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

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Backgrounds

The Gray-zone problem of the SGS turbulence model

FROM "the theoretical view"
Two traditional numerical modeling methods of turbulent flows according to Δ/l (Wyngaard 2004)

l: the scale of energy-containing turbulence
Δ: the scale of the spatial filter used in Eq. of motion

Larger scale ← → Smaller scale

$\Delta >> l$	$\Delta \sim l$	$\Delta << l$
Mesoscale modeling **: all the turbulence is parameterized** by so-called PBL parameterization.	**No SGS model** designed for this scale!	LES **: Only small-scale eddies are parameterized** (Δ in the inertial subrange).

➔ **$\Delta \sim l$:** "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 (Honnert et al. 2011; LeMone et al. 2013; Ching et al. 2014)

$$\overline{w\phi}^{\Delta} - \overline{w}^{\Delta}\overline{\phi}^{\Delta} = -K_{\phi}\frac{\partial\overline{\phi}^{\Delta}}{\partial z} + F_{w\phi}^{NL}$$

(1) Term for local (L) transport by small eddies
(2) Term for nonlocal (NL) transport by large eddies

Simulations at the gray-zone resolution show that using the SGS models

with term (2) (e.g., nonlocal PBL schemes)
➔ Overestimated SGS transport
➔ Excessive diffusion
➔ Too weak resolved motions

Between?!

without term (2) (local PBL schemes; LES SGS models)
Underestimated SGS transport ➔
Remaining instability ➔
Too strong resolved motions ➔

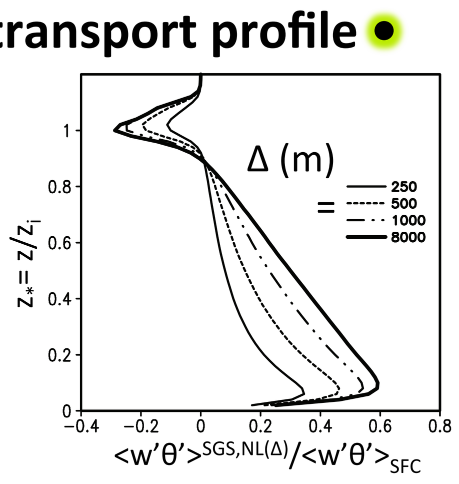
➔ The question is **how to decrease modeled SGS energy for the nonlocal PBL schemes** (or increase it for the local schemes) **while leaving an accurate amount of energy for resolved motions!**

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

Resolution dependency of the SGS nonlocal transport profile

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

1. **Benchmark LES for Δ_{LES} = 25 m** and horizontal domain $D^2 = 8^2$ km^2.
2. Through spatial filtering, **the reference fields for resolved and SGS transport** are calculated for **Δ: $\Delta_{LES} < \Delta < D$.**
3. By conditional sampling using vertical velocity and a passive scalar (Couvreux et al. 2010), **the SGS transport is decomposed into nonlocal (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 Δ.

In this study: simplification of the problem

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

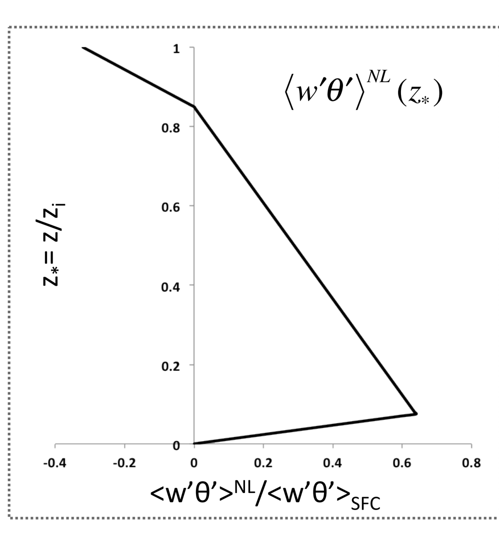
$$\overline{w\theta}^{\Delta} - \overline{w}^{\Delta}\overline{\theta}^{\Delta} = -K_{\theta}\frac{\partial\overline{\theta}^{\Delta}}{\partial z} + F_{w\theta}^{NL}$$

(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 (i.e., used for $\Delta >> l$)

(1) Local transport $K_{\theta}(\Delta_*) = K_{\theta,meso} \cdot P_L^{w\theta}(\Delta_*)$

(2) Nonlocal transport $F_{w\theta}^{NL} = \langle w'\theta'\rangle^{NL}(z_*) \cdot P_{NL}^{w\theta}(\Delta_*)$



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

Resolution dependency functions for SGS heat transport
Honnert 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 profile.

