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

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NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

MMC-Sponsored Industry Workshop

Atmospheric Challenges for the Wind Energy Industry
October 20th 2020

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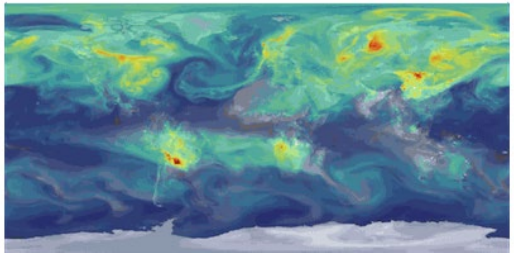
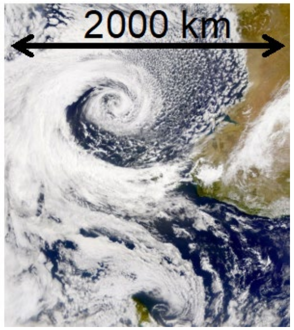
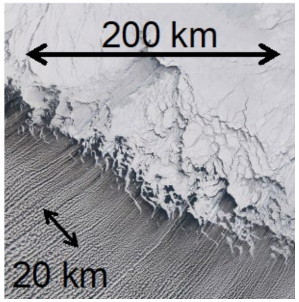
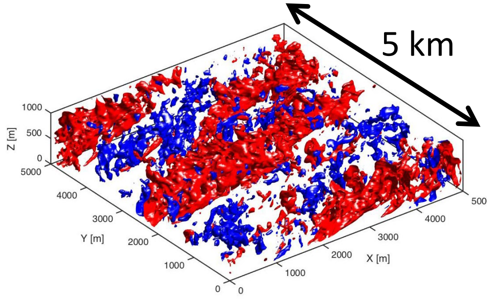
Disparate-scale atmospheric modeling





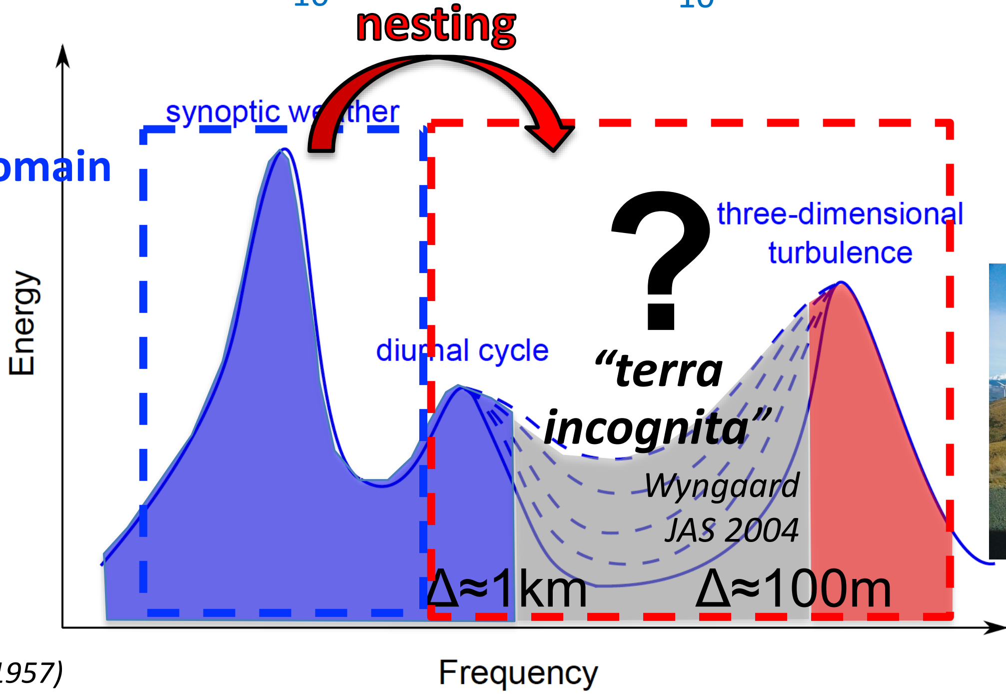




Length: 10^7 10^6 10^5 10^4 10^{-2}

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

ABL energy spectrum



Adapted from: van der Hoven (1957)

