Sensitivity of Vertical Structure in the Stable Boundary Layer to Variations of the WRF Model’s Mellor-Yamada-Janjic Turbulence Scheme

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Penn State University
- WFR-ARW configured with 4 nested domains:

  - 12 km: 421 X 271 pts
  - 4 km: 193 X 169 pts
  - 1.33 km: 121 X 121 pts
  - 0.444 km: 151 X 151 pts

- Sub-kilometer resolution is necessary to resolve fine-scale terrain important for shallow SBL flows.

- WRF wall clock **run time** on 4 nodes (dual 3 GHz cores): ~3 h per 12h fcst.
Topography of Central PA
0.444-km domain

Spring Creek Watershed – drains to north
Spruce Creek Watershed – drains to south

Field Site:
Extensive PSU-owned agric. land at Rock Springs, PA
Rock Springs Observing Network

20-site sub-canopy temperature Micronet

- 2-m tower
- 10-m tower
- 20-m tower
- 50-m tower

Scale: ~3 km
- WRF Exp. Baseline is configured with 43 layers; model top at 50 mb.
- Lowest five layers have $\Delta Z = 2$ m, gradually increasing upwards
- 11 layers below 68 m AGL.

Baseline configuration
43 layers

Low vertical resolution
34 layers
**WRF Grid Configurations and Experiment Design**

1. **Resolution experiments:**

<table>
<thead>
<tr>
<th>Exper. Name</th>
<th>Horiz. Grid (km)</th>
<th>Sfc. Layer Depth (m)</th>
<th>Layers Below 68 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>0.444</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>LrgDZ</td>
<td>0.444</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>LrgDX</td>
<td>1.333</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>LrgDXDZ</td>
<td>1.333</td>
<td>30</td>
<td>2</td>
</tr>
</tbody>
</table>

**Baseline Physics:**
- MYJ PBL
- Simple ice physics
- Dudhia shortwave
- RRTM longwave
- 5-layer soil model

2. **Turbulence physics experiments:**

<table>
<thead>
<tr>
<th>Exper. Name</th>
<th>Physics Scheme</th>
<th>$TKE_{MIN}$ (m$^2$s$^{-2}$)</th>
<th>$I_B$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MYJ std</td>
<td>MYJ</td>
<td>0.10</td>
<td>0.32</td>
</tr>
<tr>
<td>QNSE std</td>
<td>QNSE</td>
<td>0.01</td>
<td>0.32</td>
</tr>
<tr>
<td>MYJ mod</td>
<td>MYJ</td>
<td>0.01</td>
<td>0.10</td>
</tr>
</tbody>
</table>

All experiments are run for 12 h during the nocturnal period, 0000 – 1200 UTC.
Coarse Domain Evaluations
19-case composite, Oct.-Nov. 2007

12-km CONUS domain: Red; 4-km regional domain: Black

All coarse-domain statistics based on Exp. Baseline, with standard MYJ scheme

Wind Speed Error
Wind Direction Error
Temperature Error

RMSE (m/s)
RMSE (degrees)
RMSE (C)

Pressure (hPa)

Bias Error (m/s)
Bias Error (degrees)
Bias Error (C)
Fine Domain Evaluations

Oct.-Nov. 2007
Wind Speed at Rock Springs, PA

One-minute time series data
Case: 7 October 2007, 0000-1200 UTC

Observed

WRF-Predicted

Red curve:
2-h running mean filter is applied to local time series data to remove sub-meso fluctuations prior to statistical evaluations.
Nocturnal gravity-driven drainage flow modulated by transient submeso motions

Conceptual model:
Shallow gravity-driven drainage flow overrides coldest air on valley floor, gradually filling Nittany Valley.
Wind Shear at Rock Springs
In Stable Boundary Layer

Case study: 7 October 2007, Exp. Baseline

- Wind increases with height, as observed.
- Good correlation with observed trends.
- Positive speed bias: Bias Error ~0.5 ms⁻¹ at 3 m
  Bias Error ~0.7 ms⁻¹ at 9 m
Sensitivity of Wind Speed to Horizontal and Vertical Resolution

