3.5: Eddy Seeding for Improved WRF-LES Simulations Using Realistic Lateral Boundary Conditions

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Background

• Mesoscale models (e.g., WRF) include multiple atmospheric and surface processes from the synoptic scale (thousands of kilometers) down to scales of hundreds of meters.

• But – turbulent structures are not explicitly represented; rather, averaged turbulent quantities (e.g., turbulent kinetic energy (TKE)) are parameterized via closure assumptions.

• Large Eddy Simulation (LES) models can explicitly represent the largest eddies in atmospheric turbulence (up to several kilometers in scale in convective boundary layers).

• However, LES models require time to ‘spin-up’ eddies; idealized cases typically simulate beyond Lagrangian eddy spin-up time scale while using periodic lateral boundary conditions (LBCs).
Realistic Lateral Boundary Conditions

- Must accommodate mesoscale atmospheric and surface gradients

- Thus -- traditional periodic LBCs are not applicable

- The LBCs consistent with mesoscale gradients may also be variable on time scales on the order of the eddy spin-up time (~ several $z_i / w_*$).

- WRF-ARW now can support nested domains that possess LES-type subgrid closures (Moeng et al. 2007) while making use of the nonperiodic time-dependent LBCs available from the parent model – as well as the multiple physics suite options (microphysics, land surface model, radiation) found in the WRF framework.
Potential Temperature Perturbations
CM1 (Bryan and Fritsch 2002) \( z = 371 \) m, \( t = 7200 \) s
(every 0.1 K shown)

- periodic LBCs
- non-periodic LBCs

permanently eddy-deficient inflow
Possible Remedies

- Nest LES within LES within mesoscale model and utilize results from finer domains only (Zhu et al. 2010)

- Nest LES within mesoscale model, and use eddy recycling at inflow boundary with ‘magic slice’ (Mayor et al. 2002)
‘Eddy Seeding’ Method

• Realistic eddy structures are pre-computed within an offline ‘canned LES’ simulation with periodic LBCs (output every 10 s between 3600 s and 7200 s is saved)

• Retrieve canned eddy structures during an LES with nonperiodic LBCs, and add to mesoscale flow to obtain realistic inflow boundary conditions

• Use similarity theory, if necessary, to scale canned eddy structures to be appropriate to those of the nonperiodic LES (e.g., by use of $w^*$ and $z_i$ in the convective mixed layer)
Newtonian Relaxation toward Eddies

Lateral Boundary of LES

Mean wind vector

Width of Blending Zone = 20 Δx

Interior of LES

Z_i
Homogeneous Surface Tests

- A canned LES was generated using the Cloud Model 1 (CM1) (Bryan and Fritsch 2002) with no initial wind, 0.1 K m s\(^{-1}\) surface heat flux, initial thermodynamic sounding (mixed layer with \(z_i = 1350\) m) derived from Kang and Davis (2008), and periodic boundary conditions (100 x 100 x 122; \(\Delta x = \Delta y = 100\) m; \(z_{\text{top}} = 3500\) m).

- Another periodic (‘truth’) simulation was performed with the same thermodynamic sounding, but with \(u = 4\) m s\(^{-1}\) and surface heat flux of 0.2 K m s\(^{-1}\), extending out to 3 hours, and 140 x 140 in horizontal extent.
Homogeneous Surface Tests (cont.)

• A ‘control’ simulation was performed, identical to the ‘truth’ simulation, but using nonperiodic LBCs (for tests shown here, time-dependent conditions on potential temperature and normal velocity that match the evolution of the truth simulation, to mimic behavior of nested LES domain).

• A final simulation was performed in which eddy seeding was introduced into the blending zone of the control simulation.