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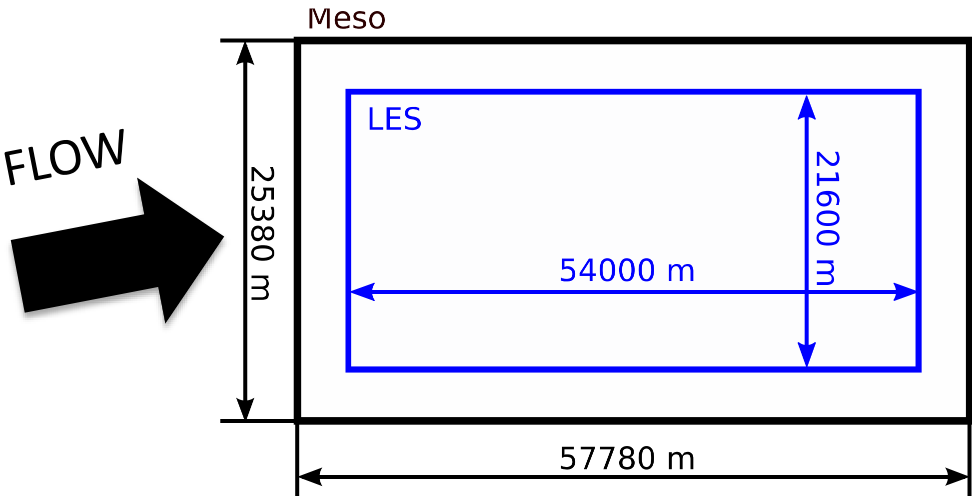
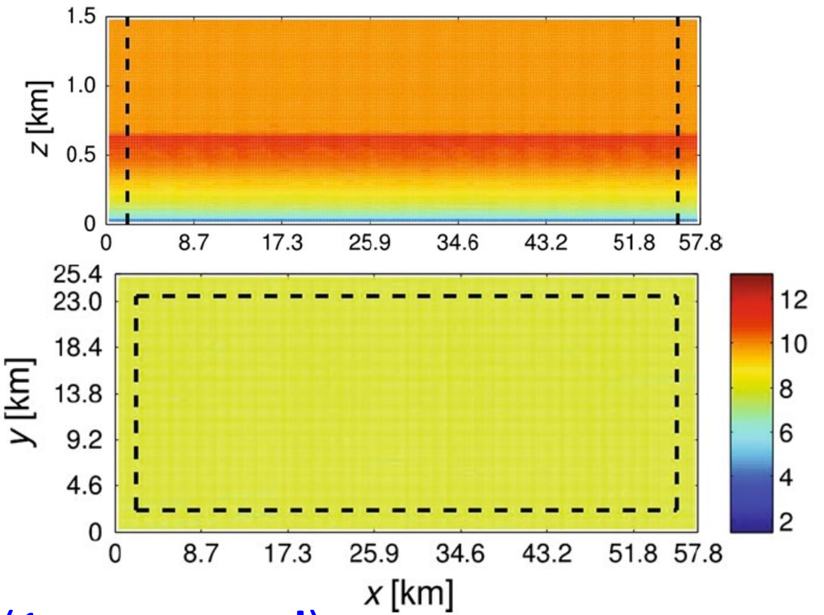
Nesting LES within idealized mesoscale flow

Neutral boundary layer

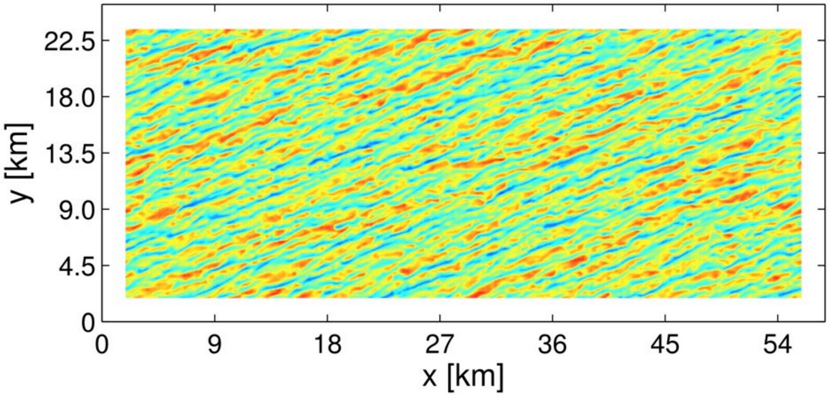


Mesoscale (xy-periodic)

