Representation of the Subgrid-Scale Turbulent Transport in Convective PBLs at Gray-Zone Resolutions

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With acknowledgement to

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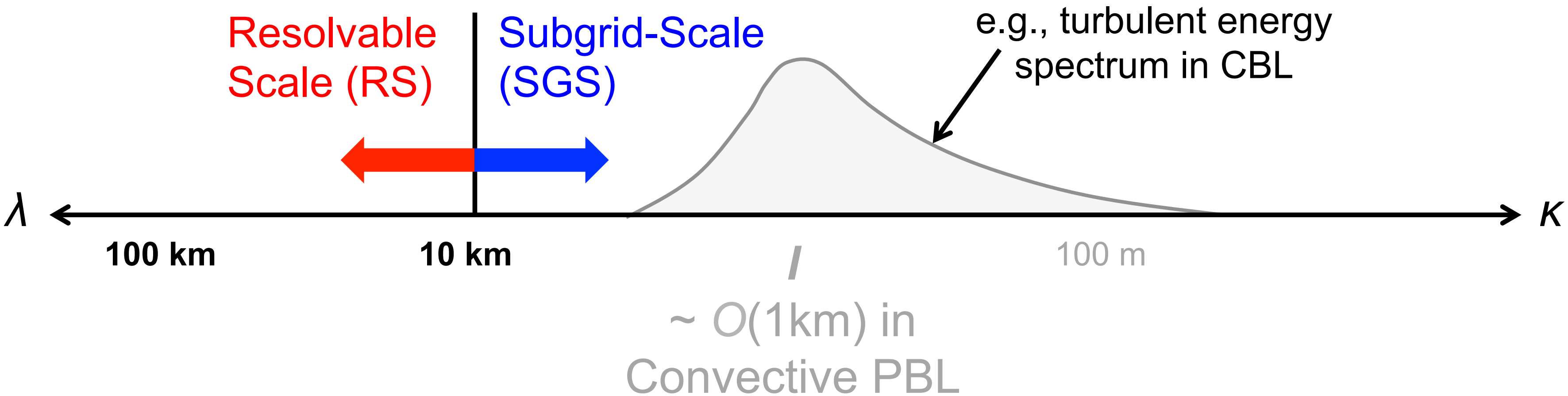
Sungsu Park (CGD/NCAR), Yign Noh (YonSei Univ.)

NWP models and GCMs: Δ ~ *O*(10-100 km)

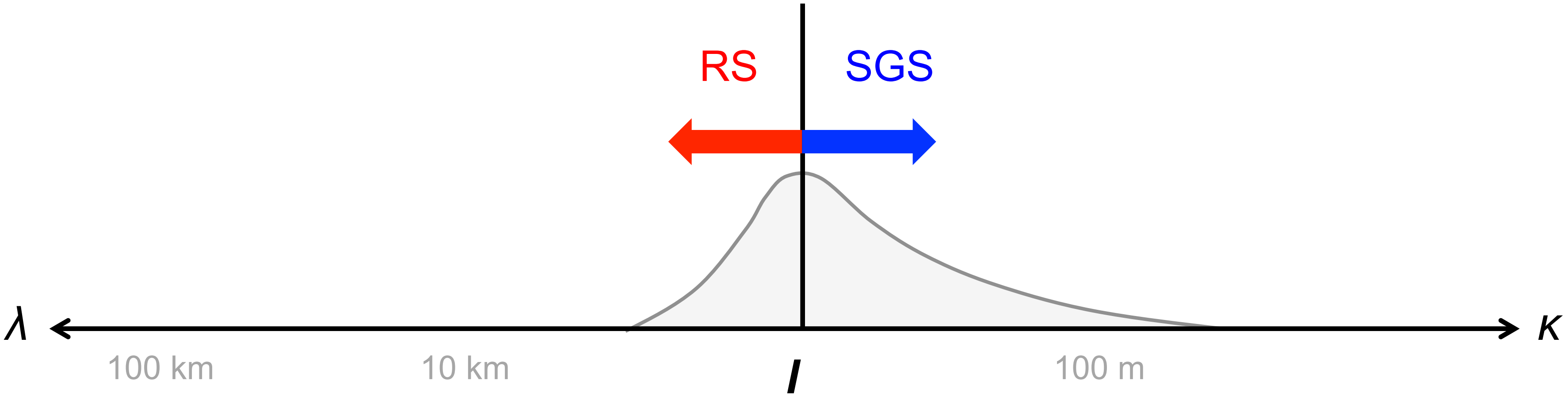
grid (Δ) mean state

$$\frac{\partial \bar{c}}{\partial t} = \cdots - \frac{\partial \overline{w'c'}}{\partial z} \; ?$$



Δ >> *l*: Totally subgrid-scale (SGS) ➔ Entirely parameterized.

At higher resolutions: Δ ~ *O*(0.1-1 km)



~ *O*(1km) in Convective PBL

Δ ~ *l*: Partly resolved, and partly parameterized.

"GRAY ZONE"

The GRAY ZONE of the SGS turbulence model

FROM "The theoretical view" (Wyngaard 2004)

Two traditional modeling methods of turbulent flows
according to the ratio Δ/l

Larger scale ⟵⟶ Smaller scale

$\Delta >> l$ | **$\Delta \sim l$** | **$\Delta << l$**

NWP/GCMs
Turbulence is parameterized by PBL scheme.

LES
Large turbulent eddies are resolved.

FROM "The theoretical view"

Two traditional modeling methods of turbulent flows
according to the ratio Δ/l

Larger scale ⟷ Smaller scale

$\Delta \gg l$	$\Delta \sim l$	$\Delta \ll l$
NWP/GCMs		**LES**
Turbulence is parameterized by PBL scheme.	**None of them**	**Large turbulent eddies are resolved.**

?

To “A practical view”

Simulations in the gray zone show **two opposite problems**

$$\overline{w'\phi'}^{\Delta} = \overset{(1)}{-K_{\phi}\frac{\partial\overline{\phi}^{\Delta}}{\partial z}} + \overset{\textbf{(2)}}{F_{w\phi}^{NL}}$$

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

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

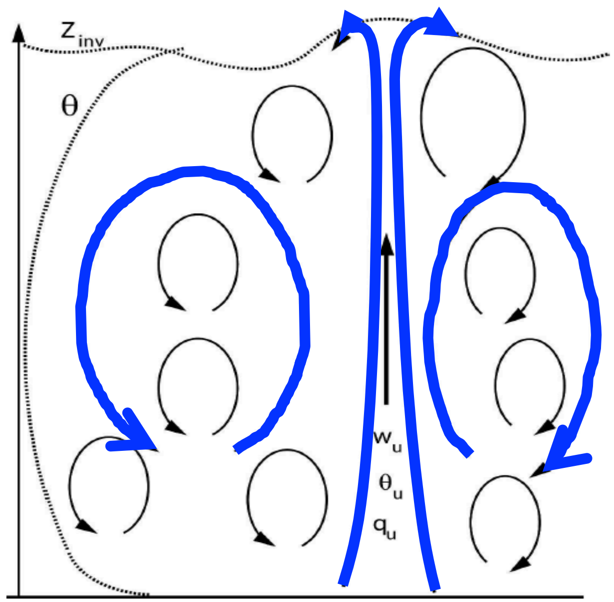


FIG. 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

Explicitly included in **nonlocal PBL parameterizations**

(i.e., Mass-flux term or counter-gradient gamma)

Figure is taken from Siebesma et al. (2007, JAS)

To “A practical view”

Simulations in the gray zone show **two opposite problems**
according to the SGS model used
(Honnert et al. 2011; LeMone et al. 2013; Ching et al. 2014)

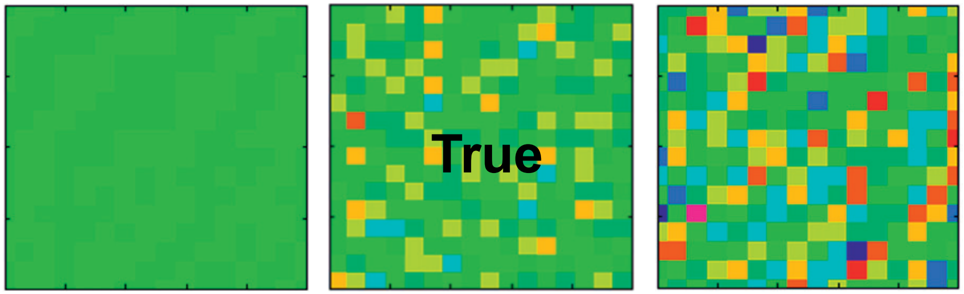
With the nonlocal term
(e.g., nonlocal PBL schemes)

➔ Overestimated SGS transport
➔ Excessive diffusion
➔ **Too weak resolved motions**

Without it
(local PBL schemes; LES SGS)

Underestimated SGS transport 🡐
Remaining instability 🡐
Too strong resolved motions 🡐

For Δ = **1 km**; vertical velocity, over 16 km^2 domain



Taken from Honnert et al. (2011)

To "A practical view"

Simulations in the gray zone show **two opposite problems according to the SGS model used**
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With the nonlocal term
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➔ Overestimated SGS transport
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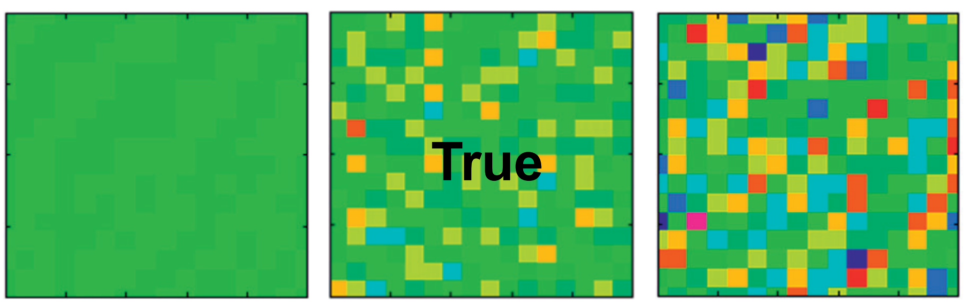
➔ **Too weak resolved motions**

Between?!

Without it
(local PBL schemes; LES SGS)

Underestimated SGS transport ←
Remaining instability ←
Too strong resolved motions ←

For Δ = **1 km**; vertical velocity, over 16 km^2 domain



Taken from Honnert et al. (2011)

Essentially, the question is

How to decrease the parameterized energy
by handling the nonlocal term,
while **leaving an accurate amount of resolvable energy**
for model dynamics?

