Details of Downscaling: “Turbulence Generation in Coupled Meso-to-Micro Simulations”

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MMC-Sponsored Industry Workshop
Atmospheric Challenges for the Wind Energy Industry
October 20th 2020
Disparate-scale atmospheric modeling

Length: $10^7$  $10^6$  $10^5$  $10^4$  $10^{-2}$

Wavenumber: $10^{-7}$  $10^{-6}$  $10^{-5}$  $10^{-4}$  $10^2$

ABL energy spectrum

NWP domain

synoptic weather

diurnal cycle

three-dimensional turbulence

“terra incognita”

Wyngaard
JAS 2004

Δ≈1 km

Δ≈100 m

Adapted from: van der Hoven (1957)
Nesting LES within idealized mesoscale flow

Neutral boundary layer

Mesoscale (xy-periodic)

Mesoscale (xy-periodic) LES (periodic: "reference")

LES (1-way nested)

U-velocity, z=100m

Muñoz-Esparza et al., Boundary-Layer Meteorology (2014)
Challenge: to develop turbulence on a LES domain from a smooth mesoscale inflow

Existing methods

Precursor/Recycling

Mayor, Spalart, Tripoli (JAS 2002)

Stevens, Graham, Meneveau (Energy 2014)

Gaudet, Deng, Stauffer, Seaman (WRF workshop 2012)

Munter, Meneveau, Meyers (Boundary-Layer Meteo. 2016)

Synthetic turbulence

\[
\tilde{u}_i = \langle U_i \rangle + u'_i = \langle U_i \rangle + a_{im} \Psi_m
\]

\[
\Psi_m(t,x_j,x_k) = \psi_m(t,x_j,x_k) \exp \left( -\frac{\pi \Delta t}{2T_L} \right) + \psi_m(t-\Delta t,x_j,x_k) \left[ 1 - \exp \left( -\frac{\pi \Delta t}{T_L} \right) \right]^{1/2}
\]

Xie & Castro (Flow, Turbulence and Comb. 2009)

- Require “a priori” knowledge of turbulence
- Rely on simplified physics/assumptions
- Computationally expensive

Not easily applicable to heterogeneous ABLs subject to atmospheric stability effects
Mesoscale-LES transition: The Cell Perturbation method

“Cell Perturbation method”: Stochastic potential temperature perturbations within LES domain (near inflow region) [Muñoz-Esparza et al. BLM2014, PoF2015, MWR2018]

• Generalized to account for stability effects
• Computationally inexpensive
Is “straight coupling” ever safe?

Convective Boundary Layer (CBL)

• CBL often requires long fetches
• Terrain helps locally, but surface disturbances still require long fetches to propagate throughout the ABL

Muñoz-Esparza and Kosović (MWR 2018)

Flow over Complex Terrain (Perdigão)

Chow et al. (Atmosphere 2019)
The value of mesoscale-LES coupling

CWEX-13 field campaign (Iowa)

- WRF downscaling to LES with CP method (9/3/1km, 90/30/8.2m)
- Meso-LES coupling is able to realistically reproduce ABL features during diurnal cycle
- Meso-LES does not only improve turbulence representation but also produces a more realistic sub-meso variability
FastEddy®: NCAR/RAL’s GPU LES model

Accelerated-GPU computing for efficient meso-to-micro coupling

- Dynamical core for Atmospheric Boundary Layer flow simulations
- Potential to provide real-time forecasts at meter-scale
- Enables more efficient scientific exploration

Significant speed up!!!
1 GPU ~ 256 CPU cores

dx = 5 m (~3km x 3km x 2km) on 32 GPUs runs at real-time pace!!!
Simulation of flow over Oklahoma city

- WRF to FastEddy downscaling with CP method for urban simulations (example of Oklahoma City)
- Urban scale validation with field data from OKC Joint Urban 2003 (winds, turbulence and dispersion)

\[ L_x, L_y, L_z = (2.0, 3.0, 1.2) \text{ km} \]

\[ \Delta x = \Delta y = 5 \text{ m} \]

\[ \Delta z = 5 - 18 \text{ m (stretched)} \]

**Vertical cross section** (30 min loop)

Muñoz-Esparza, Sauer et al. (JAMES 2020)
Conclusions

- **Downscaling** from a mesoscale NWP model to microscale regime **requires inflow turbulence generation** in the nested LES domain.

- The **Cell Perturbation (CP) method** provides an **efficient way to generate realistic turbulence** in atmospheric models [stability aware, computationally inexpensive].

- The lack of resolved turbulence degrades solution in LES models compared to mesoscale. **Neither convection nor complex terrain features prevent from long development fetches to still exist** (wasting computing resources).

- **Meso-LES coupling improves** not only **turbulence** representation but also **sub-meso variability** (intra-hour).

- **GPU-LES models like FastEddy** are more performant for meter-scale simulations than CPU-based codes, and **provide an alternative for efficient meso-to-micro coupling**.

Thanks!!!

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