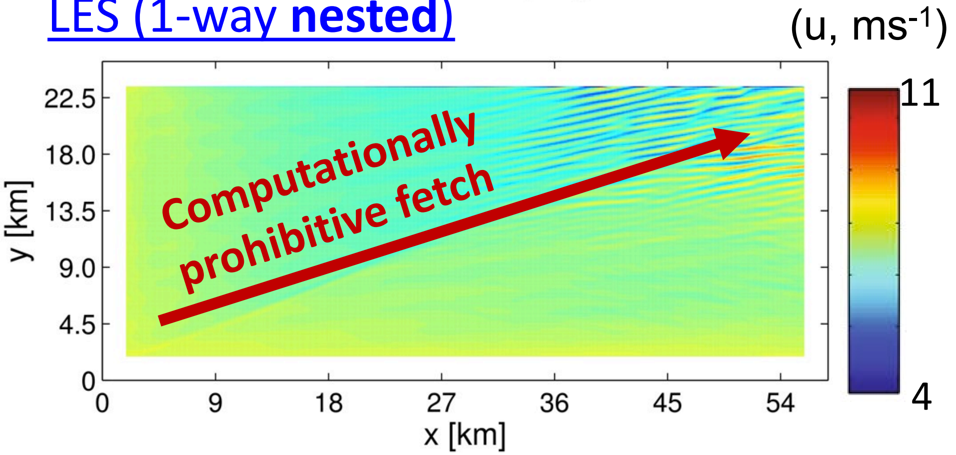


U-velocity, z=100m

LES (periodic: "**reference**")



LES (1-way **nested**)



Muñoz-Esparza *et al.*, *Boundary-Layer Meteorology* (2014)

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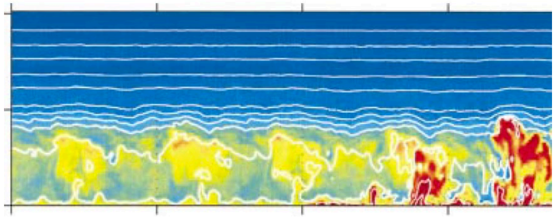
Challenge and existing methods

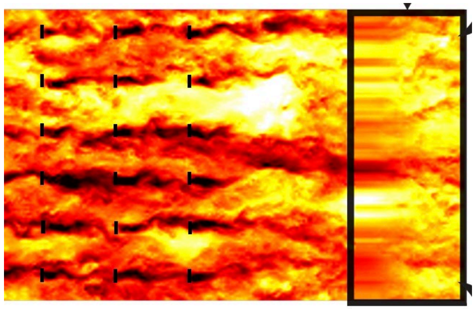
Challenge: to develop turbulence on a LES domain from a smooth mesoscale inflow

Existing methods

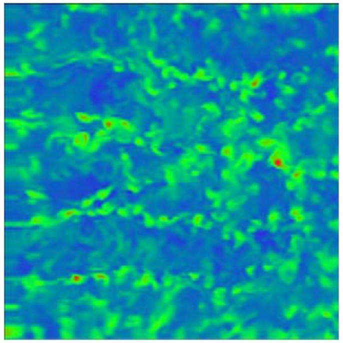
Precursor/Recycling



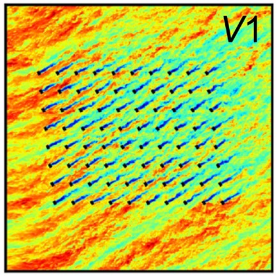
Mayor, Spalart, Tripoli (JAS 2002)



Stevens, Graham, Meneveau (Energy 2014)



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



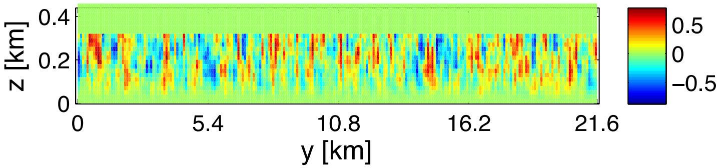
Munter, Meneveau, Meyers (Boundary-Layer Meteo. 2016)

