Coupled mesoscale-LES modeling to improve the representation of stably stratified atmospheric boundary layers

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18th WRF Users' Workshop, Boulder, CO

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The stable ABL: "still" a challenge

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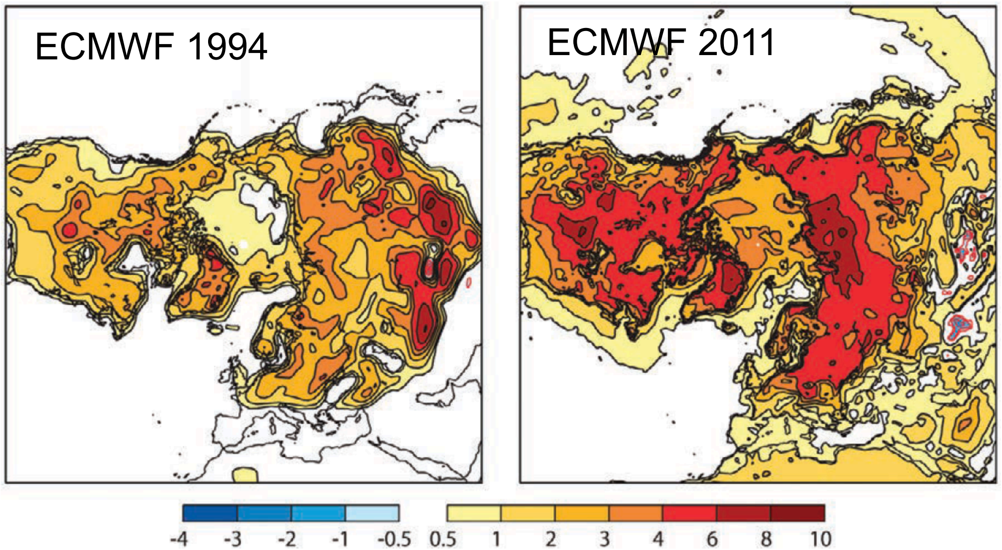
- Modeling of stably stratified ABLs in Numerical Weather Prediction (NWP) models remains a difficult task:
  - ✓ Low-level jets
  - ✓ Gravity waves
  - ✓ Turbulence intermittency
  - ✓ Kelvin–Helmholtz instabilities…

- NWP sensitivity to mixing formulation in stable conditions
  - ✓ Tight coupling between boundary layer and surface processes (soil, snow,…)
  - ✓ Model's sensitivity is increasing, also making more difficult for new parameterizations not to diminish overall performance