In this study,

1) **Resolution dependency** of the SGS nonlocal transport in the GZ

2) **Its representation** for the CBL in the GZ
: A SGS model ***"forced"*** to be scale-aware

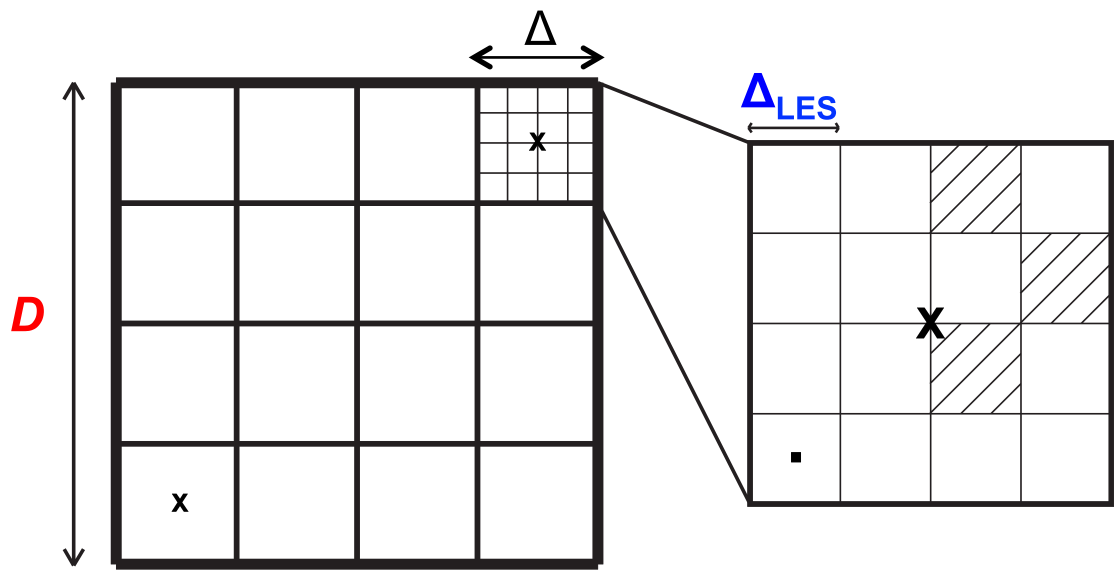
Resolution dependency of the SGS nonlocal vertical transport

Construction of the reference data

Larger scale ⟷ Smaller scale

D >> *l*	***l* ~ 1 km**	**Δ_{LES} << *l***
D = 8 km	D > Δ > Δ_{LES}	Δ_{LES} = 25 m

1. **Benchmark LES for CBLs: Δ_{LES} = 25 m and D = 8 km.**



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

Construction of the reference data

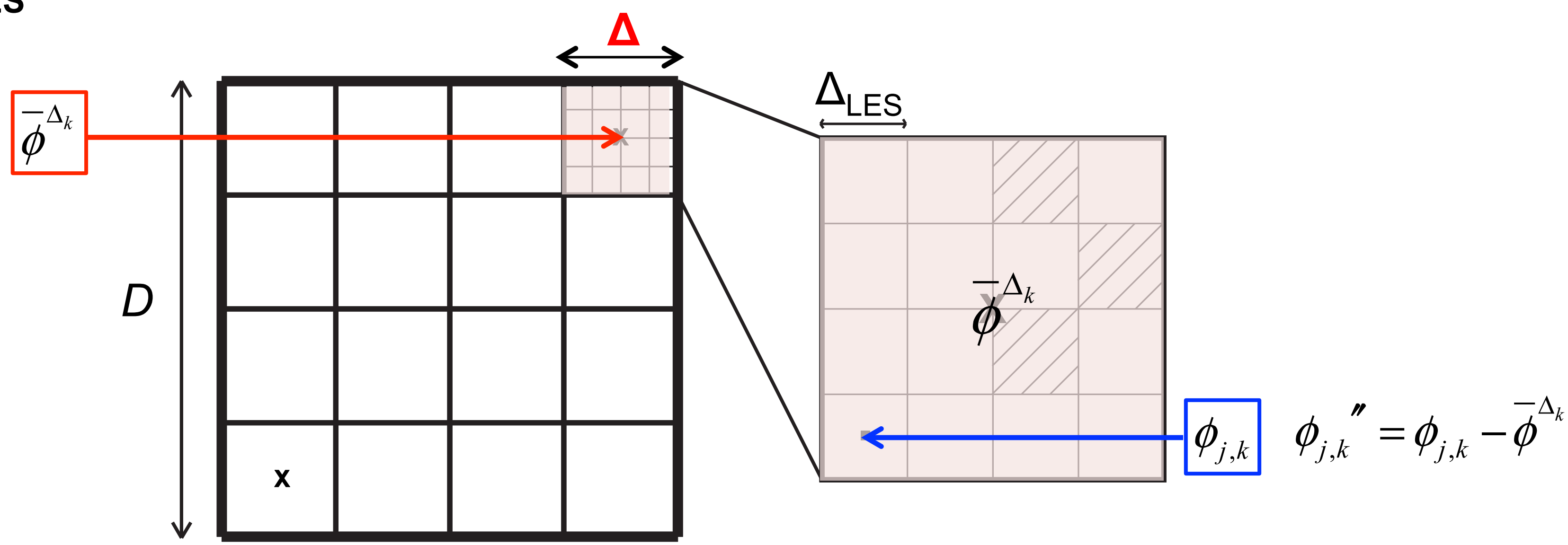
Larger scale ⟷ Smaller scale

$D >> l$
$D = 8$ km

$l \sim 1$ km
$D > \Delta > \Delta_{LES}$

$\Delta_{LES} << l$
$\Delta_{LES} = 25$ m

2. Through spatial filtering, GS and SGS transports are calculated for $\Delta_{LES} < \Delta < D$.



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Construction of the reference data

Larger scale ⟷ Smaller scale

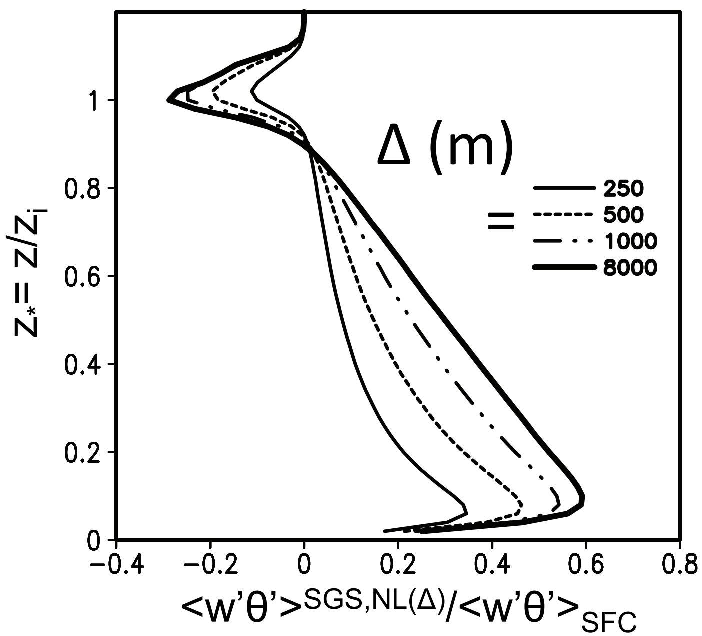
$D >> l$	$l \sim 1$ km	$\Delta_{LES} << l$
$D = 8$ km	$D > \Delta > \Delta_{LES}$	$\Delta_{LES} = 25$ m

3. **Through conditinal sampling, the SGS transport is decomposed into the nonlocal transport (via strong updrafts) and local transport (via remaining small turbulence eddies).**

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

Results – Notes for a GZ parameterization

SGS NL transport profile

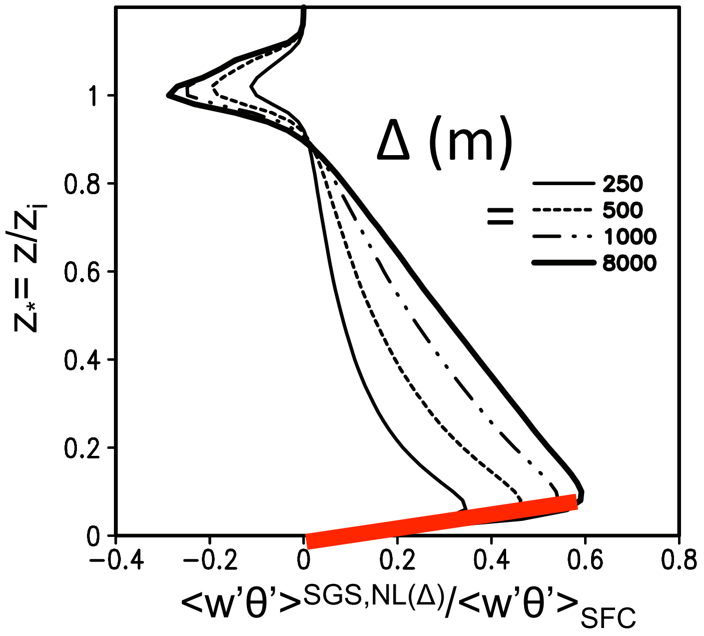


Resolution dependency of SGS NL transport

- ✓ The role of SGS NL transport: **SL cooling**, **ML heating**, **entrainment**.
- ✓ The physical role is **kept for different Δ**.

Results – Notes for a GZ parameterization

SGS NL transport profile



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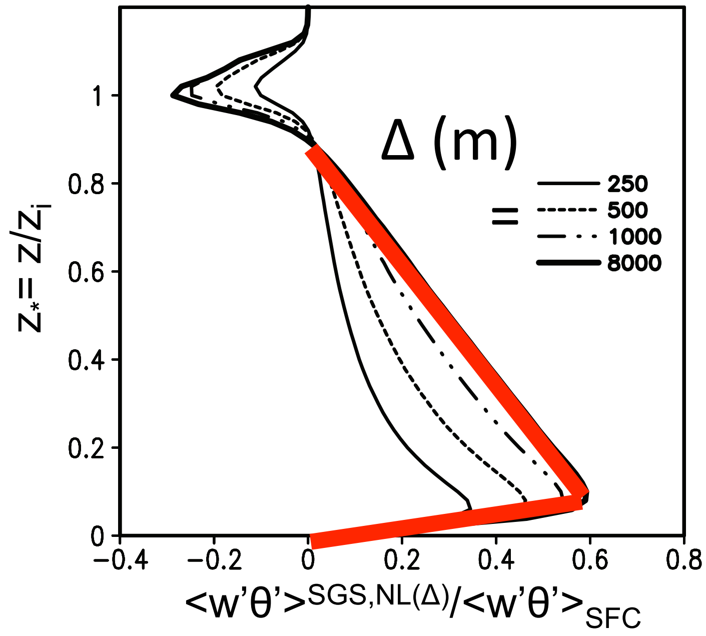