- Require "*a priori*" or "concurrent" simulation
- Data storage & computationally expensive
- Rely on scaling laws
- Assume horizontal homogeneity

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

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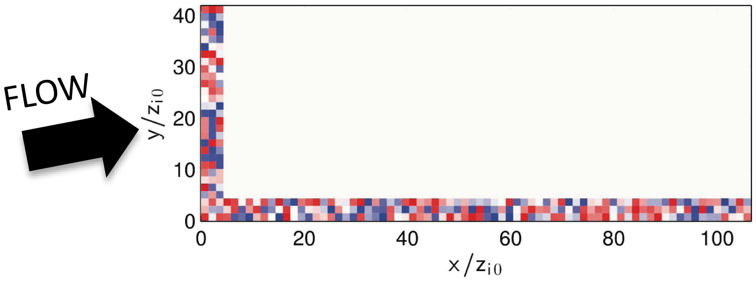
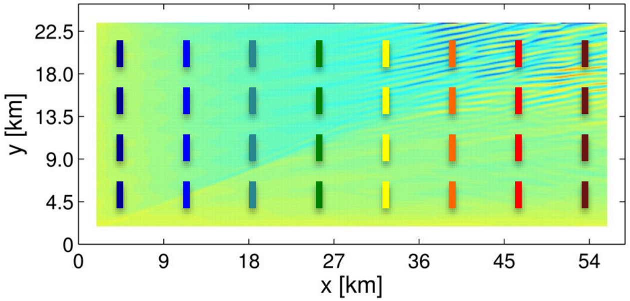
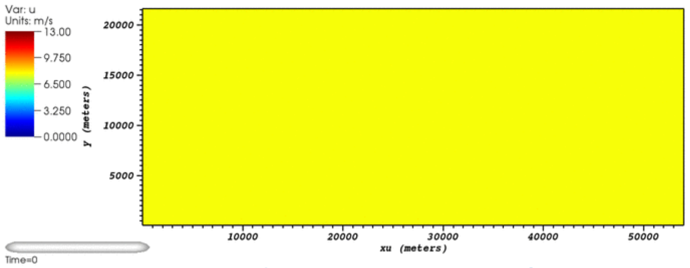
Mesoscale-LES transition: The Cell Perturbation method

