How to develop the physics algorithms in atmospheric models?

Song-You Hong

(songyouhong@gmail.com)
PBL scheme development
(Louis $\rightarrow$ MRF $\rightarrow$ YSU $\rightarrow$ ?)

Stable BL

Grey-zone physics
Development of physics algorithms

- **Theoretical development (concept) : Step 1**
  - Systematic deficiency
  - LES study/theory
  - Numerical discretization
  - Idealized experiments

- **Balance with nature (module) : Step 2**
  - Real case experiments
  - Process study
  - Refinement/reformulation

- **Evaluation at real-time testbed (package) : Step 3**
  - Short-range forecast
  - Medium-range forecast
  - Long-range forecast
Local (Louis 1979) vs. non-local (Troen and Mahrt 1986)

\[ K_{m,t} = l^2 f_{m,t} \left( \text{Rig} \right) \left| \frac{\partial U}{\partial z} \right| \]

![Diagram of Local and Non-Local](image)

**Fig. 1.** Typical variation of eddy viscosity \( K \) with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

\[
\frac{\partial C}{\partial t} = \frac{\partial}{\partial z} \left[ K_c \left( \frac{\partial C}{\partial z} - \gamma_c \right) \right],
\]

\[
K_{zm} = k \nu_s z \left( 1 - \frac{z}{h} \right)^p,
\]

\[
\gamma_c = b \frac{(w'c')}{\nu_s},
\]

\[
h = \text{Rib}_{cr} \frac{\theta_{vd} |U(h)|^2}{g(\theta_v(h) - \theta_s)},
\]
Local vs. non-local (Hong and Pan 1996) : Step 1 and 2

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Code</th>
<th>Description</th>
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<th>Vertical diffusion</th>
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<td>LD</td>
<td>Local diffusion experiment</td>
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<tr>
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<td></td>
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<td>Nonlocal diffusion experiment</td>
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<td>Nonlocal</td>
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</tbody>
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b is critical, but Ribcr is little sensitive

\[\text{counter-gradient term} \Rightarrow \text{consistent with previous PBL studies}\]
Step 2: Heavy rain case (Hong and Pan 1996)

Fig. 7. The analyzed 24-h accumulated rainfall (mm) ending at (a) 1200 UTC 16 May and (b) 1200 UTC 17 May 1995. Areas of rainfall over 8 mm are shaded. Values are box averages on the T126 spectral grid from station data.

Fig. 9. As in Fig. 7 but for the local diffusion experiment, which utilizes the improved convection scheme.

Fig. 10. As in Fig. 7 but for the control nonlocal diffusion experiment with $R_{nu} = 0.50$. Points A, B, and C designate the station points for time-height cross-sectional analyses in Figs. 11 and 13.
Step 3: Parallel run (Hong and Pan 1996)

![Graph showing ETS and Bias scores for parallel run for the month of August 1995]

ND improves both ETS and bias scores for parallel run for the month of August 1995.

The MRF PBL (non-local diffusion) became operational since October 1995.

*Fig. 15. Comparison of the (a) precipitation equitable threat scores and (b) precipitation bias scores derived from the parallel run with the nonlocal diffusion scheme and modified convective parameterization scheme (MRX) and from the current operational model physics (MRY) for the month of August 1995.*
In contrast to the dry case, the resulting rainfall is significantly affected by the critical Ri, which is due to the fact that the simulated precipitation is more sensitive to the boundary layer structure when the PBL collapses than when it develops.

PBL determines the location of convective overturning, which further affects the grid-scale large-scale rainfall downstream.

Overall, the increase of Ri_cr reduces the weak precipitation and increases heavy precipitation.
The MRFPBL (Hong and Pan 1996)

Known problems and analysis of Stevens (2000)
Based on the Troen and Mahrt (1986)

Explicit representation of the entrainment process
Based on Noh et al. (2003)

Too much mixing when wind is strong
Too early development of PBL
Too deep and dry moisture in PBL
Too high PBL height

Improvement of the K-profile model for the PLANETARY BOUNDARY LAYER
based on LARGE EDDY SIMULATION DATA
'Y. Noh*, W.G. Cheon and S.Y. Hong
S. Raasch

Step 1: Systematic deficiency

YSUPBL (Hong et al. 2006)

Step 1: LES study
YSUPBL - development

Step 1

2000.9-2001.3
To formulate a theory (LES $\rightarrow$ a new conceptual model)