More details in Shin and Hong (2014)

Evaluation

Experimental setup – Idealized simulations

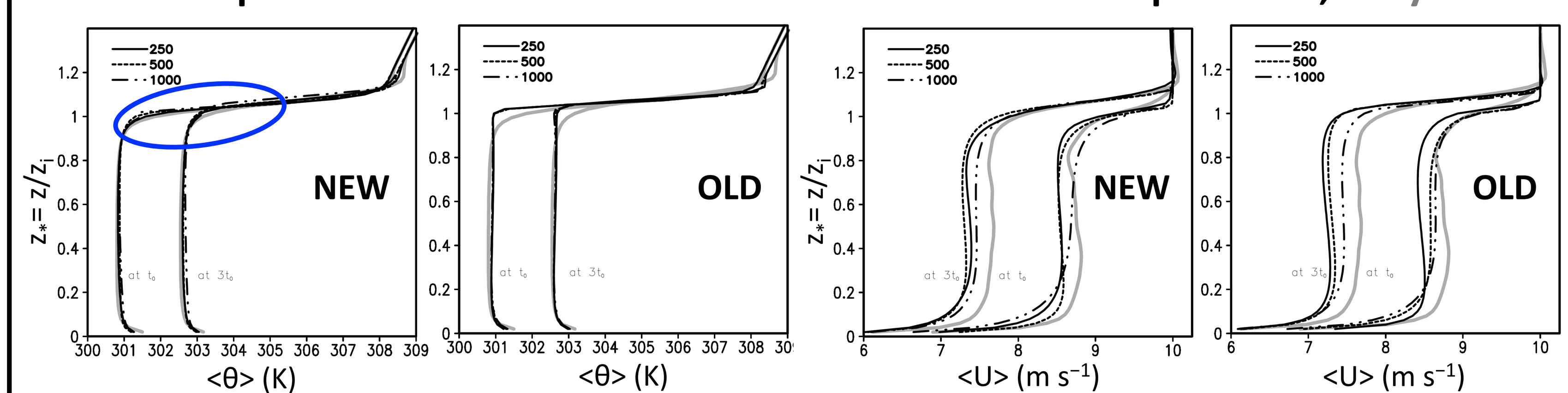
- **Model:** LES version of WRFV3.5.1
- **Forcing:** $\langle w'\theta'\rangle_{SFC}$ = 0.2 K m s^{-1}; U_g = 10 m s^{-1}
- **Initial θ profile:** θ = 300 K for z ≤ 925 m; Inversion strength = 0.053 K m^{-1}
- **Table 1:** SGS turbulence models, horizontal grid size, horizontal domain size

	Vertical SGS model	Horizontal SGS model	Grid size (m)	Horizontal domain (km²)
Benchmark LES	3D TKE (Deardorff 1980)		25	8^2
GZ Reference	Derived from the Benchmark LES		250, 500, 1000	8^2
NEW	NEW	3DTKE	250, 500, 1000	8^2, 16^2, 32^2
OLD	YSU (Hong et al. 2006)	3DTKE	250, 500, 1000	8^2, 16^2, 32^2

: The simple NEW model is evaluated against the LES and gray-zone (GZ) reference data, and compared with a conventional nonlocal PBL parameterization (OLD).

Results

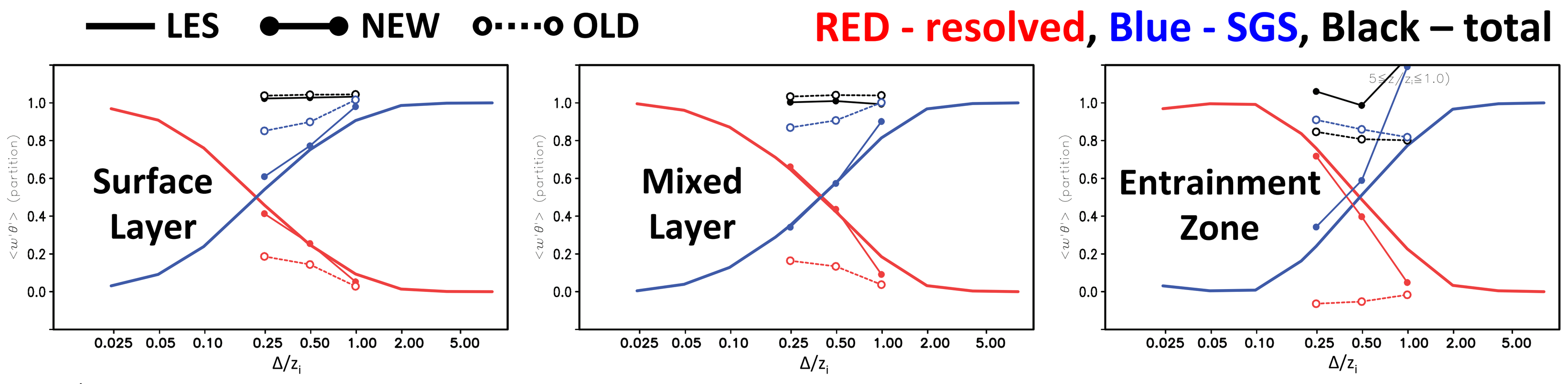
1. Mean profiles — Black - experiment, Gray - LES