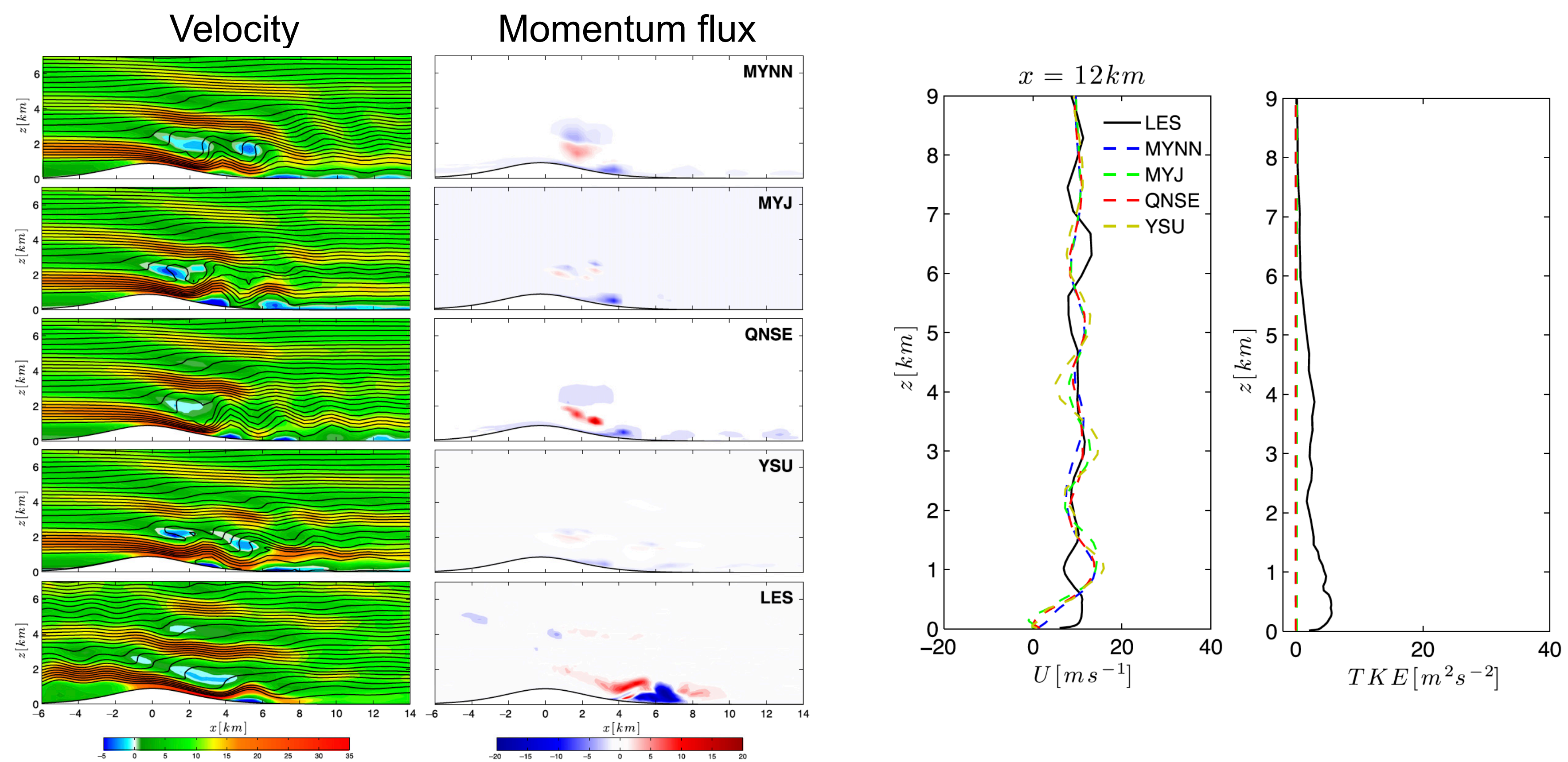
2-m temperature differences



Holtslag et *al.*, BAMS (2013)

One-dimensional closure in PBL schemes

- The lack of a three-dimensional turbulence parameterization induces errors in the presence of topography



Muñoz-Esparza et al., JAS (2016)

WRF mesoscale modeling during XPIA

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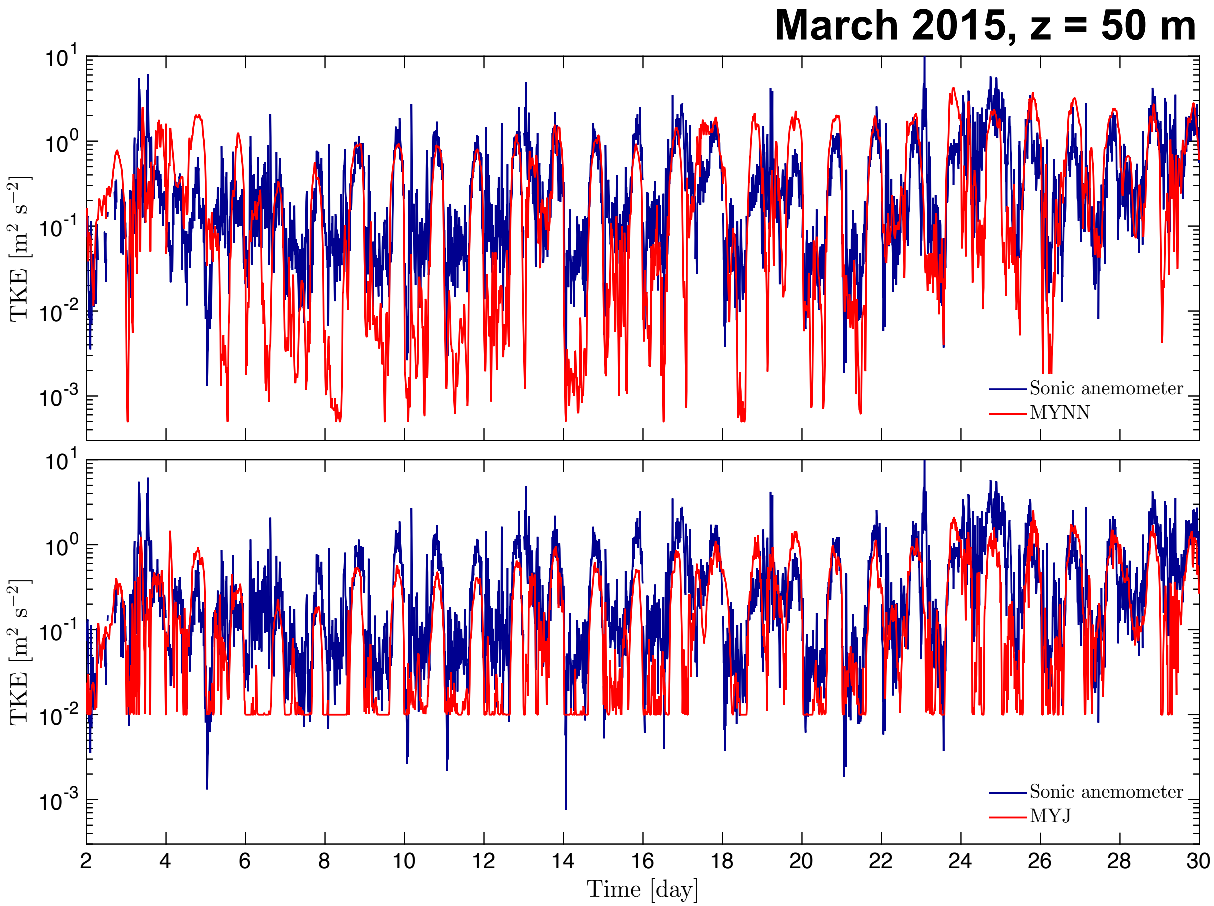
- Turbulent kinetic energy at the BAO tower during the XPIA campaign [Lundquist et al. BAMS (2017)] puts into evidence the limitations of 1D PBL schemes



Muñoz-Esparza et al., MWR (2017, submitted)