2001.3-2002.7
To develop a new numerical scheme (PDE $\rightarrow$ FDE)

Step 2

2002.9-2003.6
To evaluate the scheme and balance with nature (A new package)

Step 3

2003.7-2004.2
To revised the scheme based on the various evaluations (A revised new package)

2006.2
Further revisions (A finalized new package)
Step 1: Generalization and reformulation of the explicit entrainment (N2003)

\[-w'\theta' = K_h \left( \frac{\partial \theta}{\partial z} - \gamma_h \right) - w'\theta_h \left( \frac{z}{h} \right)^3 \text{ for } z < h\]

- Alleviate resolution dependency (staggered)
- Inclusion of moisture, tracers, and hydrometeors
- Conservation of fluxes
- Matching with free convection diffusion
Model setup: BAMEX 2002

- Cold front (10–11 Nov 2002)
- 4 km grid (cloud–resolving)
- YSU PBL compared to MRF PBL
- WSM6 microphysics
- NOAH land surface
- No cumulus parameterization scheme

Initial time: 12Z 10 November 2002
Initial and boundary data: EDAS analyses
Focus: Precipitation response due to the differences in YSU and MRF PBL
Sounding profile at 18Z in the pre-frontal regions (near Nashville Tennessee)

- PBL structure is better reproduced by YSU than MRF in the pre-frontal region → Improved the inversion above h

Cooler & moister

Warmer & drier
Maximum radar reflectivity (dBz)

YSU  MRF  OBS

Frontal Region
Pre-frontal region

18Z  10  Noon

00Z  11  Evening
Time series of domain averaged precipitation

Pre-frontal region

Frontal region

Why precipitation with the YSU is better than with MRF PBL?

See Hong et al. (2006)
Remarks

Impact of PBL on precipitation processes is intimately related with not only the onset of convection, but also the type of convection (shallow vs. deep; local vs. synoptic forcing).

The environmental structure in the lower troposphere indirectly affects the intensity of precipitating convection (dry PBL enhances the evaporation of falling hydrometeors, which results in the weakening of surface precipitation and storm intensity).
Stable boundary layer mixing in a vertical diffusion package
Step 1 : Systematic deficiency

- YSU underestimates the chemical species in stable conditions (over water)
Dear Dr. Hong,

This is Fred. I started to use the fully coupled chemistry within the WRF (WRF/Chem) since I came to Los Alamos to examine the transport and transformation of gaseous and particulate pollutions emitted by megacities such as Mexico City on local and regional scales. One thing I have noticed is that the nocturnal PBL heights in WRF using YSU scheme are nearly constant between 0 and 20 meters. Lidar data from the recent Mexico City field campaign reveal nocturnal PBL heights actually vary between 20 and 500 meters with strong winds corresponding to large PBL heights. I just attended a workshop in Boulder related with the Mexico City field campaign in which many people expressed their concerns for the nearly constant PBL heights in WRF since realistic PBL heights are important for capturing the transport of chemical species.
Step 1: Systematic deficiency

- Warm bias appears near surface in winter
- Cold bias appears near surface in the other seasons

WRF real-time operation at JHWC-GPP

Cold and wet biases
Step 1: Form a new concept


\[ \text{Rib} = h \left( \frac{g}{\bar{\theta}} \right) \left[ \theta(h) - \theta_s \right] \left( \frac{\text{U}(h)}{U(h)^2} \right) \]

the surface bulk Richardson number

where the critical value for Rib is defined by

\[ \text{Rib}_{cr} = 0.16 \left( 10^{-7} R_o \right)^{-0.18} \]

, where

\[ R_o = U_{10} / (f z_0) \]

with \( f = 10^{-4} \).
**Step 1 : Design a new algorithm**

**Bulk Ri number approach**

\[
Ri = \frac{g(\theta_v(h) - \theta_s)}{\theta_{va} |U(h)|^2} \cdot z
\]

**Over water** \( Rib_{cr} = 0.16 \left( 10^{-7} R_o \right)^{-0.18} \)

**Over land** \( Rib_{cr} = 0.25 \)
Step 1: Idealized case

One-d test: $dz = 25 \text{ m}$, sunset = $18 \text{ h}$

PBL

Theta (STBL-CNTL)

