Analysis of subgrid-scale vertical transport in convective boundary layers at grey-zone resolutions

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Backgrounds

- **Representation of vertical turbulent transport in current weather and climate models**

- *For variable φ* (φ: u, v, θ, q_v, …)

Temporal change of grid (Δ) mean state (resolved motions)

$$\frac{\partial\langle\phi\rangle}{\partial t}=\cdots-\frac{\partial\langle w'c'\rangle}{\partial z}$$

Unresolved turbulences affect the mean state.

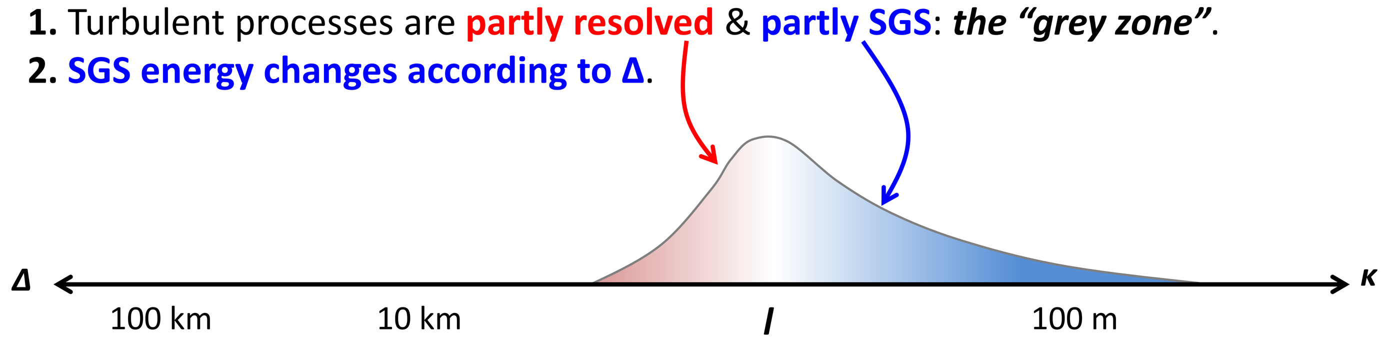
This term is expressed by the so-called planetary boundary layer (PBL) parameterization.

- *The assumption behind the PBL parameterization*
  : **Δ >> *l*** (Δ: grid or filter scale, *l*: scale of large eddies). Therefore, all the turbulent processes in the PBL are subgrid-scale (SGS) and parameterized.
  : This assumption is valid for Δ~*O*(10 km) or larger.

- **"Grey zone" or "Terra Incognita"**

- *At forthcoming high resolutions: at Δ ~ l?*

1. Turbulent processes are partly resolved & partly SGS: *the "grey zone"*.
2. SGS energy changes according to Δ.



***l* ~ *O*(1 km) for Convective PBL**

3. SGS parameterization in the grey zone?
   Δ >> *l* – all turbulences in the PBL are parameterized by the PBL parameterization.
   Δ << *l* – using LES, large eddies are explicitly calculated & only small eddies are parameterized.
   Δ ~ *l* – both methods cannot be used: ***"terra incognita"*** (Wyngaard 2004).
   ➔ **A SGS parameterization that works in the grey zone is needed.**

4. ***So, what happens in the grey zone?*** **– A precedent study of Honnert et al. (2011)**
   (1) For each variable (e.g., TKE) at each layer (e.g., mixed layer), ***a unified scale dependency function*** is suggested ***for different types of convective PBLs (CBLs)***.
   (2) **'How to make the SGS coherent structures (e.g., thermals) weaker in the grey zone'** is one of the important questions for the future SGS parameterization.

- **Two main questions of this study, motivated by Honnert et al. (2011)**
  ➔ PART A: What are ***the effects of stability in CBLs on the scale dependency?***
  ➔ PART B: Can we provide a reference for ***the grid-size dependency of the SGS non-local transports*** by the coherent structures?

Summary

We analyzed grid-size dependency of the SGS vertical transport in CBLs, which differ in relative importance of shear and buoyancy forces (i.e., stability). According to the increase of horizontal scale of the coherent structures, **the grid size corresponding to the grey zone increases as the relative importance of shear increases**. The grid-size dependency and the effects of stability on it are **largely determined by the non-local transport**.

