coordinates and pressure-velocity coupling through iteration

You have most likely all seen it plenty of times...
Complex terrain at Perdigao – strictly neutral
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Seems relatively robust (model to model)
Complex terrain at Perdigao – strictly neutral

Difference in $U_{norm}$ = impact on wind resources
Complex terrain at Perdigao – strictly neutral

Resolution in the two LES models:

\[ \Delta f_{ps} = \left( \frac{3}{2} \Delta x \Delta y \Delta z \right)^{1/3} \sim 1.3(\Delta x \Delta y \Delta z)^{1/3} \]
Final remarks

• Crucial areas are the surface layer and the entrainment layer.
• Even at highest resolution statistics are not necessarily converged – questionable if it has any effect on wind turbines (Berg et al. 2016)
• Expensive to carry out mesh studies.
• Convective boundary layers are more forgiven to resolution compared to stable– but are still capped by a stable stratified layer…
• Stable is tough – in complex terrain with large flow structures = BIG COMPUTATIONS!
• Daily cycle simulations – a tradeoff between mesh size and domain size ?