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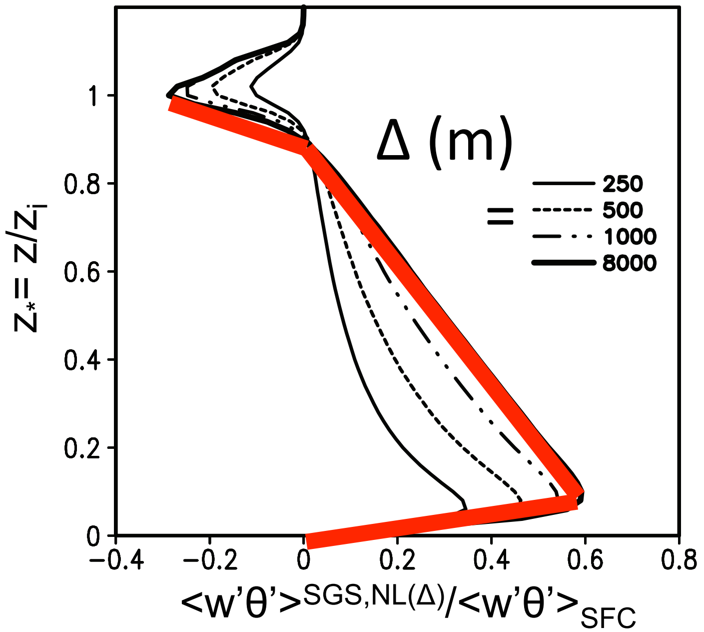

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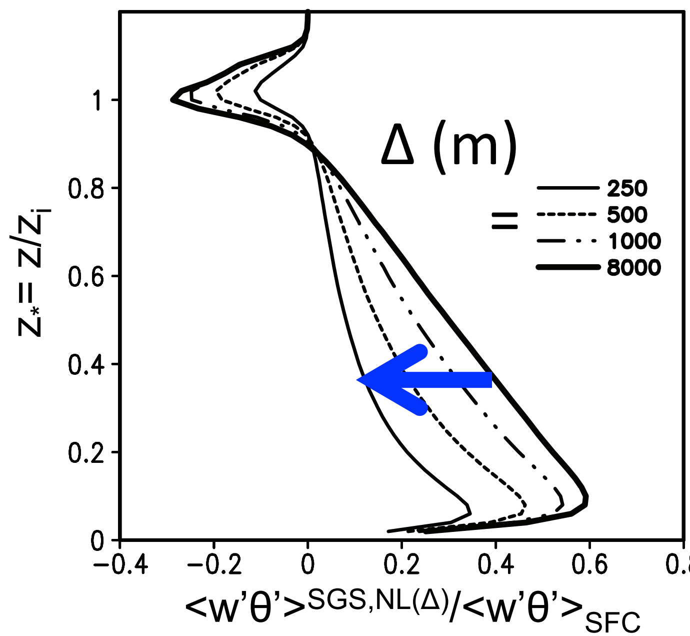
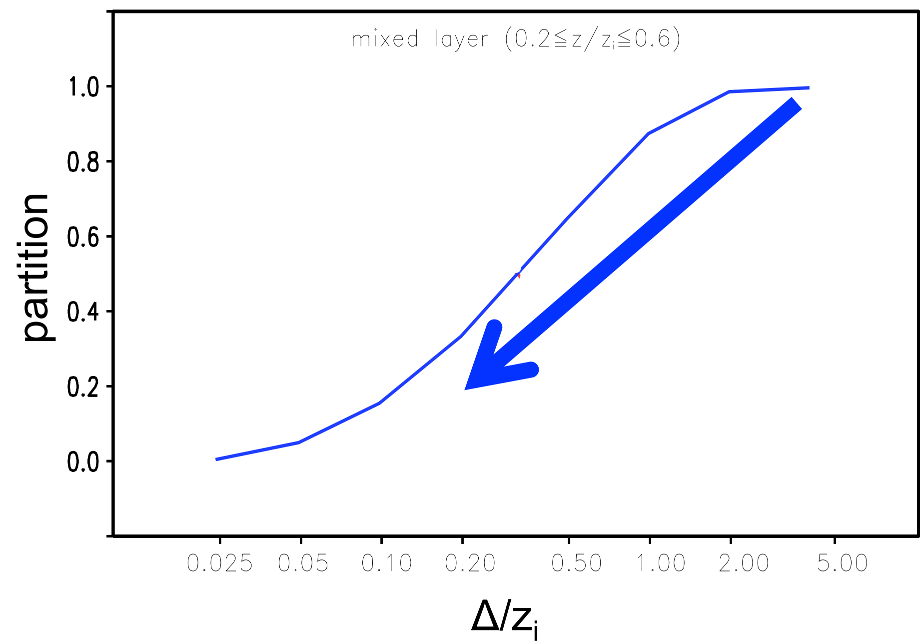


Resolution dependency of SGS NL transport



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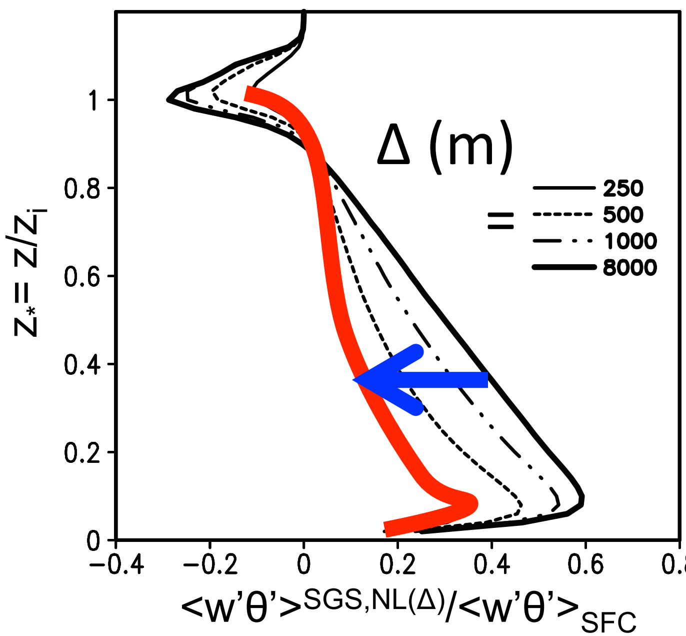
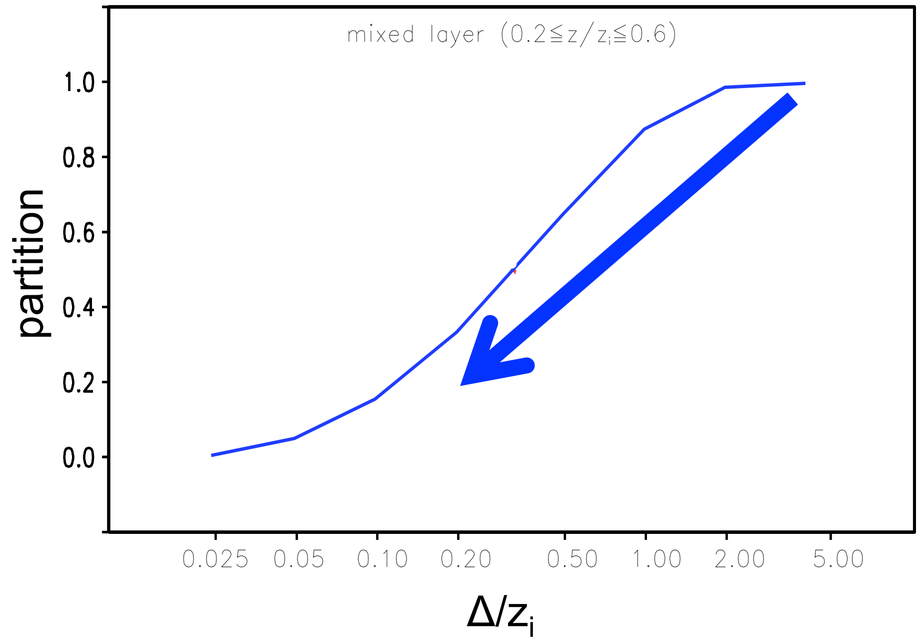
Results – Notes for a GZ parameterization

SGS NL transport profile



Resolution dependency of SGS NL transport

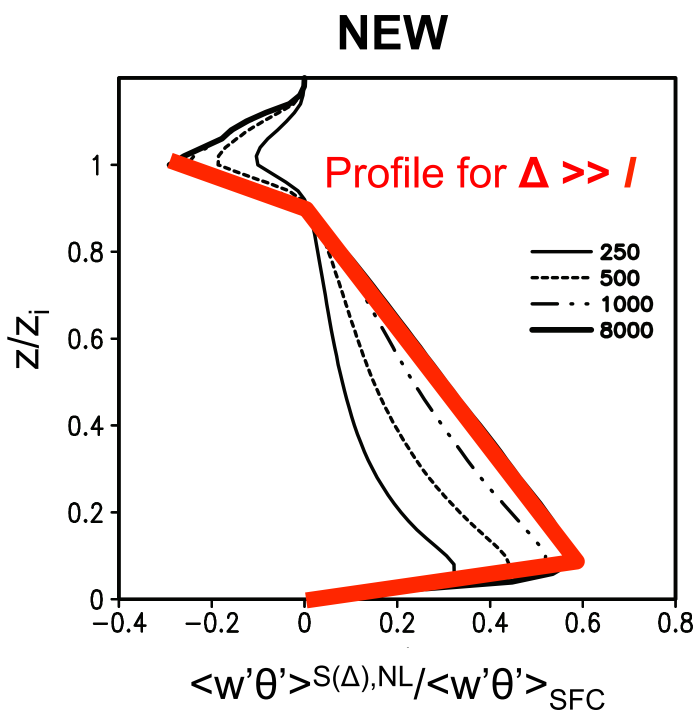


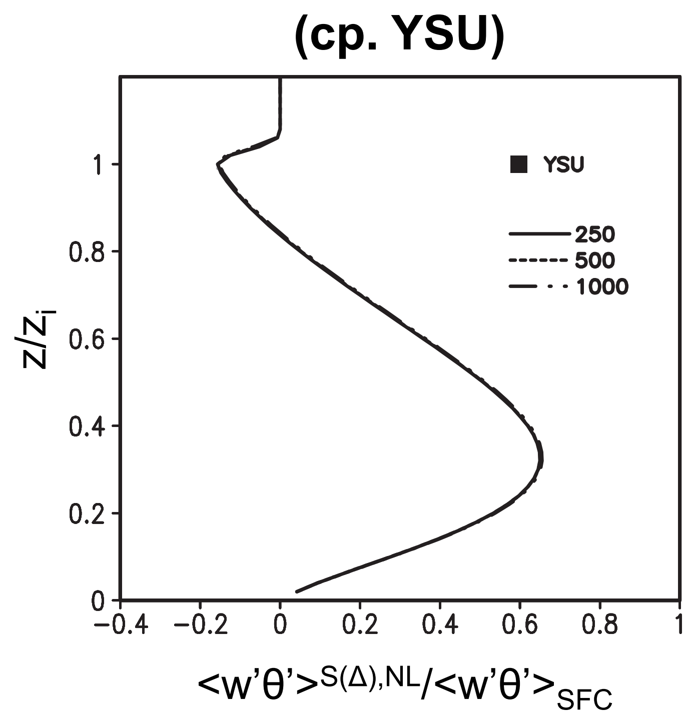
- ✓ The role of SGS NL transport: **SL cooling**, **ML heating**, **entrainment**.
- ✓ The physical role is **kept for different Δ**.