A. Effects of stability

- **Methods**

(1) Benchmark large-eddy simulations (LES) for 4 different CBLs

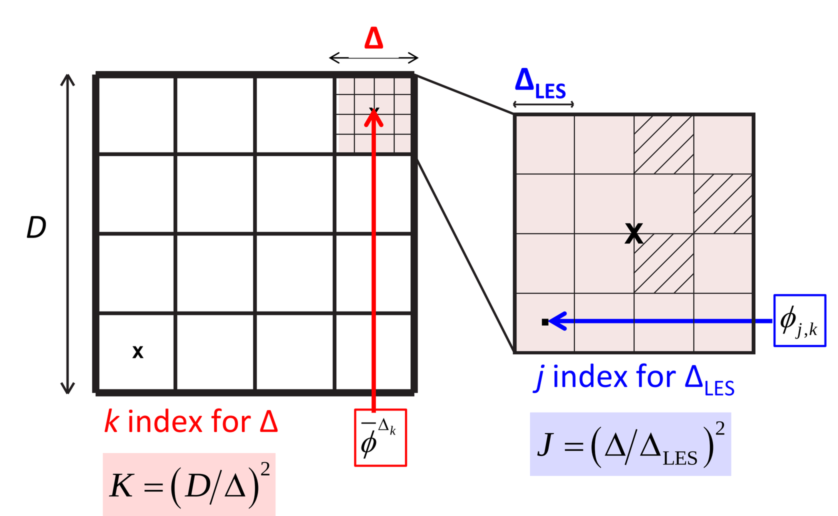
Table 1

Case		$\overline{w'\theta'}_0$ (K m s^{-1})	U_g (m s^{-1})	u_*/w_*	$-z_i/L_{MO}$	Coherent structures
BT	buoyancy-driven (B), and organized thermals (T) appear	0.20	0	***0.097***	***430.31***	thermal circulations
BF	buoyancy-driven (B), as well as wind-forced (F)	0.20	10	***0.278***	***18.58***	not well defined
SW	weaker shear	0.05	10	***0.417***	***5.01***	convective rolls
SS	stronger shear	0.05	15	***0.538***	***2.21***	convective rolls

relative importance of shear increases

- WRF-LES is used, and a SGS parameterization using a TKE equation (Deardorff 1980) is used.
- The **model domain** is 8 km×8 km×3.5 km along the x, y, and z directions: i.e., ***D*=8 km**.
- **Horizontal grid spacing** is 25 m: **Δ_{LES}=25 m**.

(2) Construction of the 'true' data for Δ=50 ~ 4000 m from the benchmark LES
(Dorrestijn *et al.* 2012; Honnert *et al.* 2011)



[cf. Figure is modified from Dorrestijn et al. (2012)]

D: Length of the LES domain (8000 m)
Δ: Subdomain size (50 m ~ 4000 m)
Δ_{LES}: LES grid size (25 m)

$\overline{\phi}^{\Delta_k}=(J)^{-1}\sum_j\phi_{j,k}$: ***average over*** the k-th subdomain of size **Δ×Δ**

$\langle\phi\rangle=(JK)^{-1}\sum_{j,k}\phi_{j,k}=K^{-1}\sum_k\overline{\phi}^{\Delta_k}$: ***averaged over D×D***

- Vertical transport of the variable *φ* over the whole domain (i.e., <*w'φ'*>) consists of ***resolved*** and ***SGS*** parts for each resolution Δ [designated by superscripts **R(Δ)** and **S(Δ)**, respectively]:

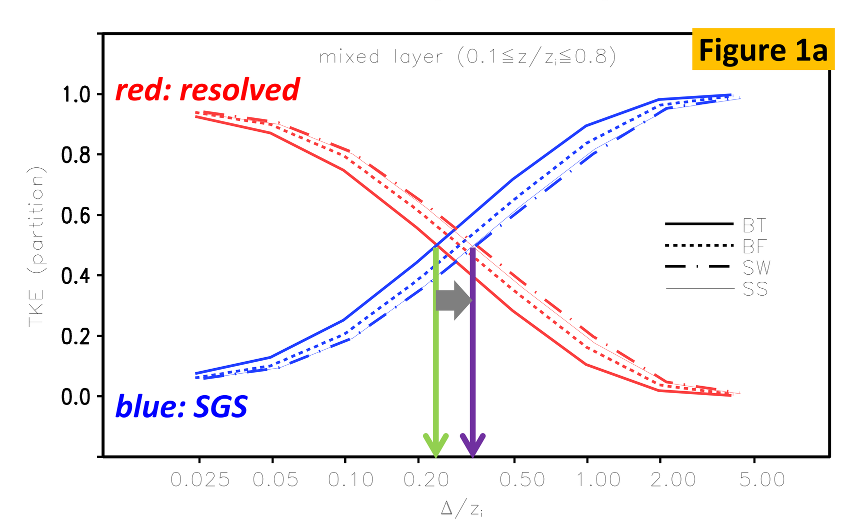
$$\langle w'\phi'\rangle=\langle w'\phi'\rangle^{R(\Delta)}+\langle w'\phi'\rangle^{S(\Delta)}$$