Coupled mesoscale-LES modeling

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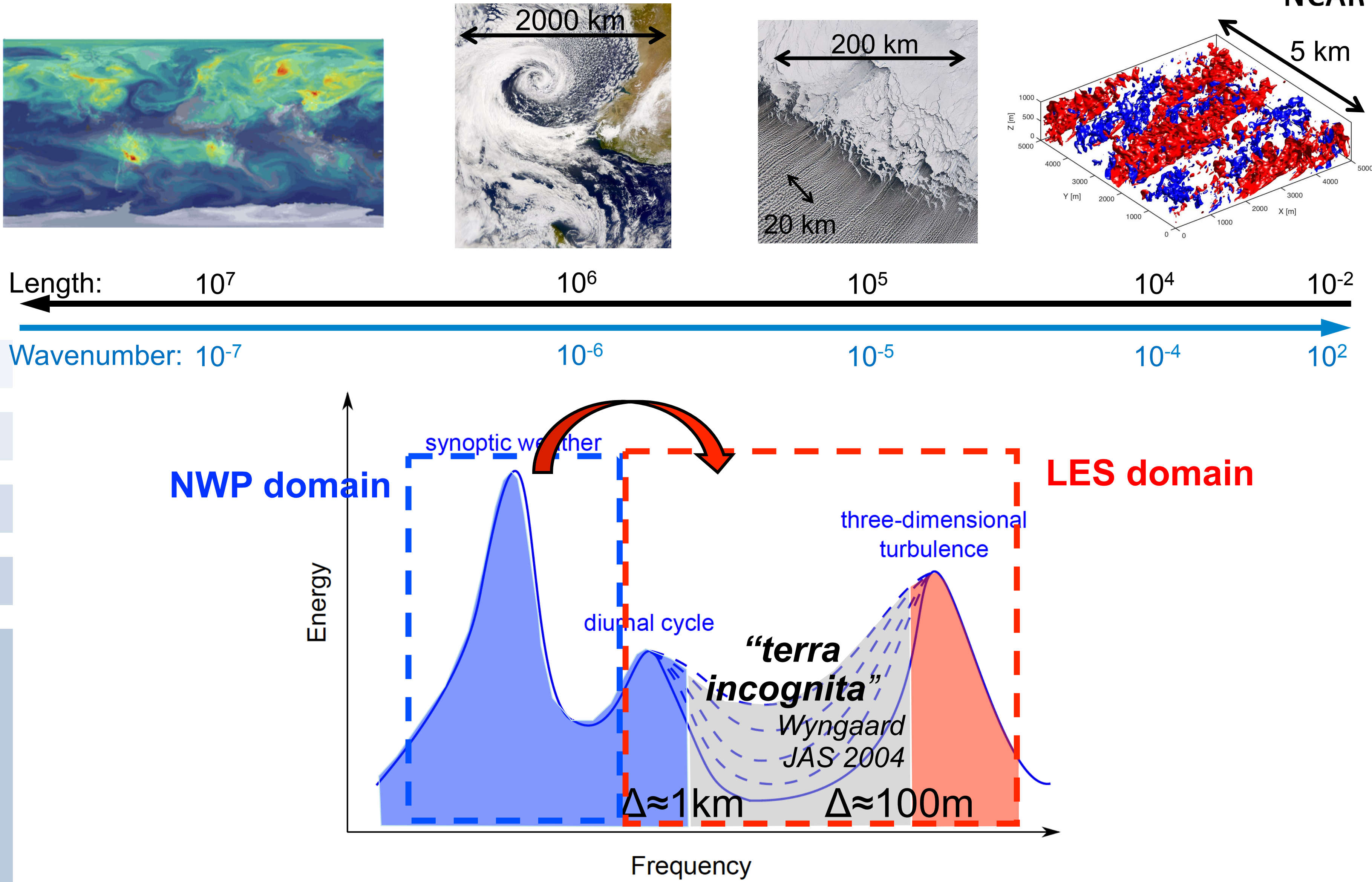

Mesoscale-LES transition

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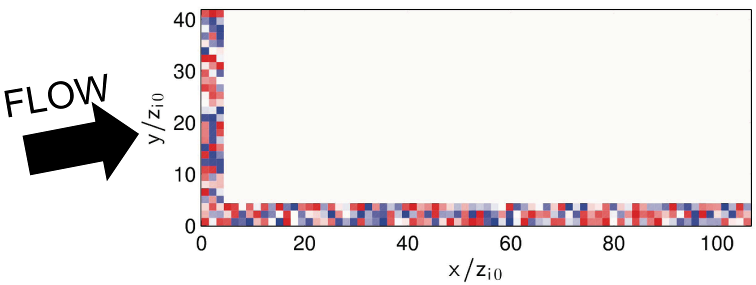
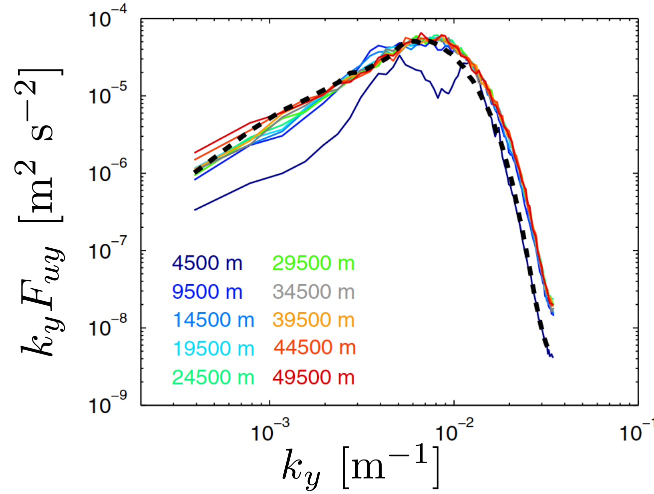
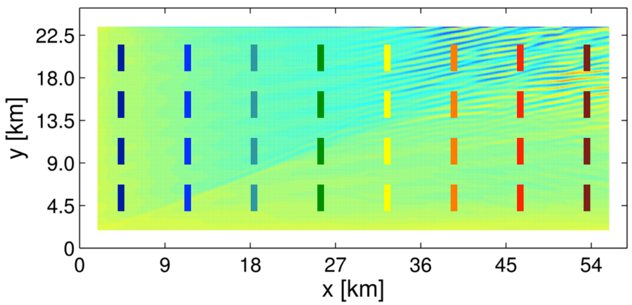
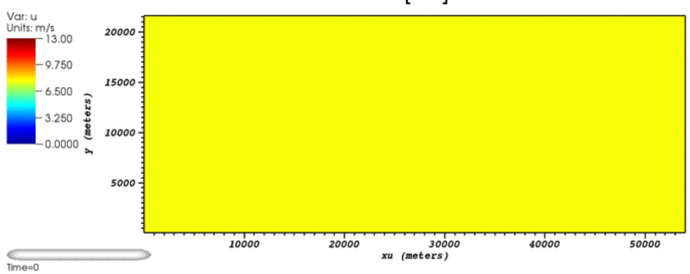
- **"Cell perturbation method"**: Stochastic potential temperature perturbations within LES domain (near inflow region) [Muñoz-Esparza et al. BLM2014, POF2015]