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

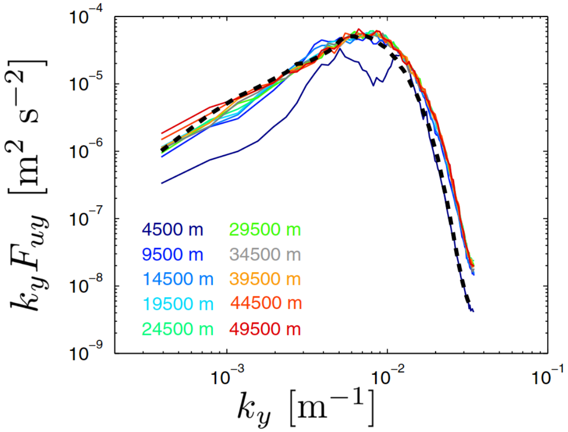


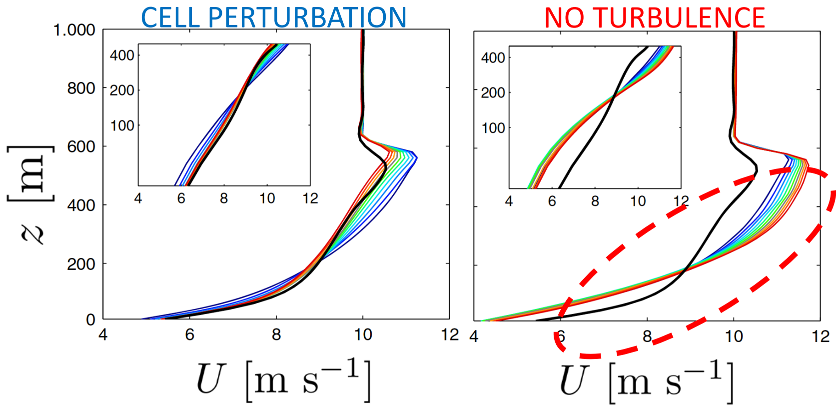
NO TURBULENCE GENERATOR





CELL PERTURBATION





- Generalized to account for stability effects
- Computationally inexpensive

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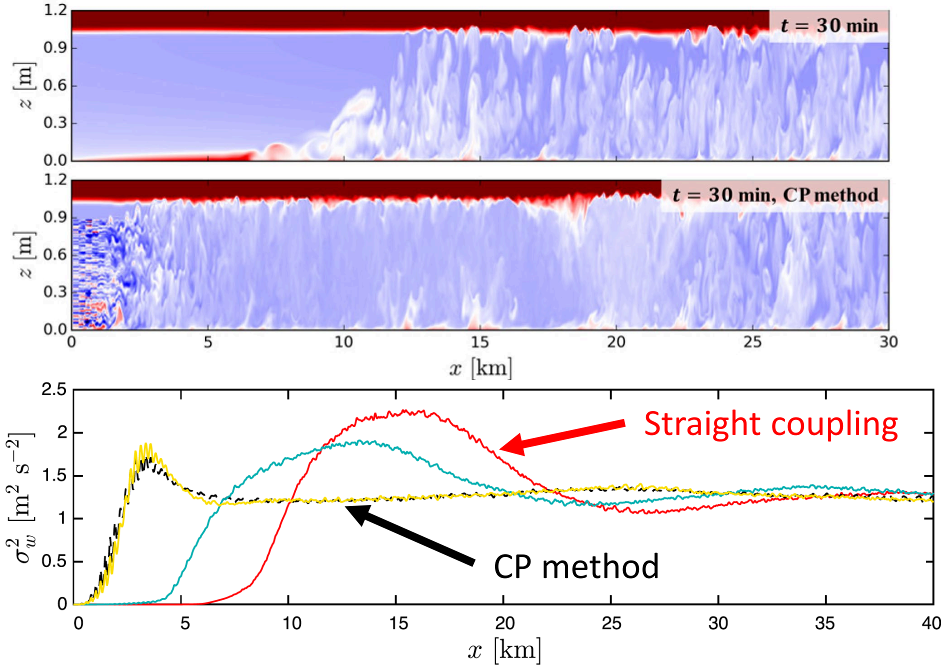
Is “straight coupling” ever safe?

Convective Boundary Layer (CBL)