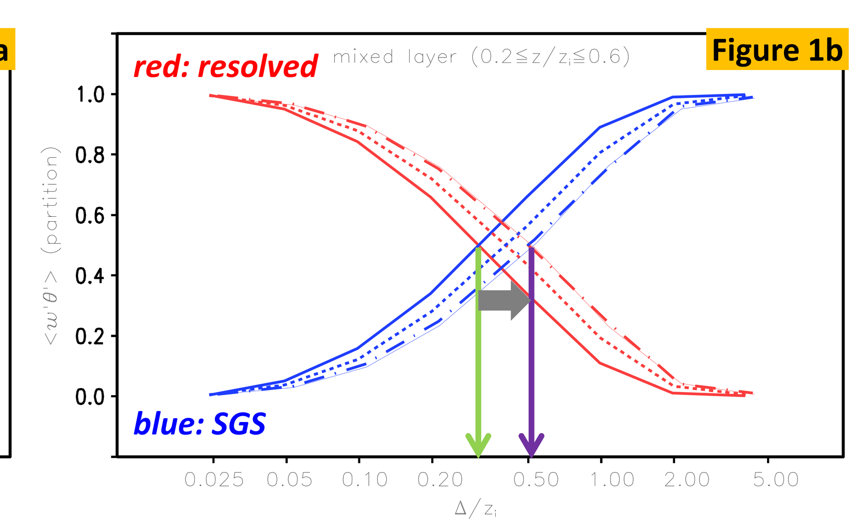
$$\langle w'\phi'\rangle^{R(\Delta)}=K^{-1}\sum_k\left(\overline{w}^{\Delta_k}-\langle w\rangle\right)\left(\overline{\phi}^{\Delta_k}-\langle\phi\rangle\right)$$

$$\langle w'\phi'\rangle^{S(\Delta)}=K^{-1}\sum_k\left[J^{-1}\sum_j\left\{\left(w_{j,k}-\overline{w}^{\Delta_k}\right)\left(\phi_{j,k}-\overline{\phi}^{\Delta_k}\right)+f^{w\phi}_{j,k}\right\}\right]=K^{-1}\sum_k\left(\overline{w''\phi''}^{\Delta_k}+\overline{f^{w\phi}}^{\Delta_k}\right)$$

from LES SGS model

- **Results – Grid-size dependency of SGS TKE (left) and vertical heat transport (right)**





- As relative importance of ***shear forcing increases*** (from BT to SW), *the grid size corresponding to the grey zone* ***increases***. This is attributed to the ***larger horizontal scale of the rolls (~ 3z_i) appearing in the SW/SS***, than the scale of the thermal circulations (~1.5z_i) in the BT case (cf. Table 1) (Moeng and Sullivan 1994). When the rolls exist, ***the energy spectrum peaks move to larger scales***.

B. Non-local and local transports

- **Methods**

(1) Decomposition of SGS vertical transport into the non-local and local parts

$$\langle w'\phi'\rangle=\langle w'\phi'\rangle^{R(\Delta)}+\langle w'\phi'\rangle^{S(\Delta)}=\langle w'\phi'\rangle^{R(\Delta)}+K^{-1}\sum_k\left(\overline{w''\phi''}^{\Delta_k}+\overline{f^{w\phi}}^{\Delta_k}\right)$$

- The total turbulent flux of any arbitrary variable φ can be decomposed into three terms.

- That is, for each Δ_k (i.e., for k-th subdomain of size Δ×Δ):
(Siebesma and Cuijpers 1995, Siebesma et al. 2007).

$$\overline{w''\phi''}^{\Delta_k}=J^{-1}\sum_j\left(w''_{j,k}\phi''_{j,k}\right)=\left[a^{\Delta_k}(1-a^{\Delta_k})(w^{\Delta_k}_{cs}-w^{\Delta_k}_{e})(\phi^{\Delta_k}_{cs}-\phi^{\Delta_k}_{e})\right]+\left[a^{\Delta_k}\overline{w''\phi''}^{\Delta_k,cs}+(1-a^{\Delta_k})\overline{w''\phi''}^{\Delta_k,e}\right]$$

Non-Local (NL) vertical transport by strong updrafts of the coherent structures $\equiv\overline{w''\phi''}^{\Delta_k,NL}$

Local (L) vertical transport within the coherent structures

Local (L) vertical transport within the environment $\equiv\overline{w''\phi''}^{\Delta_k,L}$

* Subscript *cs* (*e*) denotes an average over the coherent-structure (remaining environment) area.
* An overbar with the superscript *cs* (*e*) refers to the average of fluctuations with respect to the coherent-structure (remaining environment) averaged values.
* $a^{\Delta k}$ is the fractional area of k-th subdomain covered by the coherent structures.