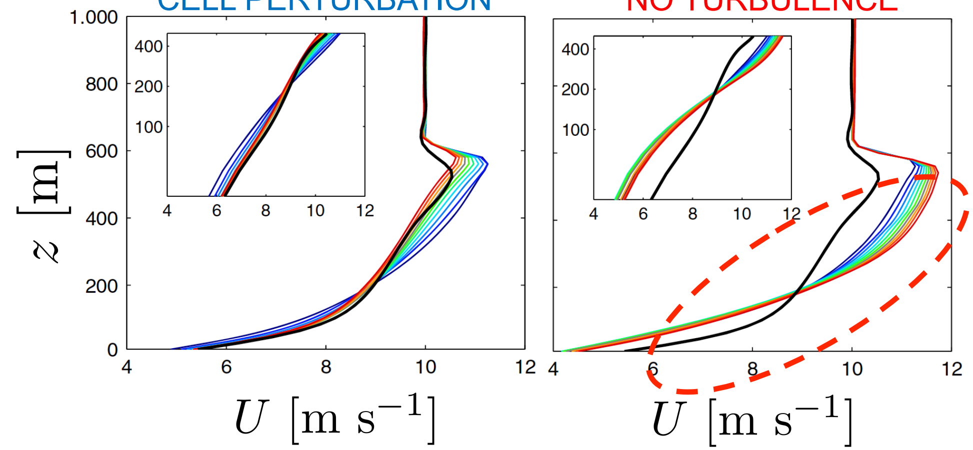


NO TURBULENCE GENERATOR





CELL PERTURBATION



- Accelerated transition to developed turbulence
- Correct wind speed profile is achieved

Muñoz-Esparza et al., BLM (2014); POF (2015)

WRF multiscale modeling of a diurnal cycle

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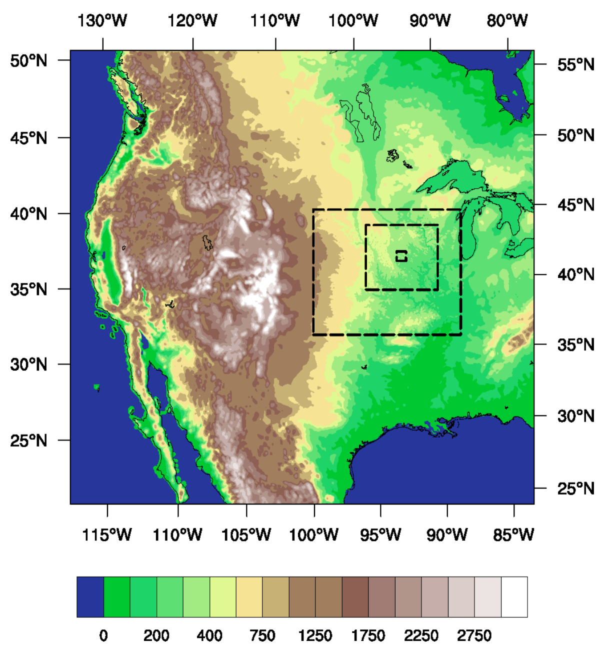
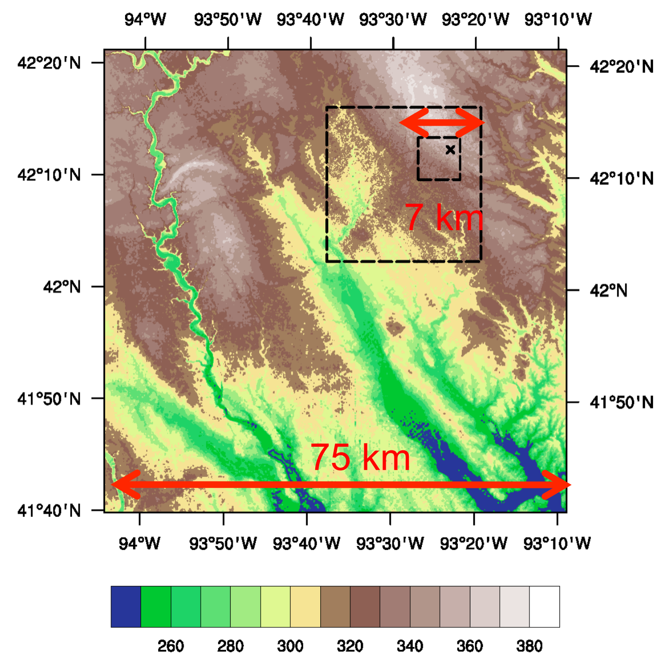
- Crop Wind Energy Experiment (CWEX-13): 26th of August, 2013





