A Simple Vertical Transport Parameterization for Convective Boundary Layer Simulations at Gray-Zone Resolutions

Hyeyum Hailey Shin¹ and Song-You Hong²

¹National Center for Atmospheric Research, Boulder, CO, USA
²Korea Institute of Atmospheric Prediction Systems, Seoul, South Korea

Backgrounds

The Gray-zone problem of the SGS turbulence model

FROM "the theoretical view"

Two traditional numerical modeling methods of turbulent flows according to $\Delta / l$:

- Larger scale $\Delta >> l$: The scale of energy-containing turbulence
- Smaller scale $\Delta << l$: The scale of the spatial filter used in Eq. of motion

$\Delta >> l$: Turbulence energy production in the inertial subrange.

$\Delta << l$: The gray zone, which is a regime where energy and enstrophy are parameterized.

$\Delta = h$: "Terra Incognita" or "Gray zone" (NWP terminology)

TO "a practical view"

The bidirectional consequences of the gray-zone problem according to the SGS vertical transport model used (Honore et al. 2011; LeMone et al. 2013; Ching et al. 2014)

- $\nu_1^-$ parameterized by so-called PBL parameterization.

Simulations at the gray-zone resolution show that using the SGS models with term (2) without term (2)

- Excessive diffusion
- Remaining instability
- Too weak resolved motions

The question is how to decrease modeled SGS energy for the nonlocal PBL schemes (for increase for the local schemes) while leaving an accurate amount of energy for resolved motions!

How to decrease the SGS energy? By reducing the SGS NL transport term!

Resolution dependency of the SGS nonlocal transport profile

Method (Honore et al. 2011; Dorey et al. 2013; Shin and Hong 2013)

1. Benchmark LES for $d_{ref} = 25 m$ and horizontal domain $D = 8^2 km^2$.
2. Through spatial filtering, the reference fields for resolved and SGS transport are calculated for $d_{ref} = \Delta \leq 25 D$.
3. By conditional sampling using vertical velocity and a passive scalar (Courneya et al. 2010), the SGS transport is decomposed into local (NL) and local (L) SGS transports.

Results – Notes for a simple parameterization

- The role of NL transport: Surface-layer cooling, Mixed-layer heating, and Entrainment.
- The basic role is kept for different $\Delta$.

A parameterization is designed to "force" the SGS vertical transport to follow the resolution dependency, and its effects are investigated for convective boundary-layer simulations at gray-zone resolutions.

A simple parameterization

- Representation of vertical heat transport in CBLS

$$\frac{\omega^{\prime} - \theta^{\prime}}{\omega^{\prime} - \theta^{\prime}} = -K_{\theta} \theta^{\prime} + F_{\theta}^{\prime} \Delta \leq l$$

(1) Term for local (L) transport by small eddies

(2) Term for nonlocal (NL) transport by large eddies

Vertical diffusivity used in conventional PBL schemes

(1) Local transport

$$K_{\theta} = K_{\theta_{\text{base}}} + P_{\text{NL}}(\Delta)$$

(2) Nonlocal transport

$$F_{\theta}^{\prime} = \left(\frac{\omega^{\prime}}{\omega^{\prime}}\right)^{\Delta l} \left(1 - \frac{\theta^{\prime}}{\theta_{\text{base}}}\right)$$

A linear profile fit to the LES-derived NL transport profile (cf. Figure in the above section)

Resolution dependency functions for SGS heat transport

Resolution dependency functions for SGS heat transport (Honore et al. 2011) for total (NL + L) SGS heat transport; Shin and Hong (2013) for its decomposition into NL and L parts

NOTE The SGS NL transport profile only depends on the external forcing (surface heating and mean wind shear), as it is fit to the domain-averaged LES shear.

Summary and Discussions

The CBL simulations are improved by using the nonlocal transport profile fit to the LES and the resolution dependency functions in the SGS model (as expected).

The new algorithm introduced here is based on the empirical fitting and corresponding numerical parameters. Accepting the algorithm as a complete scheme or not might be another part of the "gray-zone" problem.

Evaluation

Experimental setup – Idealized simulations

- Model: LES version of WRF3.51
- Forcing: $\omega^{\prime}/U_2 = 0.2 \text{K m s}^{-1}$; $U_2 = 10 \text{m s}^{-1}$
- Initial profiles: $\theta = 300 \text{K for } z < 925 \text{m}; \text{Inversion strength} = 0.053 \text{K m}^{-1}$
- Table 1: SGS turbulence models, horizontal grid size, horizontal domain size

Simulation results

1. Mean profiles

- Improvement in the entrainment and the inversion strength

2. Grid-size dependency of resolved, SGS, and total (resolved + SGS) transports

- The OLD nonlocal scheme (overestimates the SGS transport, and suppresses resolved motions (cf. Honore et al. 2011; LeMone et al. 2013; Ching et al. 2014). The NEW model improves the resolution dependency of the SGS transport, since $P_i(\Delta)$ functions fit to the LES results are used.

3. Resolved modes

- Energy spectrum

- Energy flux

Due to the reduced SGS transport the remaining resolved energy for the OLD is relatively close to the reference spectrum, compared to the OLD.

- The resolved energy is still underestimated in the NEW, especially at $\Delta = 1000 \text{m}$.

Acknowledgement

We gratefully acknowledge J. Guillaumet and P. C. M. van der Hilst for thoughtful reviews and helpful suggestions. The research was supported by the National Center for Atmospheric Research (NCAR) through the University Corporation for Atmospheric Research (UCAR) fellowship program and by the University of Colorado at Boulder (UCB). This research was also sponsored by the National Science Foundation (NSF).

References