Case study: 7 October 2007, Exp. Baseline

SBL wind speed at Rock Springs, PA

Baseline
Observations
Grid 4, 44 levels, 9 m
Grid 3, 44 levels, 9 m
Grid 4, 35 levels, 17 m
Grid 3, 35 levels, 17 m

LrgDx (1.33 km)
LrgDz (30 m)
LrgDx (9-m AGL)

(2-h running-mean filter has been applied)
16-Case Composite
Wind Speed vs. Time

Composite of wind speed in SBL
at Rock Springs, PA

LrgDx (1.33 km)
Baseline (0.44-km)
Observed

Composite obs’d speed gradually weakens thru nocturnal period as Nittany Valley fills with cold air.

(2-h running-mean filter has been applied to each case in the composite)
Sensitivity of 3-m Wind Speed to PBL Physics

Case study: 7 October 2007

Smaller $TKE_{\text{MIN}}$ in Exps. MYJ-mod and QNSE-std is important for reducing excessive mixing in the very stable nocturnal boundary layer, thereby reducing high speed bias in weak-wind conditions.
Predicted Vertical Structure of TKE & $\theta$ in Stable Boundary Layer

Case: 3 Nov. 2007, 0400 UTC

Smaller $\text{TKE}_{\text{MIN}} = 0.01 \text{ m}^2\text{s}^{-2}$ in Exp. MYJ-mod reduces mixing in the very stable nocturnal boundary layer, producing:

- shallower SBL
- colder sfc. temp.
- stronger inversion

$h_{\text{SBL}} = 18 \text{ m}$

$h_{\text{SBL}} = 9 \text{ m}$
Predicted Vertical Structure of $|V|$ in Stable Boundary Layer

Case: 3 Nov. 2007, 0400 UTC

Smaller $TKE_{\text{MIN}} = 0.01 \text{ m}^2\text{s}^{-2}$ in Exp. MYJ-mod reduces mixing in the very stable nocturnal boundary layer, producing:

- Shallower SBL
- Weaker surface wind speed
- Distinctive LLJ at top of SBL
- Stronger shear in SBL
Predicted Vertical Structure of Stable Boundary Layer

Exp. MYJ-mod

Exp. QNSE-std

\( h_{SBL} = 12 \, m \)

QNSE scheme produces:
- 2°C cooler surface temperature
- less distinct transition to free troposphere
- weaker LLJ at top of SBL (not shown)
Sensitivity of Parcel Trajectories to Horizontal Resolution

Case: 7 October 2007, 0800 – 1112 UTC

• Coarser horizontal resolution increases mean wind speed in SBL.

Exp. Baseline, 0.444 km

Exp. LrgDX, 1.333 km

(Both experiments use 43 layers, with 11 layers below 68 m AGL.)
Sensitivity of Parcel Trajectories to Vertical Resolution & PBL Physics

Trajectory Sensitivity:

- Reduced mixing in MYJ-mod allows more sub-meso motions and greater dispersion.
- Low vertical resolution suppresses gravity-driven slope flows.
- QNSE scheme exhibits faster mean flow and weaker sub-meso perturbations in SBL.

Time: 0800 – 1112 UTC  Case: 7 Oct. 2007
Summary

- WRF is tested at high resolution:
  - horizontal: 0.444-km vs. 1.333-km grid
  - vertical: 11 layers vs. 2 layers below 68 m AGL.

- Large impact on trajectories due to resolution and turbulence physics.

- Speed bias is reduced significantly by sub-kilometer (0.444-km) resolution.

- Smaller $TKE_{MIN}$ and $l_B$ (Exp. MYJ-mod) significantly reduces speed bias and promotes more dispersive sub-meso motions.

- Coarser vertical resolution in SBL severely damps gravity-driven slope flow and suppresses shallow sub-meso fluctuations.

- QNSE scheme affects vertical structure of SBL and parcel trajectories.
  - More extensive evaluations and more cases are recommended.