	Mesoscale (MYNN)			LES	
	d01	d02	d03	d04	d05
dx, dy (m)	8910	2970	990	90	8.2
dz (m)	73 grid points [10m-142m < 2 km, 42 grid points]				

Muñoz-Esparza et al., JAMES (2017)

Turbulence generation in stable conditions

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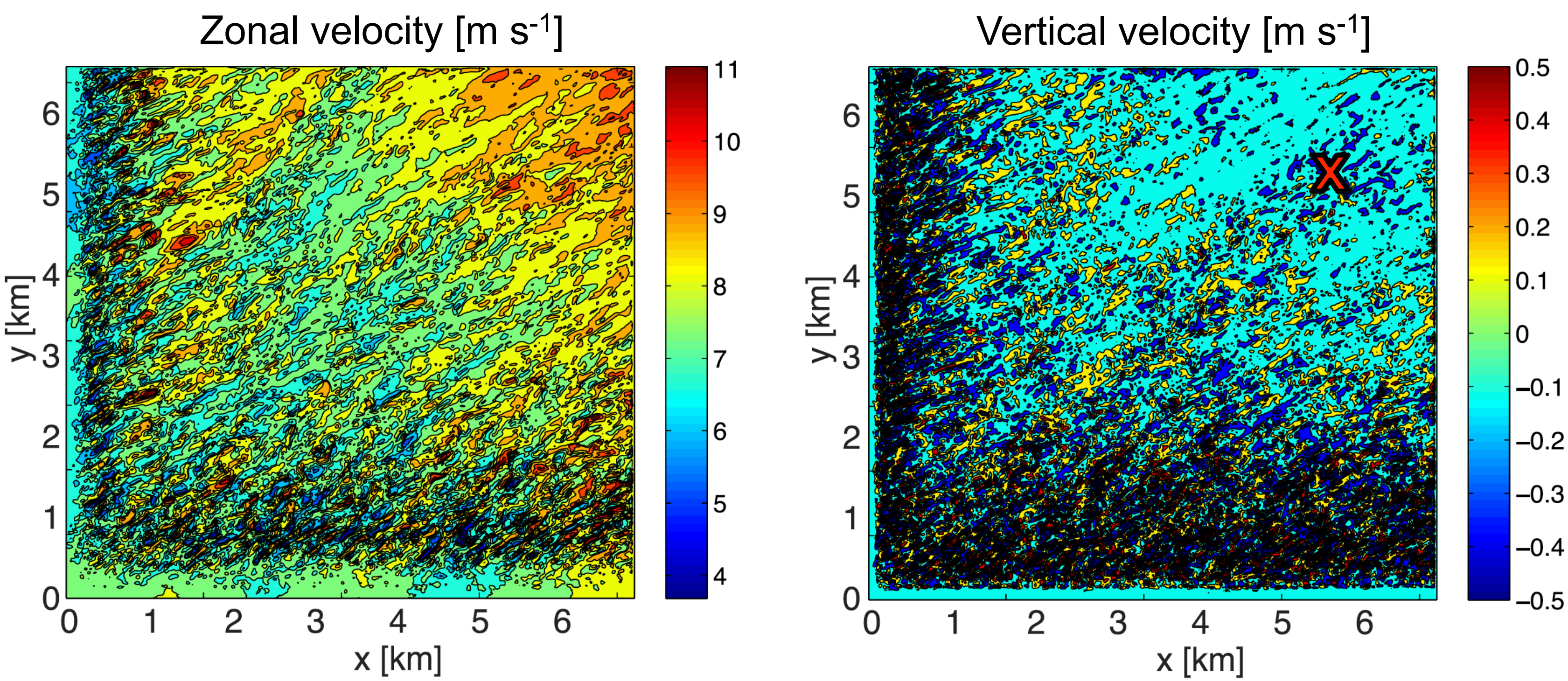
- Results on domain D05 at z = 75 m (time: 0100 LT)



✓ The cell perturbation method instigates realistic turbulence production (otherwise, no turbulence is generated)

✓ 8.2 m grid size allows resolution of stratified turbulence features [global intermittency]