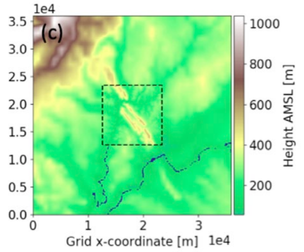
Straight coupling

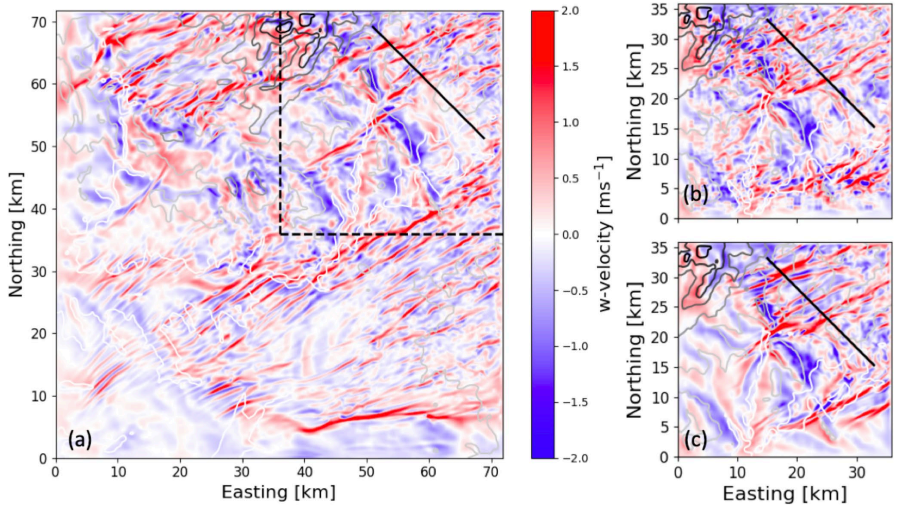
CP method

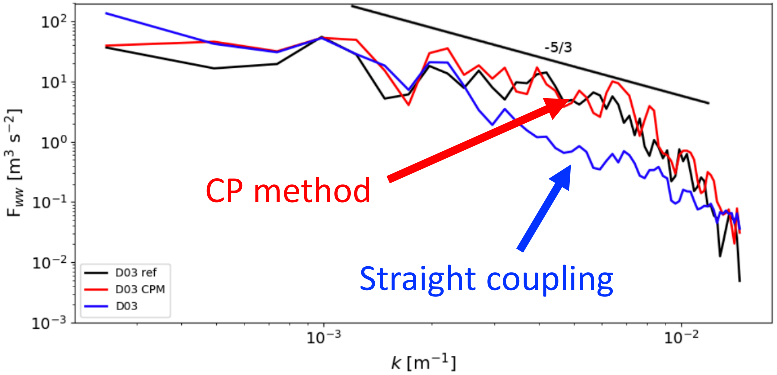
- CBL often requires long fetches
- Terrain helps locally, but surface disturbances still require long fetches to propagate throughout the ABL

Muñoz-Esparza and Kosović (MWR 2018)

Flow over Complex Terrain (Perdigão)







CP method

Straight coupling

Chow et al. (Atmosphere 2019)

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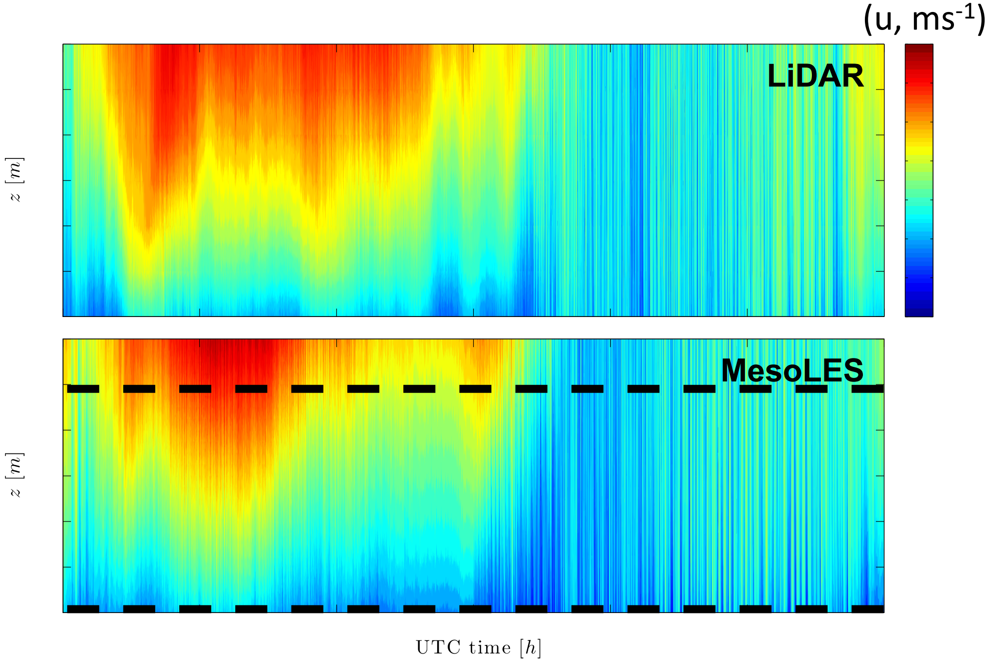
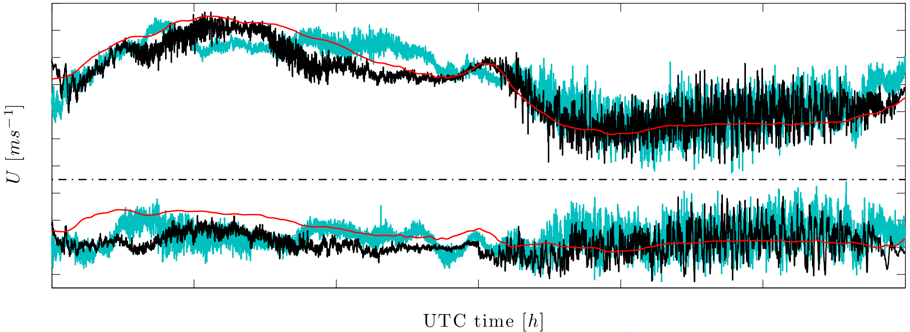
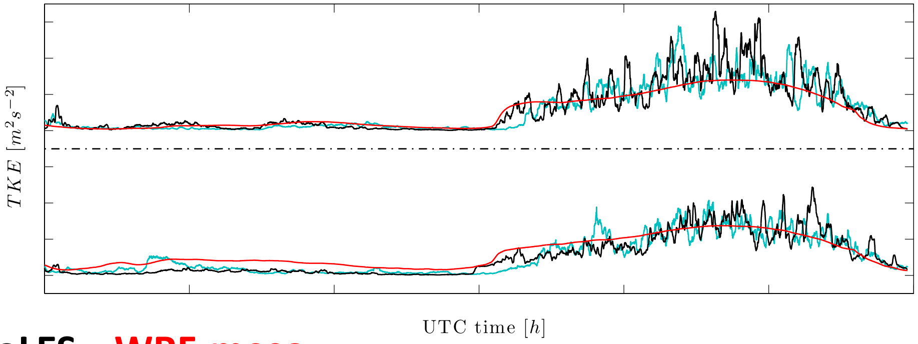
The value of mesoscale-LES coupling