- CNTL
- STBL

Cooler & moister

Warmer & dryer
Step 2: Real case – Validation with IOP


Black : OBS
Blue : old_STBL
Red : New_STBL

Kim et al. (2008)
WRF workshop
Step 2: Real case-3D

CNTL : Ribcr = 0 (local Ri dependent mixing), WRF 2.2
STBL : Ribcr > 0 (parabolic shape diffusivity), WRF 3.0

Offline test : idealized surface flux forcing
WRF : Cloud resolving resolution (4km)
RSM : Regional climate simulation (50km)
GSM : Seasonal simulation (T62 ~ 200 km)
Step 2: Interaction with precipitation – regional

RCM simulation in July 2006: RSM 50 km

OBS (TRMM)

CNTL (PC = 0.47)

STBL (PC = 0.57)

Nighttime rainfall is enhanced
Oceanic rainfall is enhanced

Hong (2010 QJRMS)
Step 2: Interaction with other physics

Seasonal simulation (T62; about 200 km)

Model: GRIMs-v2 (Global/Regional Integrated Model system)


Ensemble: 5 members

Experiments:
- **CNTL**: Hong et al. 2006
- **STBL**: Hong 2010 (enhanced mixing)
Step 2: Interaction with other physics
Seasonal simulation for JJA 1996 (rainfall)

Scheme is stable !!!
Skill is comparable
Step 2: Harmony

Zonal-averaged zonal wind (96/97 DJF):

- RA2
- GWD-KA
- NOGWD
- GWD-KA-STBL

Contour: Zonal averaged zonal wind
Shaded: Deviations from the RA2

Kim and Arakawa
→ Improves upper level jets
→ Improves the sea level pressure

(Kim and Hong, GR-letter, June 2009)
Step 3: A statistical evaluation – July 2006

- **T-bias**
  - Solid: CNTL-OBS
  - Dashed: STBL-OBS

- **T-RMSE**

- **q-bias**
  - OBS: Radiosonde data

- **q-RMSE**

Cold start run: 00 UTC → 48 hr forecasts (31 cases)

WRF, 50 km over East Asia

OBS: Radiosonde data
(grey: 12 UTC, black: 00 UTC)

Hong 2010
(QJRMS, in press)
Step 3: Medium-range forecast: December 2006 (10 day run every 00, 12 UTC)

SLP RMSE

500 GH AC

CNTL+KAGWD
STBL+KAGWD

Hong et al. 2008 (Wea Forecasting)
YSU PBL finished ???

An apparent systematic bias:

Too strong surface wind in nighttime
AFWA: WRF 6Z Run, 24 Hour Fcst (mid night)
Wind Speed >= 10kts
Stable mixing in nighttime

Collaboration with Peggy Lemone

\[ Ws = \frac{u^*}{\psi_{im}}, \quad \psi_{im} = (1 + 5z/L) \]
YSU PBL revisions: from V3.3 (2011) to v 3.4.1 (2012)
Development strategy

Physically based
Simplicity
Harmony
“Gray zone” in modeling turbulent PBLs

(see Hong and Dudhia 2012, BAMS for review)

“Gray zone” of a physical process

a range of model resolution
the process is *partly resolved by model dynamics*
and *partly subgrid*

\[ \Delta x \sim O(1 \text{km}) \] in CBL

- **\( \Delta x \gg l \)**
  - Resolved fields: *laminar*
  - Parameterization: *one-dimensional*
  - **“1DPBL”**

- **\( \Delta x \sim l \)**
  - none of two are valid
  - “Terra incognita” *(Wyngaard 2004)*
  - “Gray zone”

- **\( \Delta x \ll l \)**
  - Resolving: large eddies
  - Parameterizing: small eddies
  - *turbulent*
  - **“3DLES”**

\( \Delta x \ll l \) (\( \Delta \) in the inertial subrange)

Two broad classes of methods

**Resolving:**
- mean flows
- large eddies

**Parameterizing:**
- all the turbulence
- small eddies

\[ \frac{l}{\Delta x} \ll 1 \]

\[ \frac{l}{\Delta x} \sim 1 \]

\[ \frac{l}{\Delta x} \gg 1 \]
3-km heavy rainfall simulation

No-CPS run looks better, but on the other hand we may say that the current-state of CPS cannot handle the grey-zone physics
0.75 km heavy rainfall simulation

Another issue like initial condition should exist in this resolution, but we may say that column turbulence physics do not work properly in this resolution.
Derivation of TKE from the YSU PBL Parameterization
(Shin, Hong, Noh, and Dudhia 2013, JAS, in press)