• For these buoyancy-driven boundary layer tests, only potential temperature eddy structures were used.
Potential Temperature Perturbations
(every 0.1 K shown)
t = 900 s, z = 371 m

periodic LBCs

non-periodic LBCs

non-periodic LBCs with canned eddy relaxation
Resolved Turbulent Statistics

Left Blending Region

Interior Region
Temporally- and Horizontally-Averaged Potential Temperature Profile at $t = 120 \text{ min}$

- **Left Blending Region**
  - Periodic LBCs
  - Non-Periodic Time-Dependent LBCs, With Eddy Seeding
  - Non-Periodic Time-Dependent LBCs, No Eddy Seeding

- **Interior Region**
Non-periodic mean fields can match periodic mean fields, but only when particular time-dependent lateral boundary conditions are imposed.
Temporally- and Horizontally-Averaged Resolved Normalized Heat Flux at $t = 120$ min

- **Left Blending Region**
  - Non-Periodic Time-Dependent LBCs, With Eddy Seeding
  - Periodic LBCs
  - Non-Periodic Time-Dependent LBCs, No Eddy Seeding

- **Interior Region**
Temporally- and Horizontally-Averaged Resolved Normalized Heat Flux at $t = 120\text{ min}$

- **Left Blending Region**
  - Non-Periodic Time-Dependent LBCs, With Eddy Seeding
  - Periodic LBCs
  - Non-Periodic Time-Dependent LBCs, No Eddy Seeding

- **Central Region**

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Temporally- and Horizontally-Averaged Resolved Normalized Vertical Velocity Variance at t = 120 min

**Left Blending Region**
- Non-Periodic Time-Dependent LBCs, With Eddy Seeding
- Periodic LBCs

**Interior Region**
- Non-Periodic Time-Dependent LBCs, No Eddy Seeding
Temporally- and Horizontally-Averaged Resolved Normalized Vertical Velocity Variance at $t = 120$ min

Left Blending Region

- Non-Periodic Time-Dependent LBCs, With Eddy Seeding

Central Region

- Non-periodic resolved turbulent statistics are severely depressed in inflow region, with unrealistic compensation even in the domain center.

- Eddy-seeded resolved turbulent statistics are improved in inflow region, and closely approximate the periodic solution near the domain center.

Periodic LBCs

Non-Periodic Time-Dependent LBCs, No Eddy Seeding
WRF-LES Experiments

- WRF-LES experiments (version 3.3.1) have been set up using the same (single) domain size, thermodynamic sounding, and surface heat flux as the set of CM1 experiments.

- There are a few small differences between the WRF-LES and CM1 applications (eta coordinate vs. height coordinate, and differences in scaling with physical height; 1-minute vs. 10-second data storage in canned simulation)

- Open / radiative LBCs here for both control and eddy-seeded experiments
WRF-LES Turbulent Profiles (Periodic Case)

Normalized Vertical Heat Flux

Normalized Vertical Velocity Variance

(every five minutes shown)
CM1 vs. WRF-LES

$t = 3600 \text{ s}$

CM1
$z = 371 \text{ m}$

WRF
$z = 375 \text{ m}$

periodic
open / radiative
open / radiative with eddy seeding
Proposed Mesoscale / LES Nested Modeling System

Parent Mesoscale Model
- provides realistic LBCs, surface fluxes, $z_i$, and wind profiles to nested LES

“Canned LES”
- homogeneous with periodic LBCs
- after rescaling, provides realistic eddy structures within blending zone

Nested LES
- possesses realistic non-periodic LBCs and heterogeneities in atmospheric and surface fields
Summary

• Qualitatively, the eddy seeding method shows promise in being able to quickly generate realistic eddy structures in nonperiodic nested LES models.

• Resolved turbulent statistical quantities in nonperiodic LESs without eddy seeding were highly deficient, as expected, near the inflow region, but even in the domain center suffered from unrealistic ‘overcompensated’ values.
• The use of eddy seeding alleviates the deficient turbulent statistics in the inflow nudging region, and closely matches the turbulent statistics from the periodic truth simulation in the central region of the domain.

• A preliminary implementation of the method has been performed in WRF-LES and is consistent with corresponding CM1 LES experiments.
Current / Future Work

- Complete WRF-LES implementation of eddy seeding
- Apply to parent mesoscale / nested LES configuration
- Apply to cases of heterogeneous surface fluxes and/or different atmospheric soundings
- Evaluate utility of more rigorous scaling (e.g., momentum variables)
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