Representation of the SGS vertical transport in the CBL at the GZ resolutions

A simple, but physics-based algorithm

SGS NL transport





Linear Fitting

$$\langle w'\theta'\rangle^{S(\Delta_*),NL} = \boxed{\langle w'\theta'\rangle^{NL}}\, P_{NL}(\Delta_*),$$

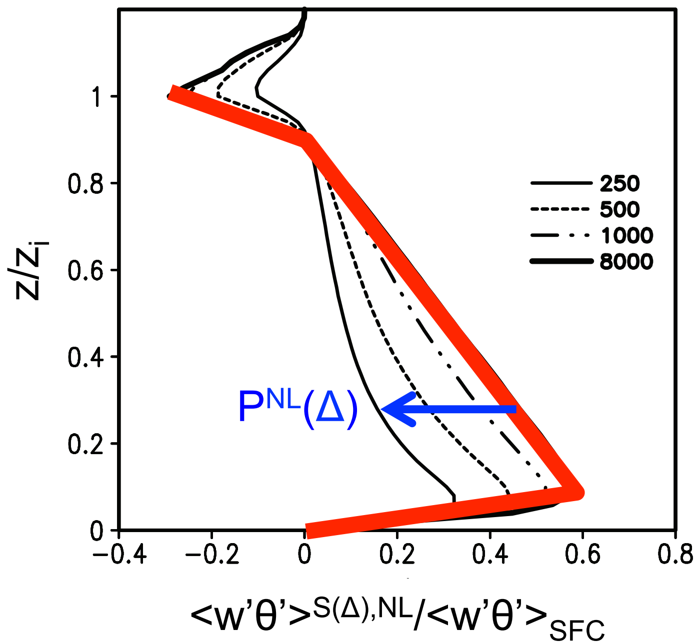
$$P_{NL}(\Delta_*) = 0.243\frac{(\Delta_*)^2 + 0.936(\Delta_*)^{7/8} - 1.110}{(\Delta_*)^2 + 0.312(\Delta_*)^{7/8} + 0.329} + 0.757.$$

$$\langle w'\theta'\rangle^{NL} = K_{H,PBL}\gamma_H + \overline{w'\theta'}^h\left(\frac{z}{h}\right)^3$$

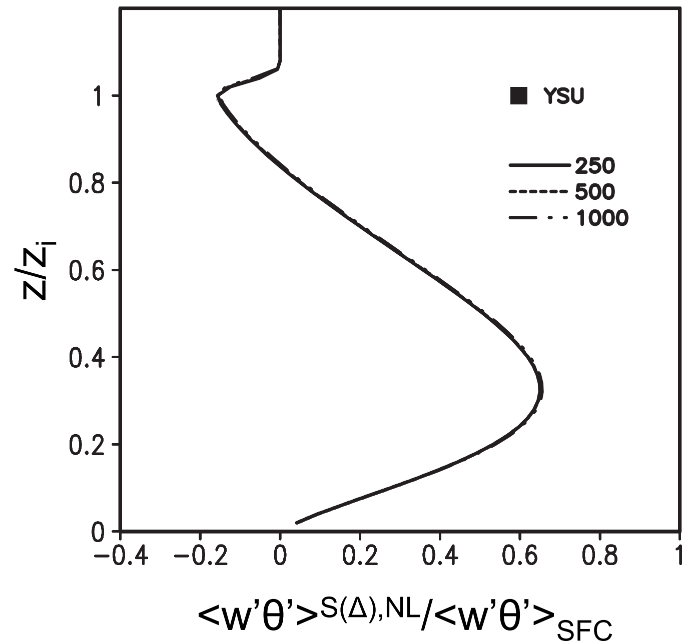
A simple, but physics-based algorithm

SGS NL transport

NEW



(cp. YSU)



$$\left\langle w'\theta' \right\rangle^{S(\Delta_*),NL} = \boxed{\left\langle w'\theta' \right\rangle^{NL}} P_{NL}\left(\Delta_*\right),$$

$$P_{NL}\left(\Delta_*\right) = 0.243 \frac{\left(\Delta_*\right)^2 + 0.936\left(\Delta_*\right)^{7/8} - 1.110}{\left(\Delta_*\right)^2 + 0.312\left(\Delta_*\right)^{7/8} + 0.329} + 0.757.$$

$$\left\langle w'\theta' \right\rangle^{NL} = K_{H,PBL}\gamma_H + \overline{w'\theta'}^h \left(\frac{z}{h}\right)^3$$

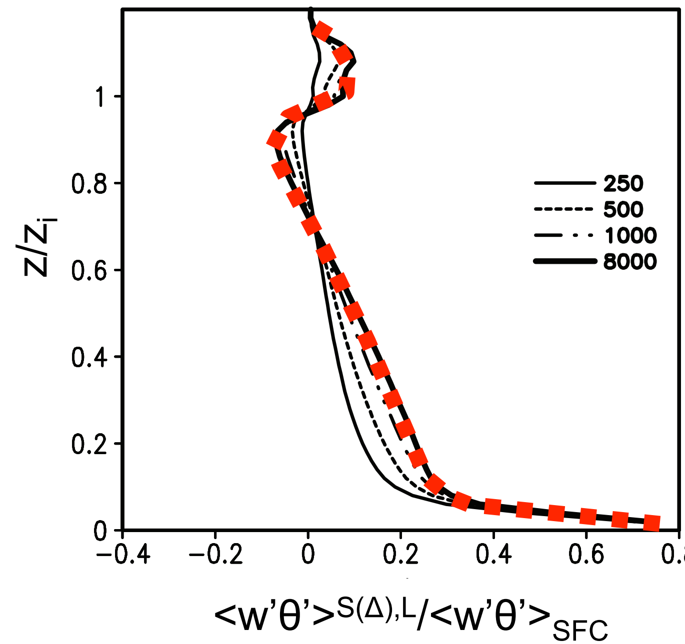
A simple, but physics-based algorithm

SGS NL transport

NEW

SGS L transport

NEW



$$\langle w'\theta'\rangle^{S(\Delta_*),NL} = \langle w'\theta'\rangle^{NL} P_{NL}(\Delta_*),$$

$$P_{NL}(\Delta_*) = 0.243\frac{(\Delta_*)^2 + 0.936(\Delta_*)^{7/8} - 1.110}{(\Delta_*)^2 + 0.312(\Delta_*)^{7/8} + 0.329} + 0.757.$$

$$\langle w'\theta'\rangle^{S(\Delta_*),L} = -K_H(\Delta_*)\frac{\partial\bar{\theta}^{\Delta}}{\partial z} = \boxed{-K_{H,PBL}} P_L(\Delta_*)\boxed{\frac{\partial\bar{\theta}^{\Delta}}{\partial z}},$$

$$P_L(\Delta_*) = 0.280\frac{(\Delta_*)^2 + 0.870(\Delta_*)^{1/2} - 0.913}{(\Delta_*)^2 + 0.153(\Delta_*)^{1/2} + 0.278} + 0.720.$$

A simple, but physics-based algorithm

SGS NL transport

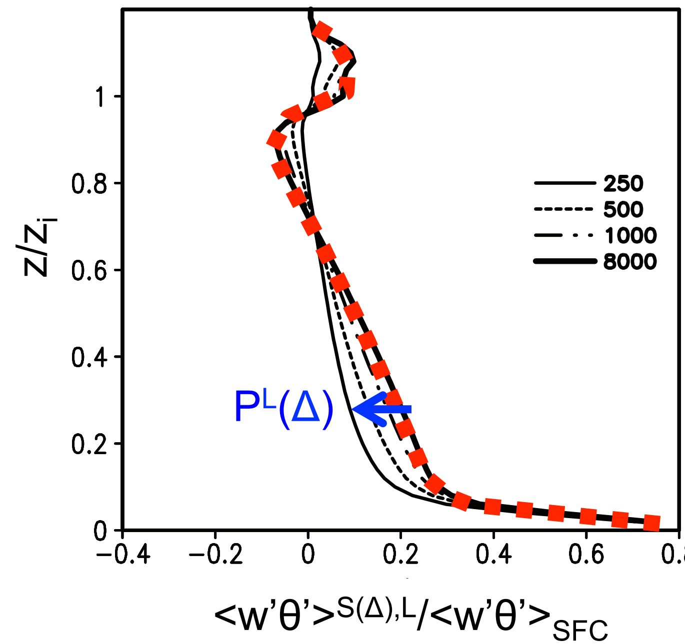
NEW

$$\langle w'\theta'\rangle^{S(\Delta_*),NL} = \langle w'\theta'\rangle^{NL} P_{NL}(\Delta_*),$$

$$P_{NL}(\Delta_*) = 0.243\frac{(\Delta_*)^2 + 0.936(\Delta_*)^{7/8} - 1.110}{(\Delta_*)^2 + 0.312(\Delta_*)^{7/8} + 0.329} + 0.757.$$

SGS L transport

NEW



$$\langle w'\theta'\rangle^{S(\Delta_*),L} = -K_H(\Delta_*)\frac{\partial\bar{\theta}^{\Delta}}{\partial z} = \boxed{-K_{H,PBL}} P_L(\Delta_*)\boxed{\frac{\partial\bar{\theta}^{\Delta}}{\partial z}},$$

$$P_L(\Delta_*) = 0.280\frac{(\Delta_*)^2 + 0.870(\Delta_*)^{1/2} - 0.913}{(\Delta_*)^2 + 0.153(\Delta_*)^{1/2} + 0.278} + 0.720.$$