- Over the whole domain: $\langle w'\phi'\rangle^{S(\Delta),NL}\equiv K^{-1}\sum_k\left(\overline{w''\phi''}^{\Delta_k,NL}\right)$ ➔ ***SGS non-local transport***

$\langle w'\phi'\rangle^{S(\Delta),L}\equiv K^{-1}\sum_k\left(\overline{w''\phi''}^{\Delta_k,L}+\overline{f^{w\phi}}^{\Delta_k}\right)$ ➔ ***SGS local transport***

assumption: all coherent structures are resolved at Δ_{LES}. Therefore, LES SGS model wholly contributes to the SGS local transport at Δ_{LES}.

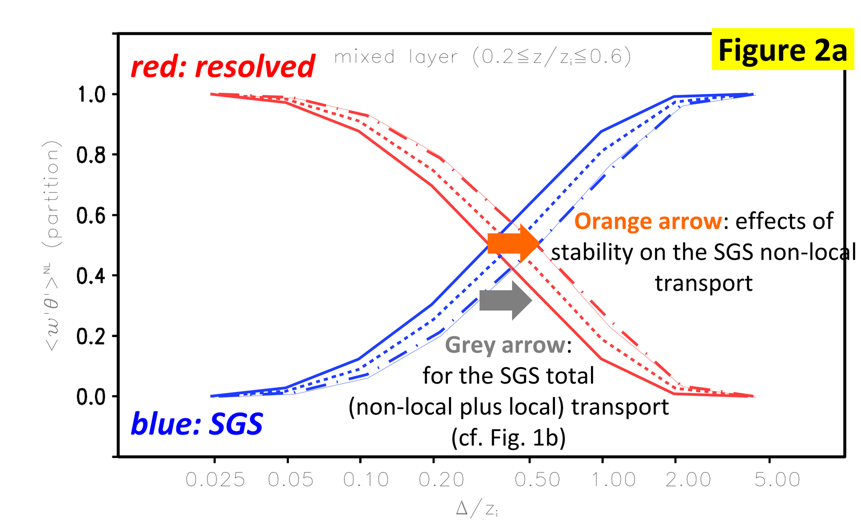
(2) Conditional sampling

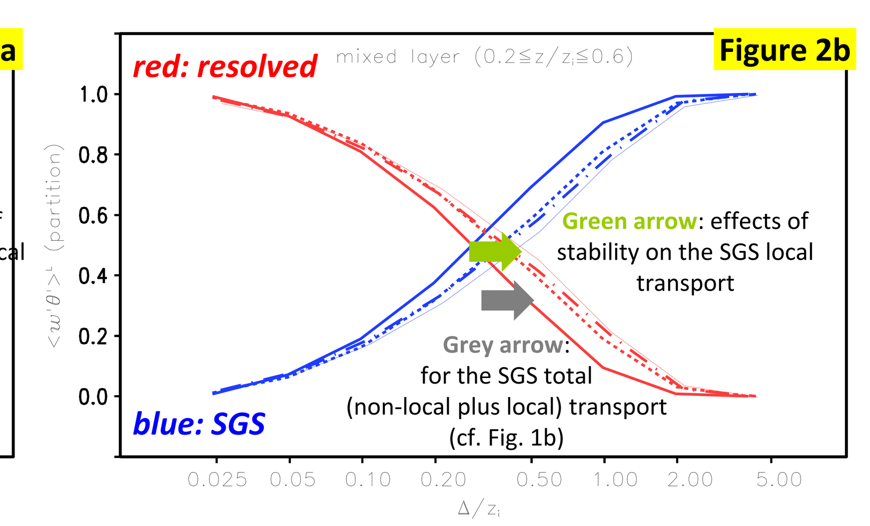
- To detect the coherent structures and separate the corresponding non-local vertical transport from the total transport, two conditional sampling methods are applied to the benchmark LES.

Table 2

	Method 1 (M1)	Method 2 (M2)
	An LES point (x,y,z) is sorted into the CS category if	
Criteria	$c'_{bu}(x,y,z)>\max(\sigma_{c_{bu}}(z),\sigma_{min})$ and $w(z)>0$	$w(x,y,z)>w_{10\%}(z)$
Reference	Couvreux et al. (2010)	Siebesma et al. (2007)

- **Results – Grid-size dependency of SGS non-local (left) and local (right) heat transports**
[Only the results using M1 (Couvreux et al. 2010) are presented here.]





- The grid size corresponding to the grey zone: ***largest for <w'φ'>^{NL}*** **and** ***smallest for <w'φ'>^{L}***.
- The grid-size dependency of the *total SGS vertical transport* (i.e., non-local plus local) and effects of stability on it ***largely depend on the non-local transport*** (cf. similarity between Fig. 1b and Fig. 2a).
- These results are kept regardless of the conditional sampling method (not shown).