Time evolution of U, w and TKE

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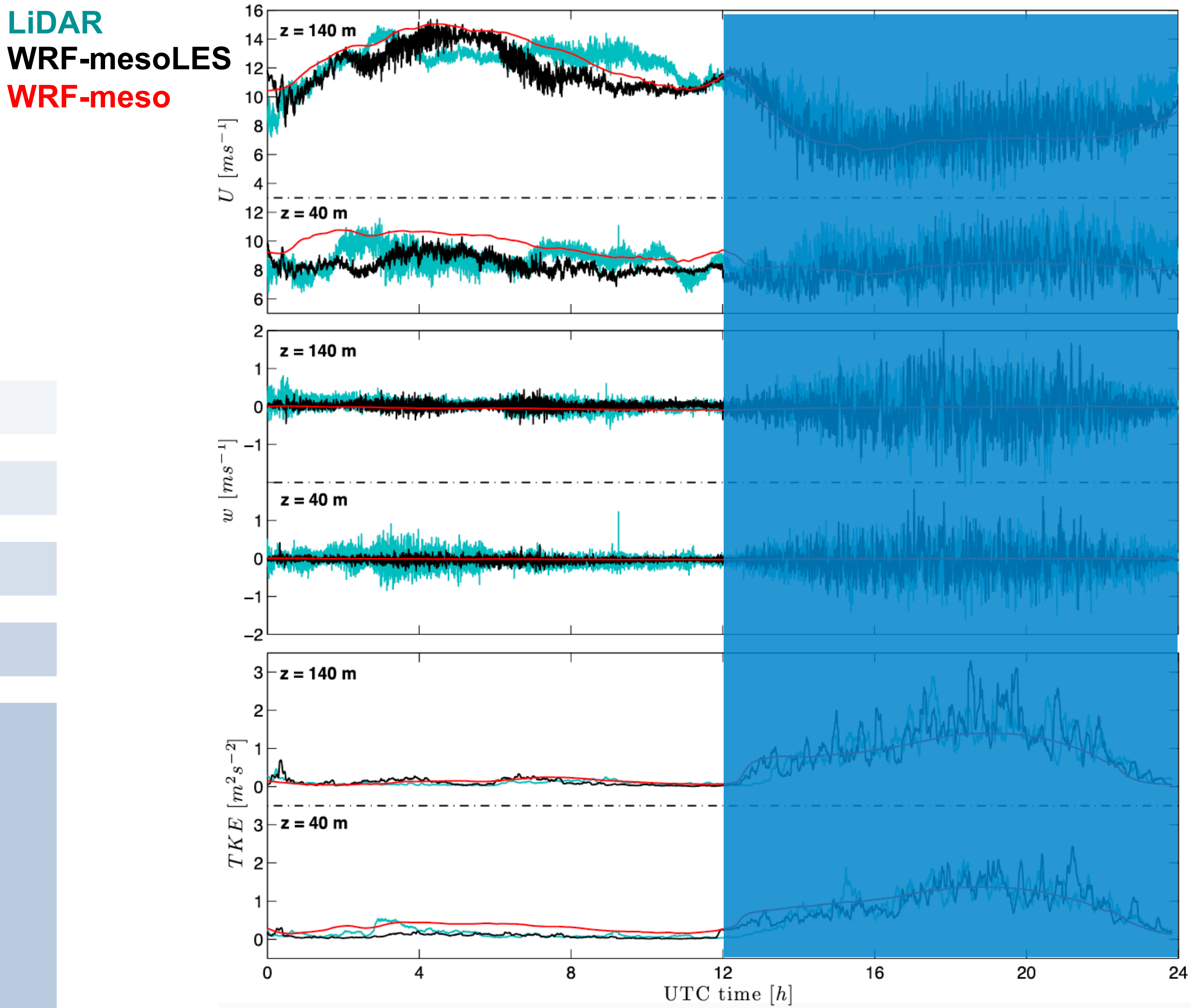

Meso-LES does not only improve turbulence representation but also produces a more realistic intra-hour variability (frequency and amplitude)

More realistic TKE at the near-surface improves wind speed prediction

Time evolution of 8-m temperature

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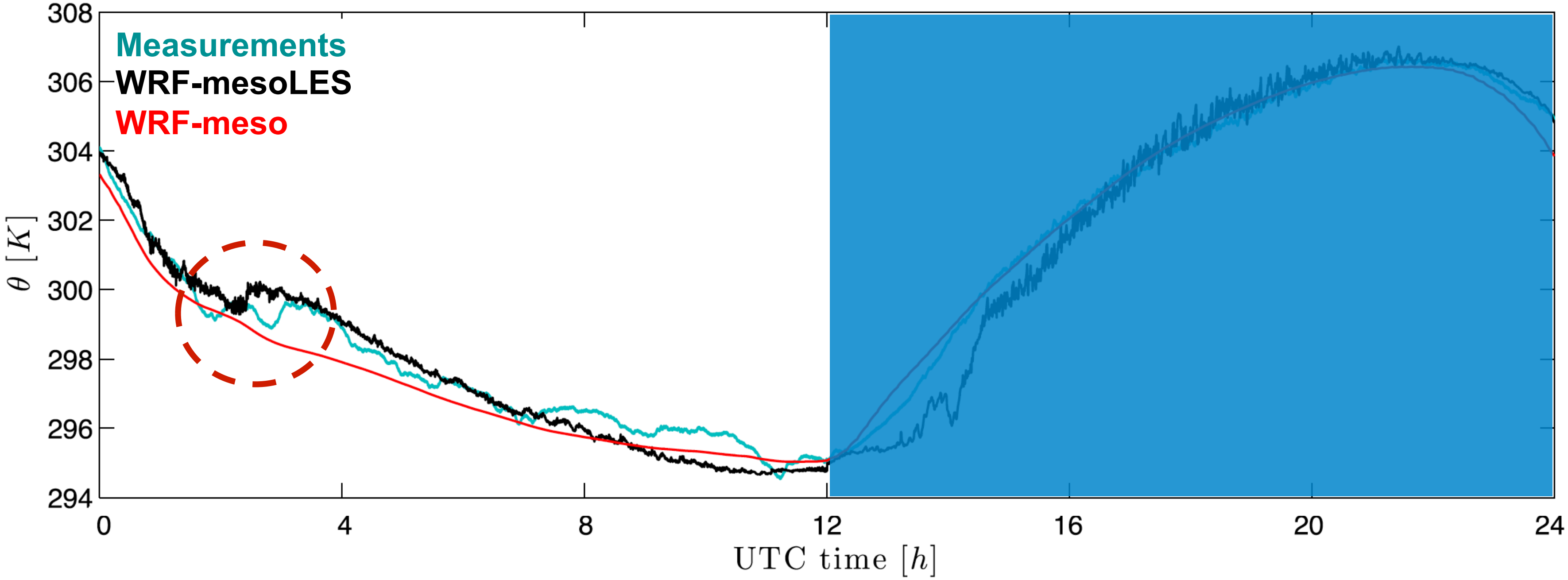