✓ **Improvement** in the entrainment and the inversion strength
✓ No degradation or improvement in <U>

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

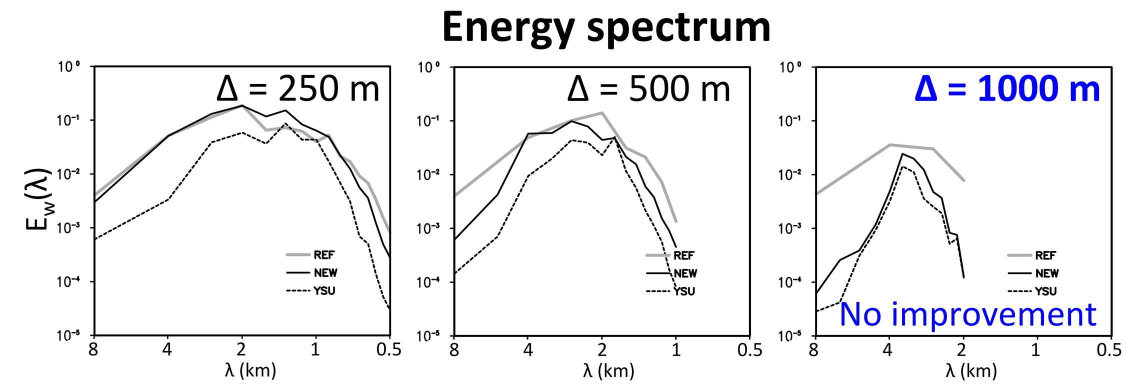
LES ●—● NEW o····o OLD — RED - resolved, Blue - SGS, Black – total



- ✓ **The OLD** nonlocal scheme (**o····o**) **overestimates the SGS transport**, and **suppresses resolved motions** (cf. Honnert et al. 2011; LeMone et al. 2013; Ching et al. 2014).
- ✓ **The NEW model (●—●) improves the resolution dependency of the SGS transport**, since P(Δ) functions fit to the LES results are used.

3. Resolved motions

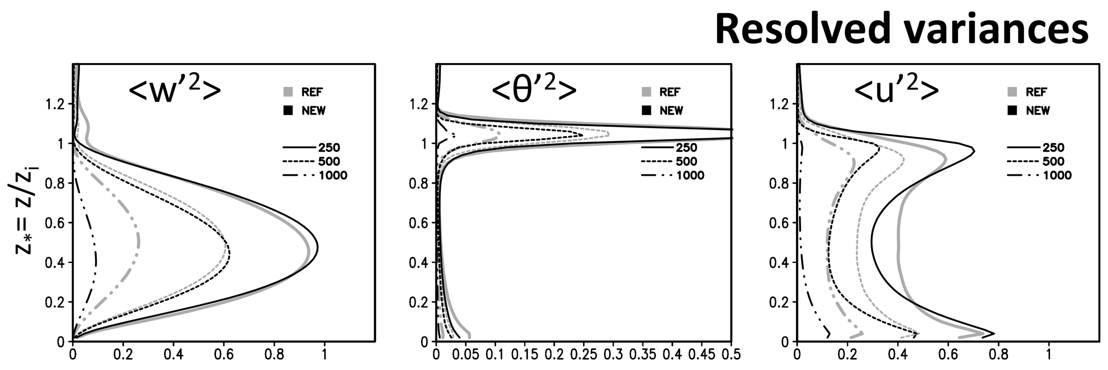
Energy spectrum



NOTE For λ < 6-7Δ, the NEW & OLD experiments are affected by the 6th-order numerical diffusion due to the 5th-order advection scheme (cf. Skamarock 2004).
For a better comparison, the reference fields (gray) are filtered by a 6th-order numerical filter.

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

Resolved variances



✓ **The resolved energy are still underestimated** in the NEW, especially at Δ = 1000 m.

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.

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