TKE equation

\[
\frac{\partial \varepsilon}{\partial t} = -\frac{\partial}{\partial z} \left( \frac{w'v'}{\rho} + \frac{1}{\rho} \frac{w'}{\rho} \right) + \left( -u'w' - v'w' \right) + \frac{g}{\theta} \frac{w'}{w'} - \varepsilon
\]

- **dissipation**
- **transport** (TR)
- **shear production** (SP)
- **buoyant production** (BP)

**TR**

\[
\frac{w'v'}{\rho} + \frac{1}{\rho} \frac{w'}{\rho} = -K_e \left( \frac{\partial \varepsilon}{\partial z} - \gamma_e \right) + w' v' \left( \frac{z}{h} \right)^3
\]

consistent with the YSU PBL algorithm

\[
K_e = K_H \quad \gamma_e = C_1^* \frac{g}{\theta} w_c w' \theta' \quad \text{Therry and Lacarrère (1983)}
\]

\[
\bar{w}' \theta' h = w_c \Delta \varepsilon |_h
\]

**DIS**

\[
\varepsilon = \left( \frac{\bar{u}^2}{l} \right)^{3/2} = C_e \bar{e}^{3/2} l \]

\[
l \begin{cases} 
1 = \frac{1} {C_{KP} k z} + \frac{1} {l_0} \\
1 = \frac{1} {k z} + \frac{1} {l_0} \\
1 = \frac{1} {l_s} + \frac{1} {l_B} + \frac{1} {l_0}
\end{cases}
\]

for convective BLs

\[
l_0 = \frac{\int_{z_{top}}^{z_{top}} \bar{e} \varepsilon dz}{\int_{z_{top}}^{z_{top}} \bar{e} dz}
\]

by matching \( K_{prof,CBL} \) and \( K_{MY,NBL} \)

for neutral BLs

\[
\text{Mellor and Yamada (1982)}
\]

for convective BLs

\[
\text{Nakanishi (2001)}
\]
Derivation of TKE from the YSU PBL Parameterization
(Shin, Hong, Noh, and Dudhia 2013, JAS, in press)

Experiments

CTL
\[ l = \frac{1}{l_1} + \frac{1}{C_{Kp} k z} + \frac{1}{l_0} \]

ML2
\[ l = \frac{1}{l_2} + \frac{1}{k z} + \frac{1}{l_0} \]

ML3
\[ l = \frac{1}{l_3} + \frac{1}{l_s} + \frac{1}{l_B} + \frac{1}{l_0} \]

Derived TKE matches well with mixed-layer development.

Length scale (l) ↑
→ TKE dissipation (∝1/l) ↓
→ TKE ↑
Analysis on Resolved and Parameterized Vertical Transport in Convective Boundary Layers at Gray-Zone Resolution

Hyeyum Hailey Shin and Song-You Hong

(under review in J. Atmos. Sci.)
Testbeds for WRF/MPAS physics modules written by myself

The Global/Regional Integrated Model System (GRIMs)

Song You Hong¹, Hoon Park¹,², Hyeong-Bin Cheong³, Jung-Eun Esther Kim⁴, Myung-Seo Koo¹, Jihyeon Jang¹, Suryun Ham¹, Seung-On Hwang⁵, Byoung-Kwon Park¹,², Eun-Chul Chang⁵, and Haiqin Li⁶

¹Department of Atmospheric Sciences, Yonsei University, Seoul, Korea
²Numerical Weather Prediction Center, Korea Meteorological Administration, Seoul, Korea
³Department of Environmental Atmospheric Sciences, Pukyong National University, Pusan, Korea
⁴National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory (ESRL), Boulder, Colorado, U. S. A.
⁵Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan
⁶Center for Ocean-Atmospheric Prediction Studies, Florida State University, Florida, U. S. A.

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Abstract: A multiscale atmospheric/oceanic model system with unified physics, the Global/Regional Integrated Model system (GRIMs) has been created for use in numerical weather prediction, seasonal simulations, and climate research projects, from global to regional scales. It includes not only the model code, but also the test cases and scripts. The model system is developed and practiced by taking advantage of both operational and research applications. This article outlines the 1 km in five years.

In the research community, there have been relatively few activities on the development of advanced physics algorithms. These efforts have been visualized by implementing testing new algorithms in the community model such as Weather and Research Forecasting (WRF) model (Skam...