Evaluations

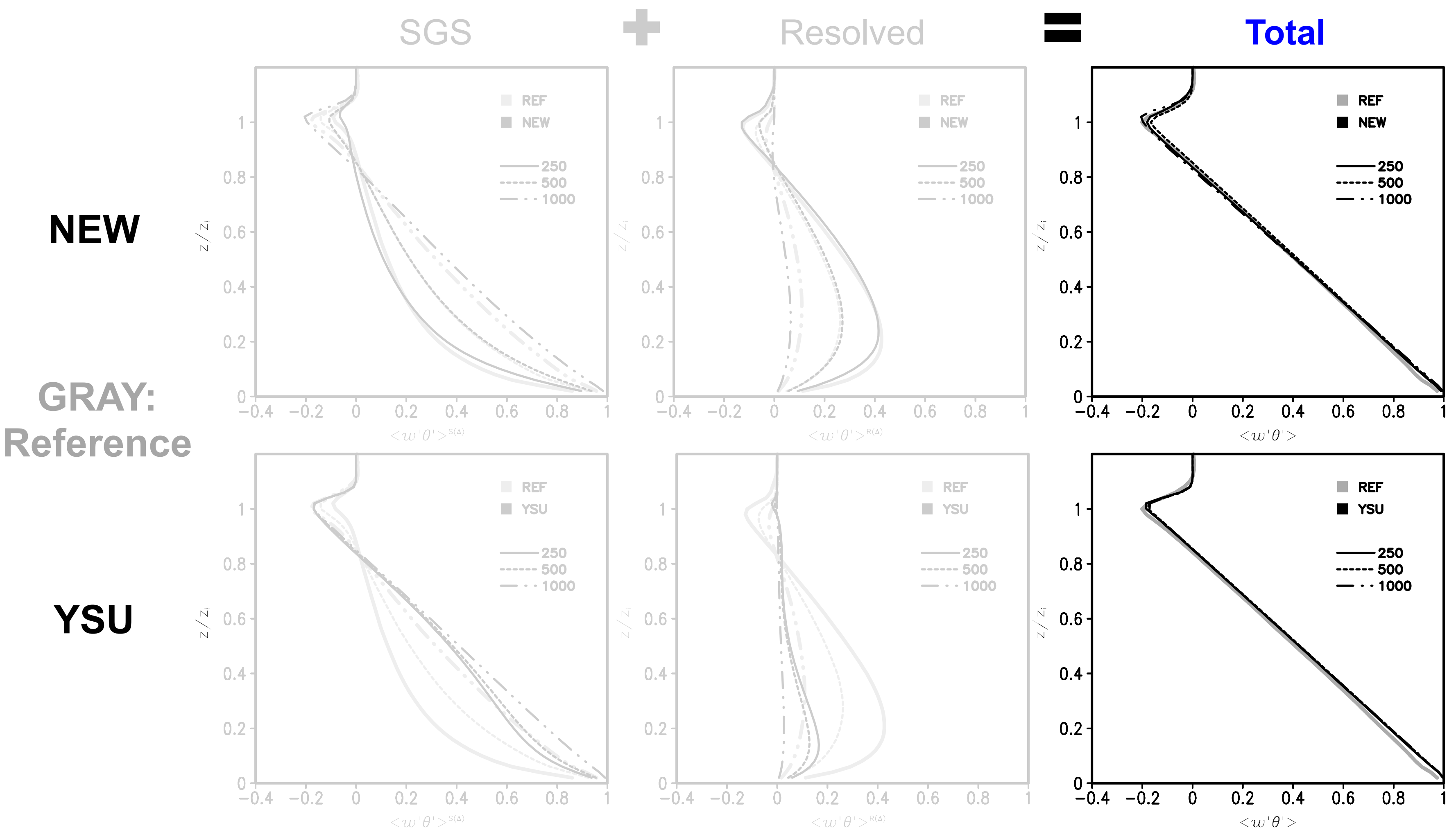
Idealized CBL case

$\overline{w'\theta'}_{SFC}$ (K m s^{-1})	U_g (m s^{-1})	w_* (m s^{-1})	u_* (m s^{-1})	z_i (m)	τ_* (s)	L_{MO} (m)
0.20	10	1.864	0.518	996.98	535	−53.65

Experimental setup

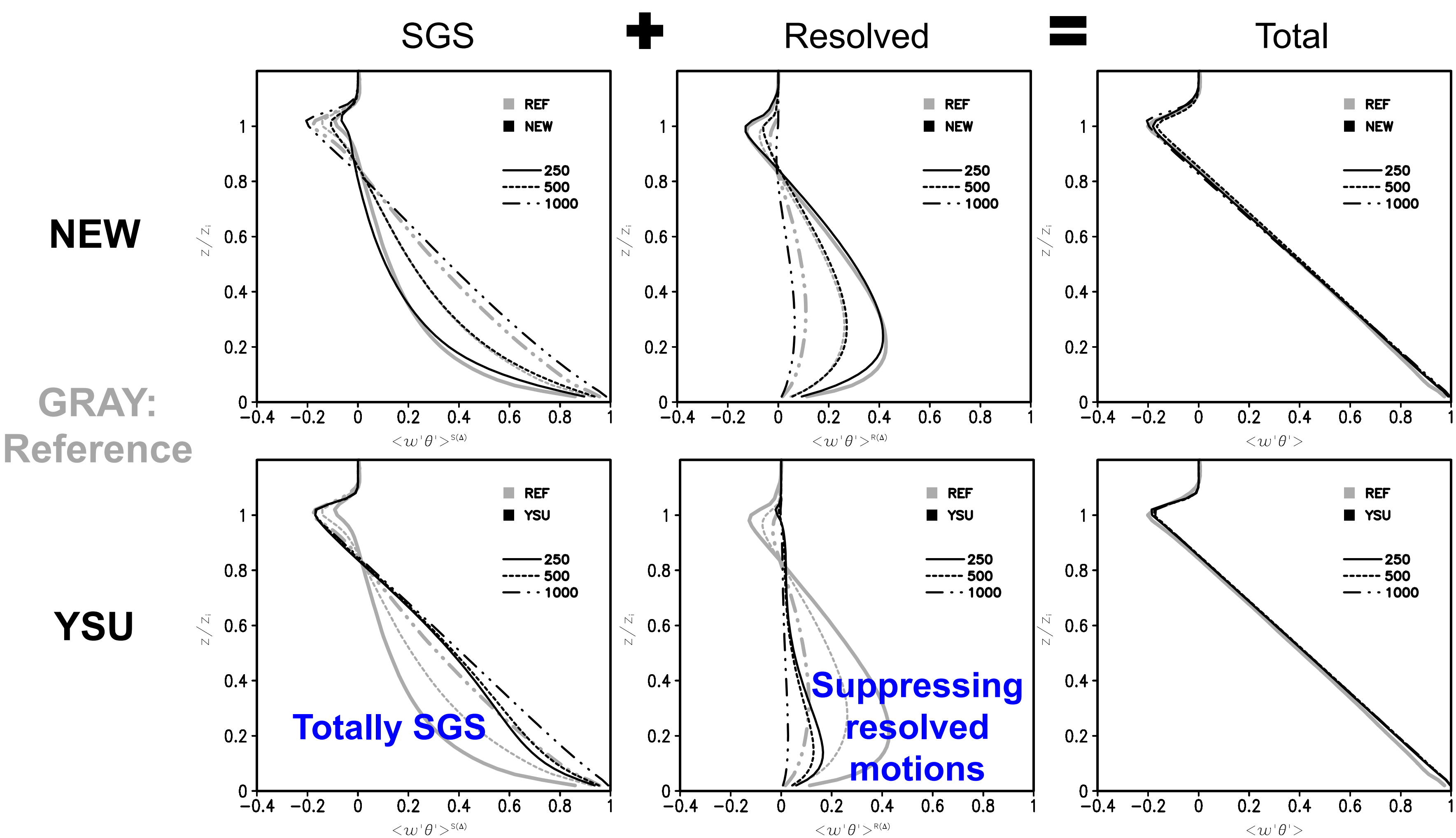
	Vertical SGS	Horizontal SGS	Grid size (m)	No. of grids	Domain size (km^2)
Benchmark LES	3D TKE	3D TKE	25	320^2	8^2
Reference (REF)	Filtered from the LES		250, 500, 1000	32^2,16^2, 8^2	8^2
NEW	NEW	3D TKE	250, 500, 1000	32^2	##8^2, 16^2, 32^2
YSU	YSU	3D TKE	250, 500, 1000	32^2	##8^2, 16^2, 32^2

Vertical heat transport profiles

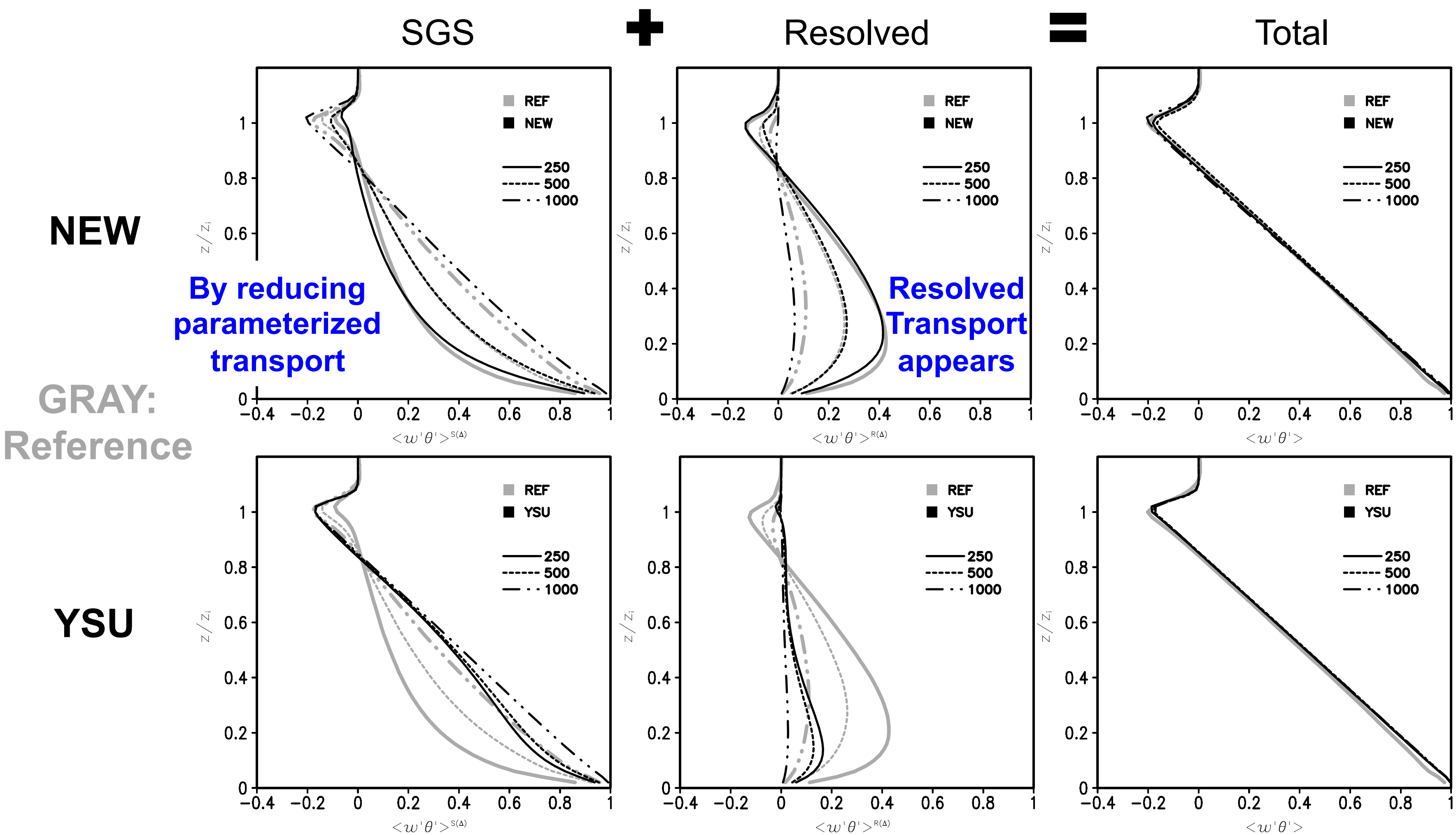


✓ The **NEW and YSU** well follow the reference transport, **in terms of the total transport**.

