Evaluation of PBL Parameterizations in WRF at Subkilometer Grid Spacings: Response of Resolved Dry Convection to Parameterized Turbulence

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With acknowledgement to Peggy LeMone (NCAR)
Model Grid Spacing: $O(0.1\text{-}1\text{km})$

For coarse grid spacing

- PBL schemes have been developed for $\Delta >> l$.

For finer grid spacing

- No traditional PBL schemes designed for $\Delta \sim l$.
  
  “Terra Incognita” or “Gray Zone”
From “Parameterized” to “Resolved” Turbulence Statistics

At coarse grid spacing
✔ None of turbulence is resolved.
✔ Evaluation for:
\[ \frac{\partial \bar{c}}{\partial t} = \ldots - \frac{\partial w'c'}{\partial z} \]
Mean and parameterized total flux

At finer grid spacing
✔ Turbulence is partially resolved.
✔ Turbulence statistics:
  “parameterized” + “resolved”
The performance of PBL parameterizations in WRF model is re-evaluated at sub-kilometer grid spacings, for resolved turbulence statistics.

Methods

1. **Evaluation using reference data:** spatially filtered LES output
   The most popular way to obtain “reference” for evaluating parameterizations at kilometric and sub-kilometer scales (Honnert et al. 2011; followed by Dorrestijn et al. 2013; Shin and Hong 2013)

2. **PBL schemes selected:** characterized by different nonlocal terms
   Importance of nonlocal terms in sub-kilometer and kilometric grid spacing
   (Honnert et al. 2011; Shin and Hong 2013, 2015)
Spatially filtered LES output for sub-kilometer grid spacing

(Cheng et al. 2010; Honnert et al. 2011; Dorrestijn et al. 2013; Shin and Hong 2013)

“benchmark” LES fields: \( W \)

reference “resolved” fields: \( W \)

reference “subgrid-scale” perturbations:

\[ W' = W - W \]

\( \Delta = 25 \text{ m} \)

\( \Delta = 250 \text{ m} \)
Experimental Setup

An idealized convective boundary layer (CBL)

Initial profiles

- no moisture
- a constant surface heat flux: $0.2 \text{ K m s}^{-1}$
- $U_{\text{initial}} = 10 \text{ m s}^{-1}$
- $u^*/w^* = 0.27 \ (-z_i/L = 18.58)$; not in a roll regime

Model setup

<table>
<thead>
<tr>
<th></th>
<th>Subgrid-Scale vertical transport</th>
<th>Subgrid-Scale horizontal transport</th>
<th>Grid spacing (m)</th>
<th>No. of grids</th>
<th>Domain size (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LES</td>
<td>3D TKE</td>
<td>3D TKE</td>
<td>25</td>
<td>$320^2$</td>
<td>$8^2$</td>
</tr>
<tr>
<td>Reference</td>
<td>Filtered from the LES</td>
<td></td>
<td>250, 500, 1000</td>
<td>$32^2$, $16^2$, $8^2$</td>
<td>$8^2$</td>
</tr>
<tr>
<td>Simulations</td>
<td>PBL schemes</td>
<td>3D TKE</td>
<td>250, 500, 1000</td>
<td>$32^2$</td>
<td>$8^2$, $16^2$, $32^2$</td>
</tr>
</tbody>
</table>
An Overview of PBL Parameterizations in WRF

Representation of unresolved vertical transport

\[
\bar{w} \bar{c} = K_c \frac{\bar{c}}{z} + C_{NL}
\]

1st-order vs. 1.5-order (TKE)  nonlocal vs. local

An important part that determines a scheme’s performance at sub-kilometer grid spacing

<table>
<thead>
<tr>
<th></th>
<th>(K_c)</th>
<th>(C_{NL})</th>
</tr>
</thead>
<tbody>
<tr>
<td>YSU</td>
<td>1st-order [K_{u,v} = kw_z \left(1 - \frac{z}{h}\right)^2]</td>
<td>(C_{NL} = K_c \gamma_c + \bar{w} \bar{e}'_z \left(\frac{z}{h}\right)^3)</td>
</tr>
<tr>
<td>ACM2</td>
<td>(K_c = kw_z \left(1 - \frac{z}{h}\right)^2)</td>
<td>(C_{NL} = M_u (c_u - \bar{c}^A) M_u = a_u w_u)</td>
</tr>
<tr>
<td>EDMF</td>
<td>1.5-order (K_c = l \sqrt{e} S_c)</td>
<td>(C_{NL} = M_u (c_u - \bar{c}^A) M_u = a_u w_u)</td>
</tr>
<tr>
<td>TEMF</td>
<td>(K_c = l \sqrt{e} S_c)</td>
<td>(C_{NL} = M_u (c_u - \bar{c}^A) M_u = a_u w_u)</td>
</tr>
<tr>
<td>MYNN</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>
Examples of previous studies