Resolved turbulence enables local temperature increases resulting from mixing with upper layers

Temperature evolution is overall improved

The strongest stratification at the end of the night may require higher resolution (and/or a less dissipative advection scheme)

Turbulence statistics

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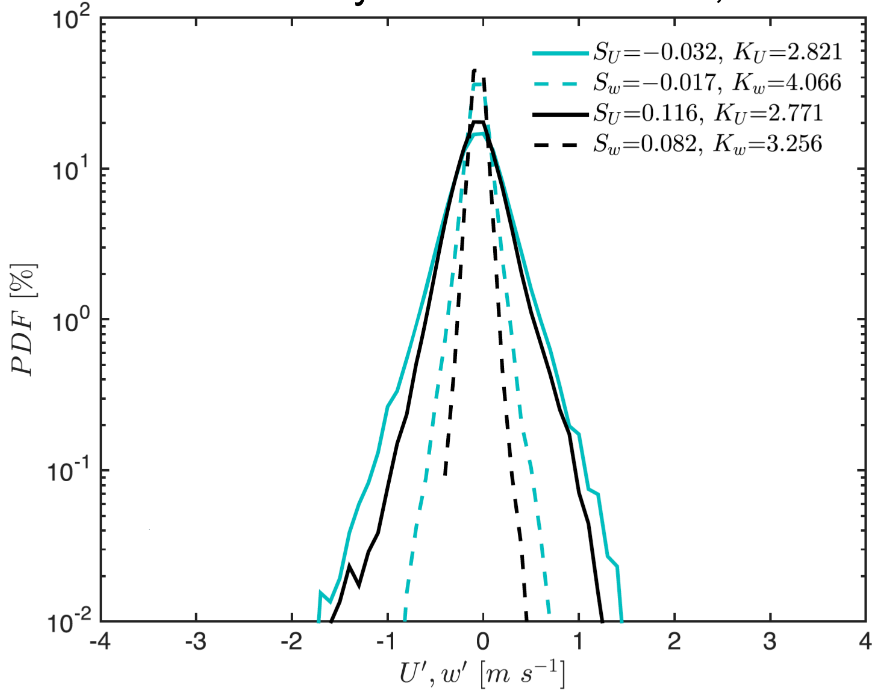
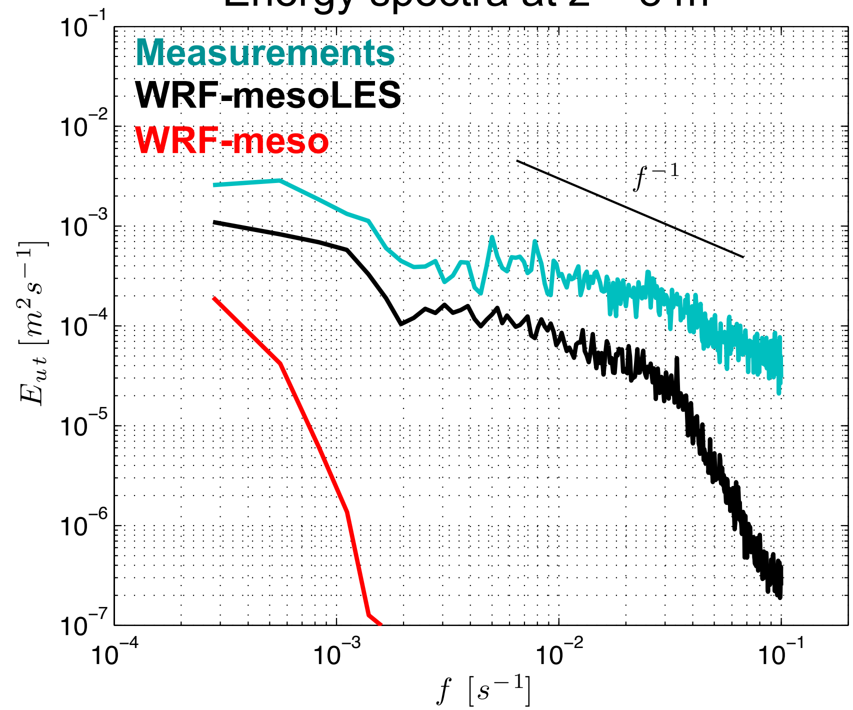
Probability distributions of U’, w’



Energy spectra at z = 8 m



PDFs of resolved turbulent fluctuations almost identical to lidar observations

Realistic energy distribution even at z = 8 m (1st vertical grid point)
[even better agreement found at higher heights]

Conclusions

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- ✓ Parameterization of SBLs in NWP models remains a challenge
- ✓ Coupled WRF mesoscale-LES enabled by the cell perturbation method improves the representation of stably stratified turbulence in the ABL [waves, global intermittency, vertical mixing]
- ✓ Not only improving turbulence statistics but also intra-hour variability, wind shear and surface temperature
- ✓ With increasing computing capability, forecast at LES resolution is becoming a reality [see Talk 8.7 on Thursday at 12:00]

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Thanks for your attention!!!