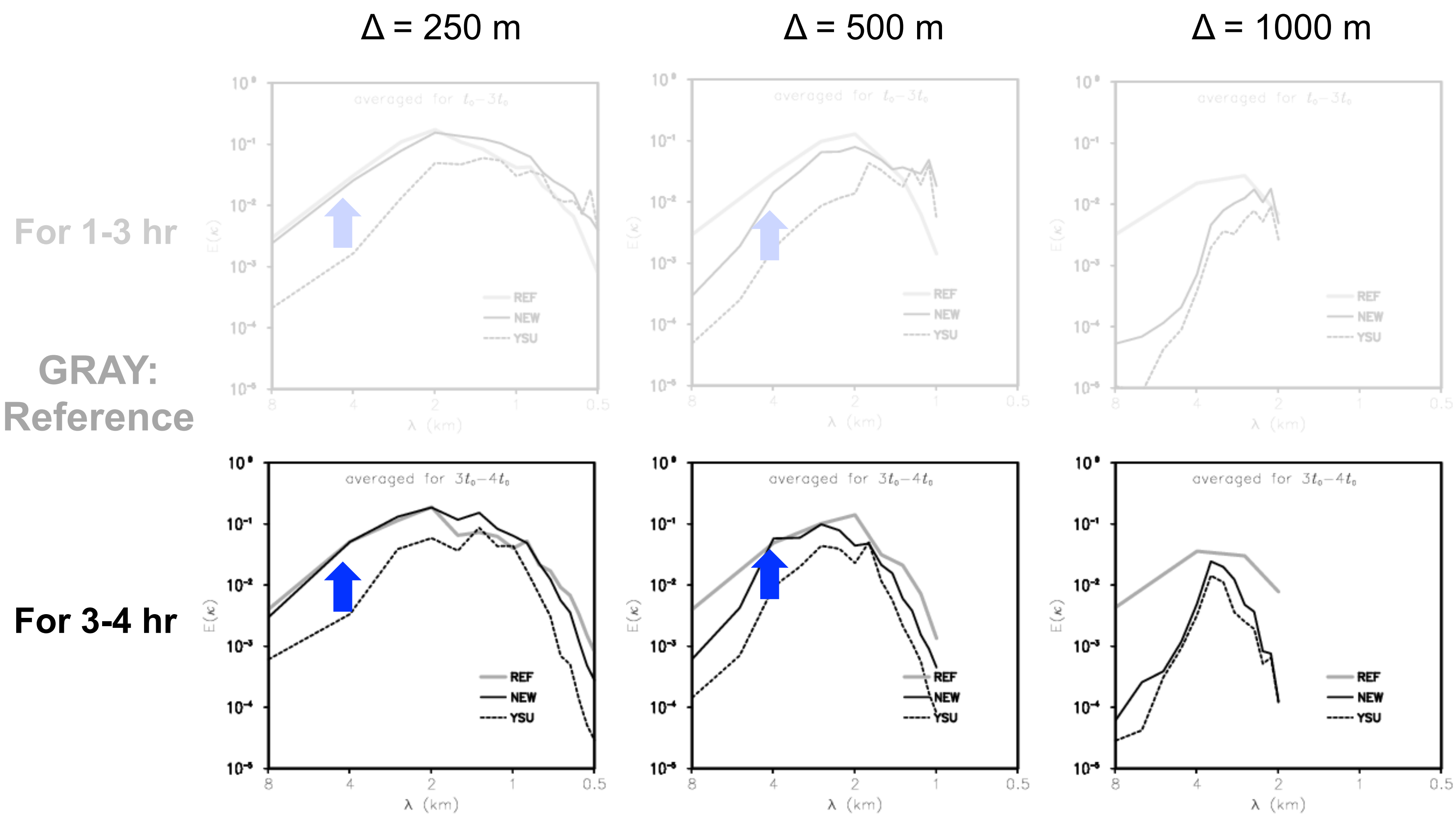
Vertical heat transport profiles



Vertical heat transport profiles



Energy spectrum for w



- ✓ **NOTE: The reference spectrum is filtered by a 6-th order numerical filter** for a better comparison with the NEW/YSU simulations (S.-H. Park, personal communication), since the simulations affected by a numerical diffusion due to the 5-th order advection scheme used (Skamarock 2004).

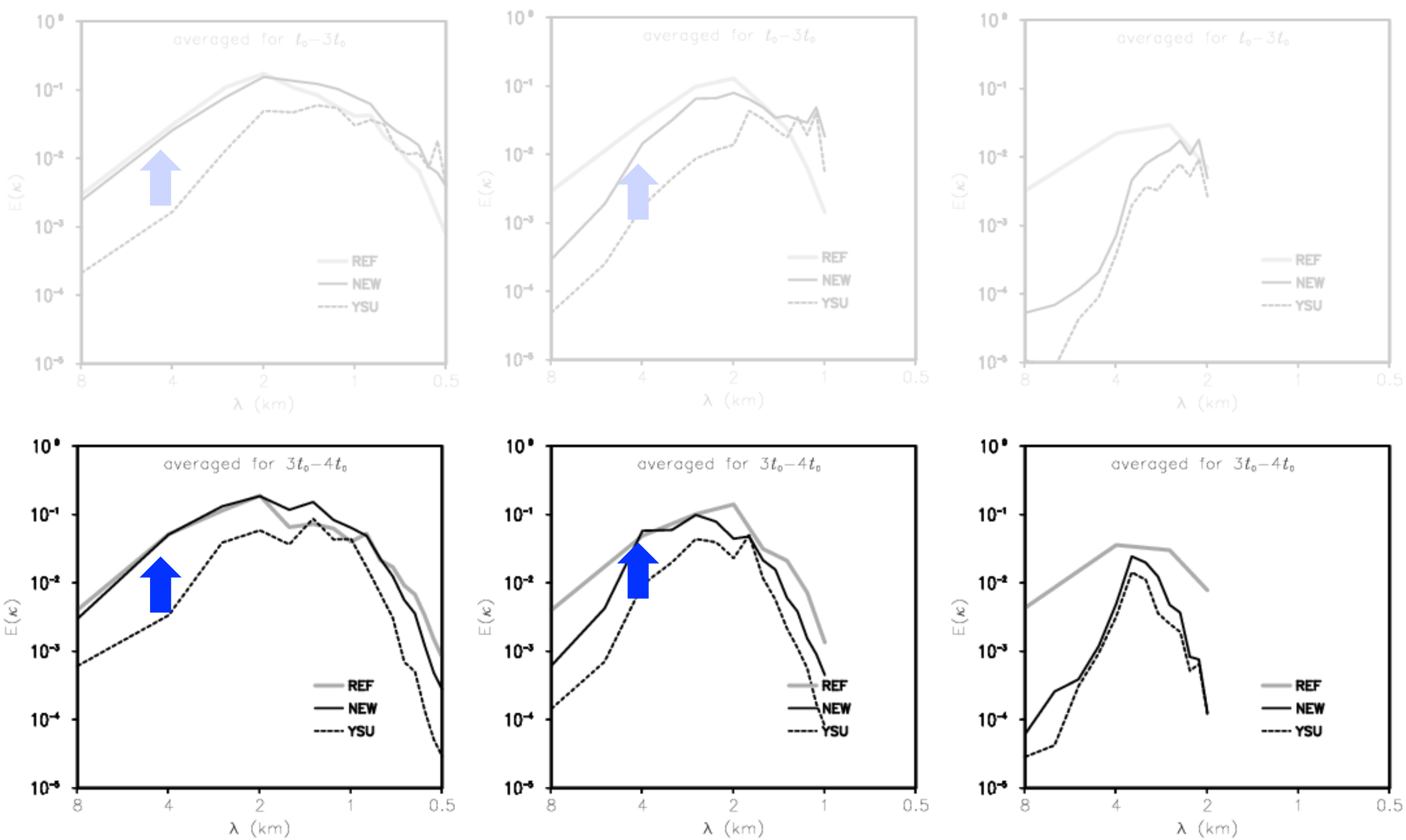
Energy spectrum for w

Δ = 250 m | Δ = 500 m | **Δ = 1000 m**

For 1-3 hr

GRAY: Reference

For 3-4 hr



No improvement, No degradation

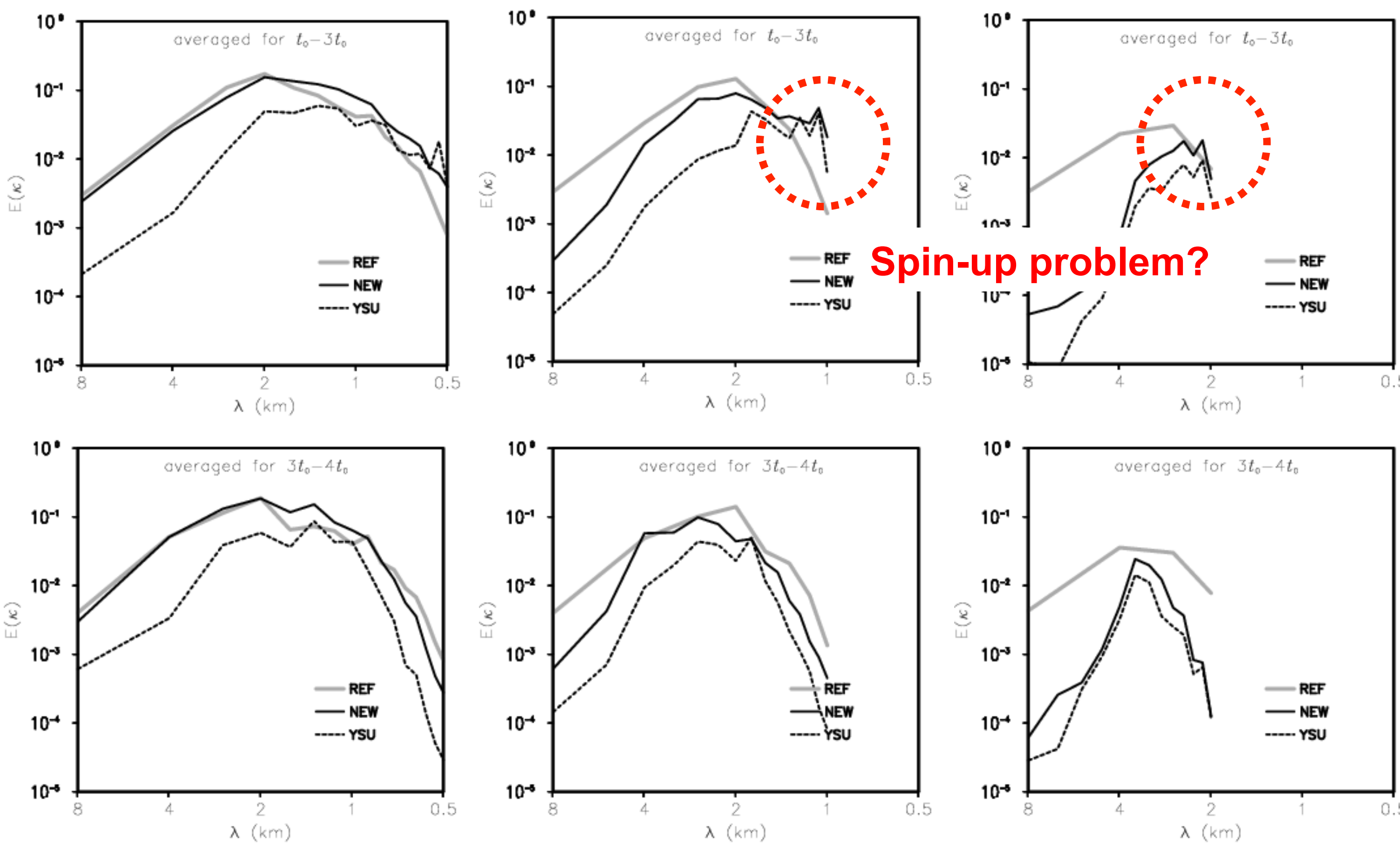
Energy spectrum for w

Δ = 250 m | Δ = 500 m | Δ = 1000 m

For 1-3 hr

GRAY: Reference

For 3-4 hr



✓ Ching et al. (2014): the growth rate ∝ grid size

Summary & Discussions

In a practical view:

"How to decrease the parameterized energy by handling the NL term?"