Coarse grid spacing ($\Delta \gg l$)

Fine grid spacing ($\Delta \sim l$)

Observed profile: weakly stable

Local schemes maintain unstable profiles

Figure is taken from Shin and Hong (2011)

at 1-km grid spacing with 25 pts averaging

Figure is taken from LeMone et al. (2013)
At sub-kilometer and 1-km grid spacing

1. The local PBL scheme reproduces a weakly stable/neutral profile.
2. There is almost no resolution dependency.
“Parameterized” vertical heat transport

GRAY: reference
BLACK: experiments

1. None of them are scale-aware: little resolution dependency.
2. Each parameterization has its own best-performing grid size.
"Parameterized" vertical transport $<w' \theta'>$ in mixed layer
“Parameterized” vertical transport \(<w'\theta'>\)

Parameterized “nonlocal” transport \(C_{NL}\)  + Parameterized “local” transport  

\(-K_\theta \frac{\partial \theta}{\partial z}\)

Grid size for the best performance

- YSU: 1000 m
- ACM2: 500 m
- EDMF: 250 m
- TEMF: < 250 m
- MYNN: < 250 m
Parameterizations’ Resolution Dependency

“Parameterized” vertical transport \(<w’\theta’>\)

\[ \text{Parameterized “nonlocal” transport} \quad C_{NL} \quad + \quad \text{Parameterized “local” transport} \quad -K_{\theta} \frac{\partial \theta}{\partial z} \]

: shows little resolution dependency.

: decreases as \(\Delta\) decreases.
Vertical Heat Transport Profile

YSU and ACM2: 1000 m  EDMF: ~500 m  TEMF: 250 m  MYNN: <250 m
Interactions between Parameterized and Resolved Components

**YSU**

SGS heat transport is overestimated.

\[\Rightarrow\text{Resolved } \theta' \text{ and } w' \text{ are underestimated.}\]

**MYNN**

SGS heat transport is underestimated.

\[\Rightarrow\text{Resolved } \theta' \text{ and } w' \text{ are overestimated.}\]
All the tested PBL parameterizations reproduce well total (resolved + parameterized) vertical transport, therefore mean temperature profiles.

➡ High-resolution modeling for improving resolved fields
$w$ Spectrum

Underestimated SGS
(less diffusion)

Overestimated SGS
(more diffusion)
PDF of $w$

Statistical representation of the distribution of $w$

$\Delta = 500 \text{ m}$

Gray shaded area: Reference

Reference: **positively skewed** (a few strong thermal updrafts surrounded by a large number of weak inter-thermal downdrafts)

YSU and ACM2: near-zero $w$

EDMF: $\sim$ Reference

TEMF and MYNN: more downdrafts, less updrafts
Distribution of $w$ at $0.5z_i$

$W_{\text{max}} = 2.38 \text{ m s}^{-1}$
$W_{\text{min}} = -1.34 \text{ m s}^{-1}$

$b)$ YSU
$W_{\text{max}} = 1.07 \text{ m s}^{-1}$
$W_{\text{min}} = -0.96 \text{ m s}^{-1}$

$c)$ ACM2
$W_{\text{max}} = 1.19 \text{ m s}^{-1}$
$W_{\text{min}} = -0.93 \text{ m s}^{-1}$

$d)$ EDMF
$W_{\text{max}} = 1.74 \text{ m s}^{-1}$
$W_{\text{min}} = -1.54 \text{ m s}^{-1}$

$e)$ TEMF
$W_{\text{max}} = 2.03 \text{ m s}^{-1}$
$W_{\text{min}} = -1.20 \text{ m s}^{-1}$

$f)$ MYNN
$W_{\text{max}} = 2.75 \text{ m s}^{-1}$
$W_{\text{min}} = -2.31 \text{ m s}^{-1}$
At higher morel resolution, $\Delta \sim O(0.1-1 \text{ km})$: $\Delta \sim l$

partly resolved by model dynamics

“as if” not resolved at all!

Gray-zone problem = “Double counting” problem?
At higher morel resolution, $\Delta \sim O(0.1-1 \text{ km})$: $\Delta \sim I$

Scale of motions (wave length) 100 km 10 km 100 m

Energy

“Partitioning”

Recent development by modifying traditional schemes

Shin and Hong (2015), replacing YSU PBL (Hong et al. 2006) in WRF

Boutle et al. (2014), replacing Lock PBL (Lock et al. 2000) in UM