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





LiDAR **WRF-mesoLES** **WRF-meso**

Muñoz-Esparza et al. (JAMES 2017)

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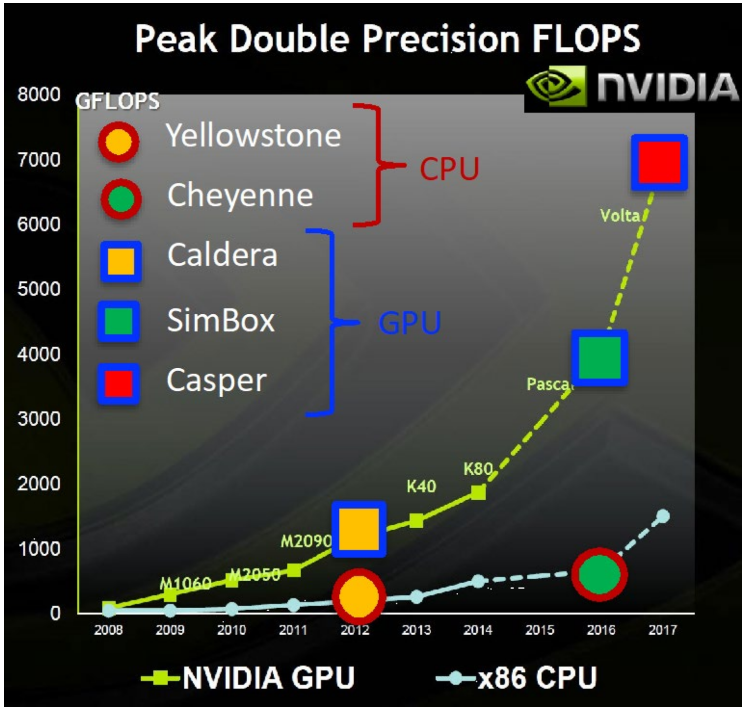
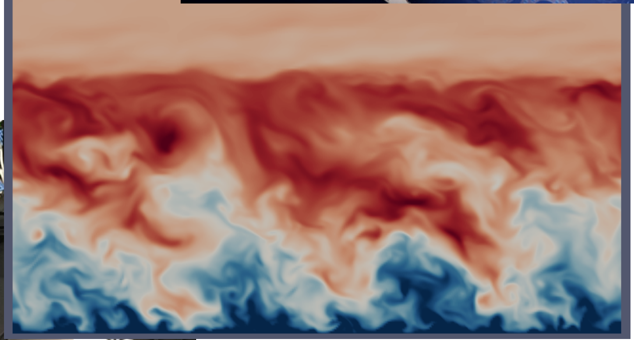
FastEddy®: NCAR/RAL's GPU LES model

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!!!

Sauer & Muñoz-Esparza (2020)

Mesoscale WRF to FastEddy downscaling example

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, Ly, L_z = (2.0,3.0,1.2) km
$\Delta x = \Delta y$ = 5 m
Δz = 5 – 18 m (stretched)

Horizontal cross section (z = 7.5 m)

Vertical cross section (30 min loop)

0 0.5 1.0 1.5 2.0 2.5 3.0
y [km]

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

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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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