A parameterization fit to the reference is introduced and tested for an ideal CBL case.

- ✔ **Improvement in**
  mean profiles, resolved-scale/SGS partition, resolved energy.
- ✔ **However, the spin-up problem and insufficient energy as Δ is larger:**
  due to the "forced (prescribed)" profile, which is fixed for the forcing.
- ✔ **Moreover, Δ functions and numerical const. used in our fitting depend on height, variable, CBL stability (u_*/w_*)** (Honnert et al. 2011; Shin and Hong 2013)**.**

Thank you!
Questions and comments?

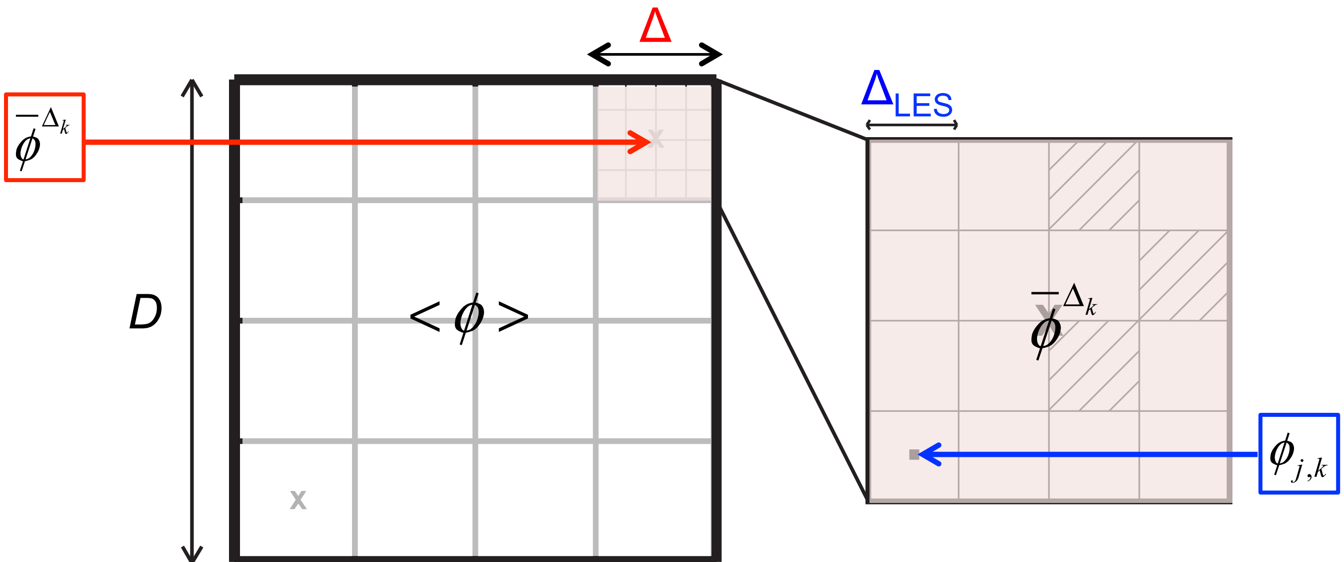
Already the end of 15 min? (I hope not!): hshin@ucar.edu

Methods

Dorrestijn et al. (2012)
Honnert et al. (2011)
Cheng et al. (2010)

(1) Construction of the 'true' data for 50–4000 m Δ

Turbulent vertical transport over the whole domain, **for Δ grids**



$$\phi_{j,k}'' = \phi_{j,k} - \overline{\phi}^{\Delta_k}$$

SGS for Δ_{LES}

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

Resolved for Δ **SGS for Δ**

Methods

(2) Benchmark large-eddy simulations for four CBLs

- Four cases

Case	$\overline{w'\theta'}_0$ (K m s^{-1})	U_g (m s^{-1})	u_*/w_*	$-z_i/L_{MO}$
BT	**0.20**	**0**	0.097	430.31
BF	**0.20**	**10**	0.278	18.58
SW	**0.05**	**10**	0.417	5.01
SS	**0.05**	**15**	0.538	2.21

- The WRFV3.2.1 model (non-hydrostatic version)

- SGS parameterization: Deardorff (1980) with correction factor for the deviation from an isotropic grid system [Scotti et al. (1993)]

- Domain and resolution: Over **8 km×8 km**×3.5 km domain [**Δ =(Δx=Δy)=25 m**, 12 m~Δz~35 m]

- Initial profiles:

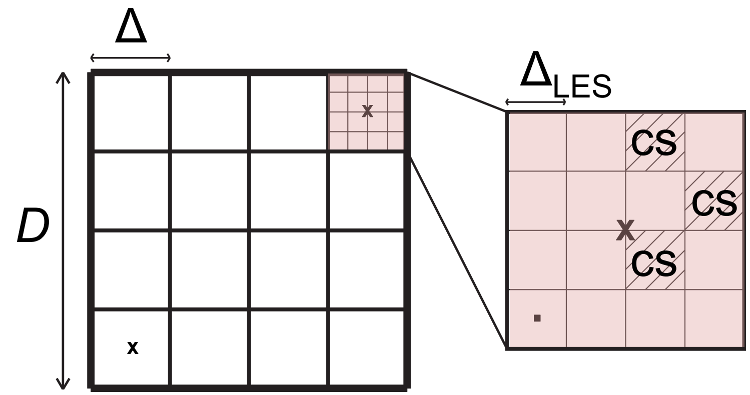
$$\theta = \begin{cases} 300\ \mathrm{K} & : 0 < z \le 925\ \mathrm{m} \\ 300\ \mathrm{K} + (z - 925\ \mathrm{m}) \times 0.0536\ \mathrm{K\ m^{-1}} & : 925 < z \le 1075\ \mathrm{m} \\ 308.05\ \mathrm{K} + (z - 1075\ \mathrm{m}) \times 0.003\ \mathrm{K\ m^{-1}} & : z > 1075\ \mathrm{m} \end{cases}$$

Comparison between non-local and local transport

Decomposition of vertical transport

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

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



For each Δ_k

Siebesma and Cuijpers (1995), Siebesma et al. (2007)

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

non-local vertical transport by strong updrafts of the organized structures

$$\overline{w''\phi''}^{\Delta_k,NL}$$

local vertical transport within the organized structures

local vertical transport within the environment

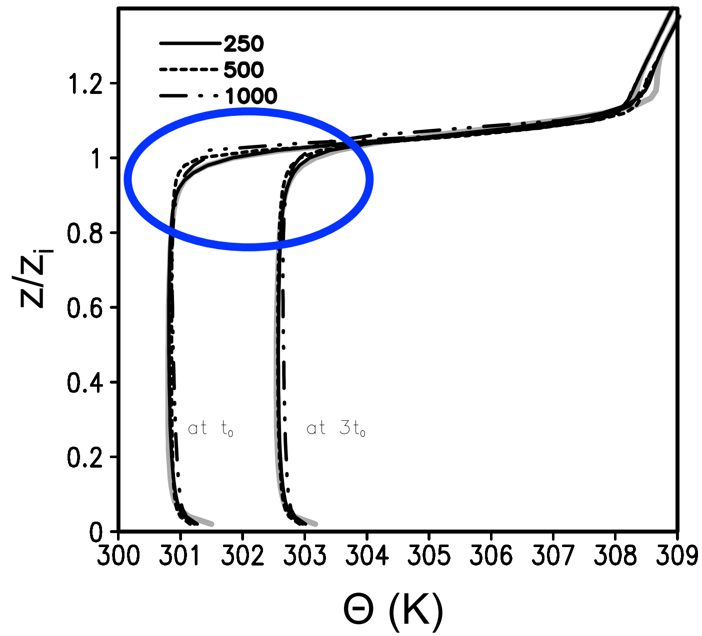
$$\overline{w''\phi''}^{\Delta_k,L}$$

$$\langle w'\phi' \rangle^{S(\Delta),NL} \equiv K^{-1}\sum_k \left(\overline{w''\phi''}^{\Delta_k,NL} \right)$$

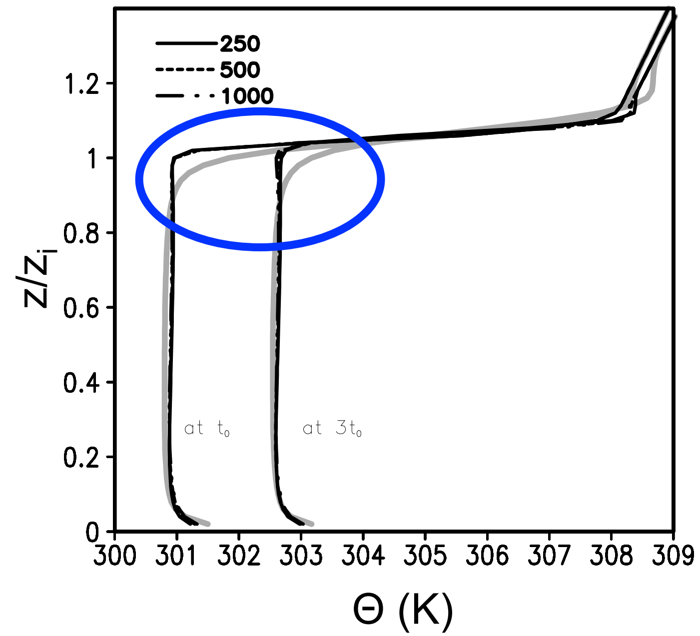
$$\langle w'\phi' \rangle^{S(\Delta),L} \equiv K^{-1}\sum_k \left(\overline{w''\phi''}^{\Delta_k,L} + \overline{f^{w\phi}}^{\Delta_k} \right)$$

Domain-averaged temperature profiles

NEW (GRAY: LES)



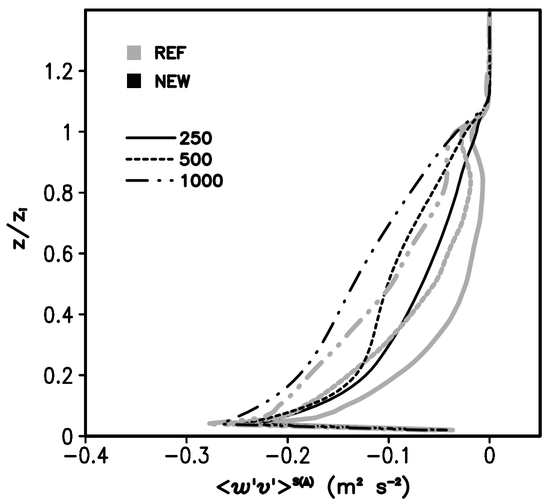
YSU (GRAY: LES)

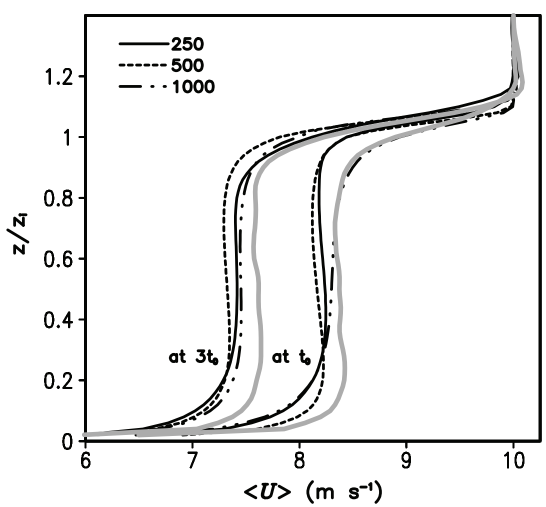


✓ Improvement in the entrainment zone:
mainly due to the new profile (linear), rather than the resolution-dependency function.