"Coupled mesoscale-LES modeling to improve the representation of stably stratified atmospheric boundary layers"

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Generalized cell perturbation method (II)

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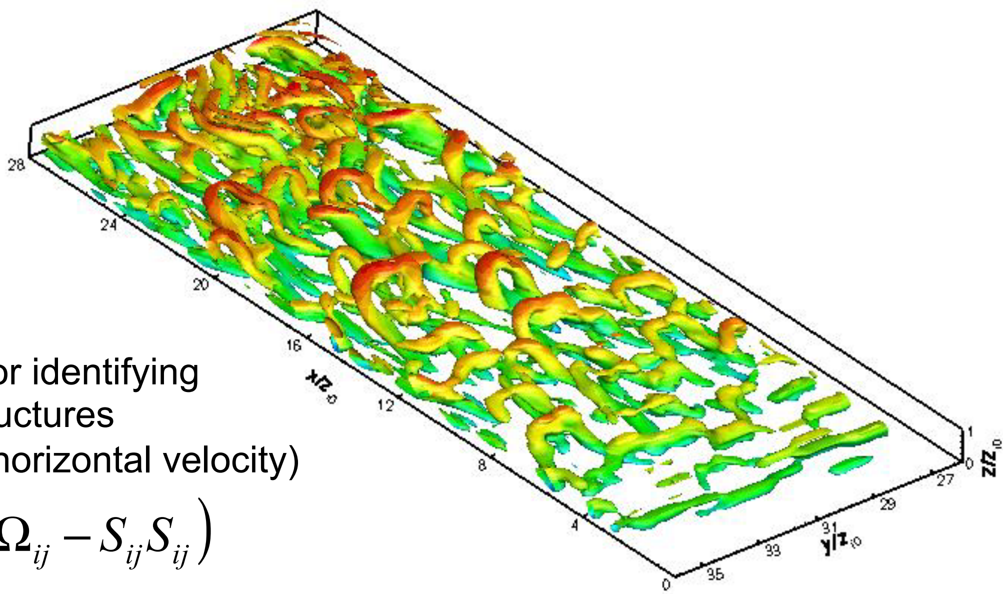
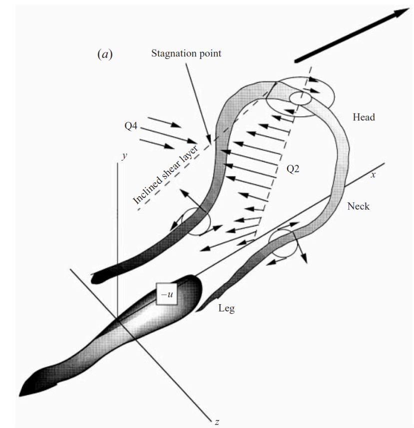
"Perturbation Eckert number" $Ec = U_g^2 / c_p \theta_{pm} = \mathit{mechanical/thermal} = 0.2$





Adrian et al. (JFM 2000)

Q criterion for identifying turbulent structures (colored by horizontal velocity)

$$Q = \frac{1}{2}\left(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij}\right)$$

Hairpin-like vortices develop for *Ec* = 0.2, breaking down into developed streaks
Similar mechanism to laminar-turbulent transition in wall-bounded viscous layers
Optimum transition to turbulence

Muñoz-Esparza *et al.*, *Physics of Fluids* (2015)

Cell perturbation vs. synthetic turbulence

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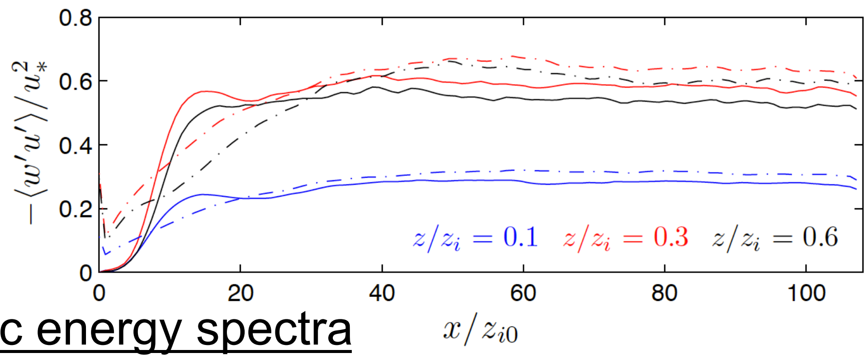
- <u>Momentum fluxes</u>

Cell Perturbation (solid)
Synthetic Turb. (dashed)
[Xie & Castro, FTC2009]



Cell perturbation method requires HALF the fetch

Cell perturbation method is 1000 TIMES faster

- <u>Turbulent kinetic energy spectra</u>

Cell perturbation

Synthetic turbulence