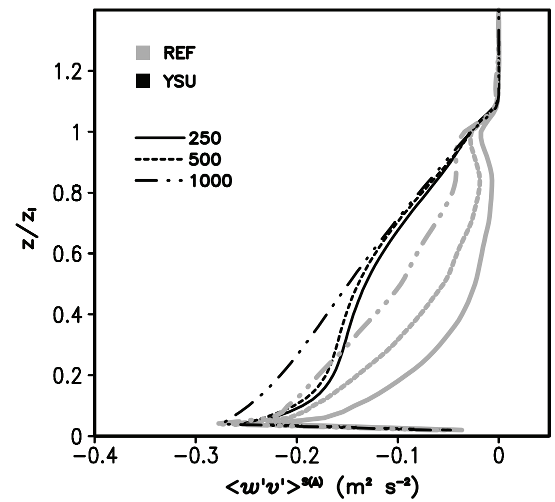
Momentum transport & Mean wind profiles

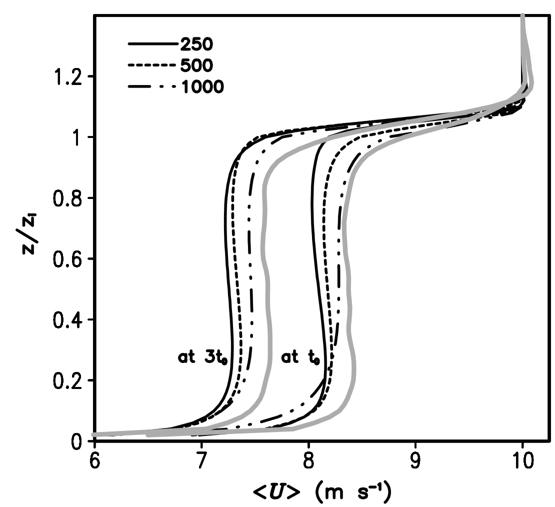
NEW





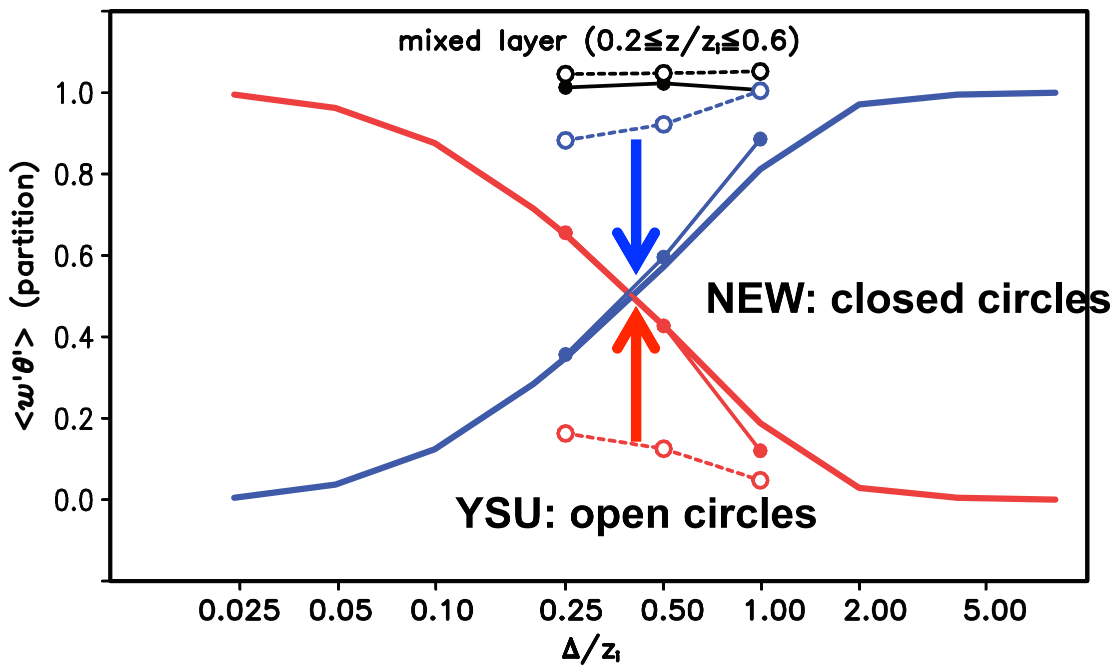
YSU





Resolution dependency

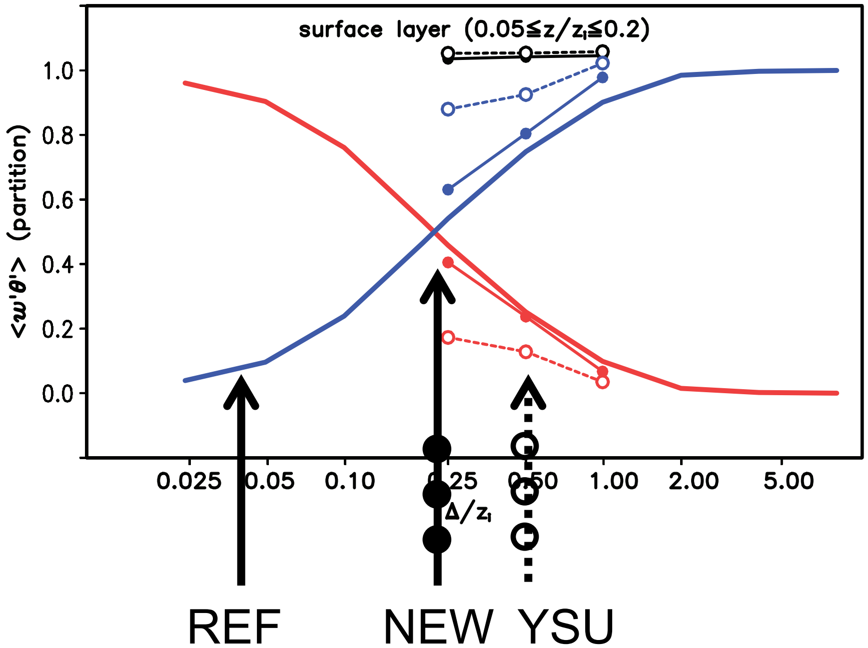
Resolved (red) + SGS (blue) = Total (black)

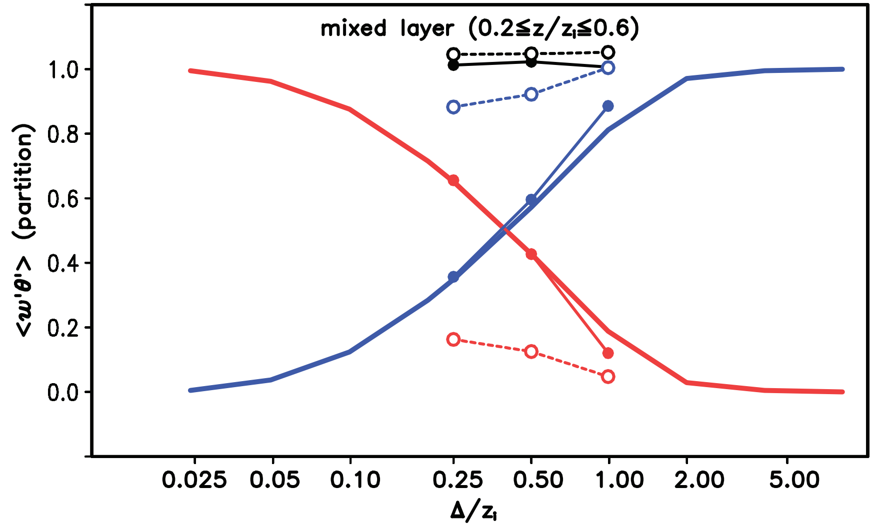


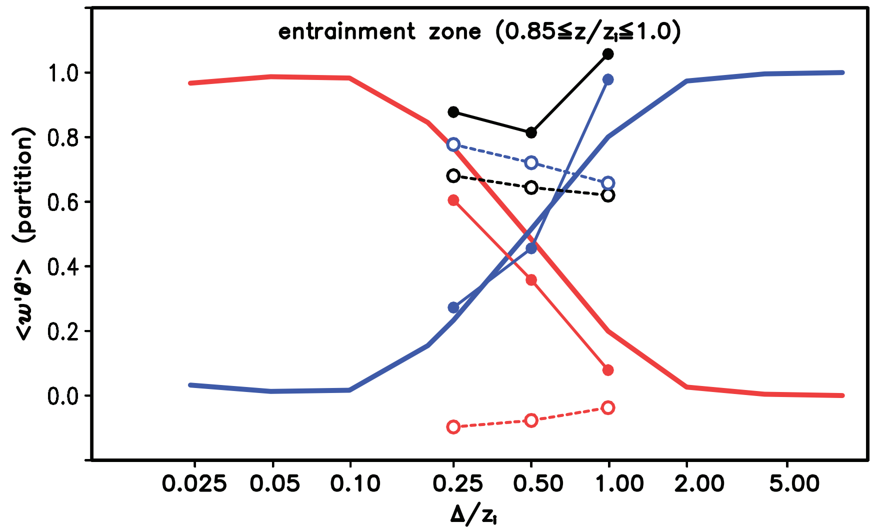
✓ Improvement in the partition between the **RS**/**SGS**.

Resolution dependency

Resolved (red) + SGS (blue) = Total (black)







Resolved w at $0.5z_i$

- Resolved fields – *w* at $0.5z_i$