Arakawa & I, and the Planetary Boundary Layer

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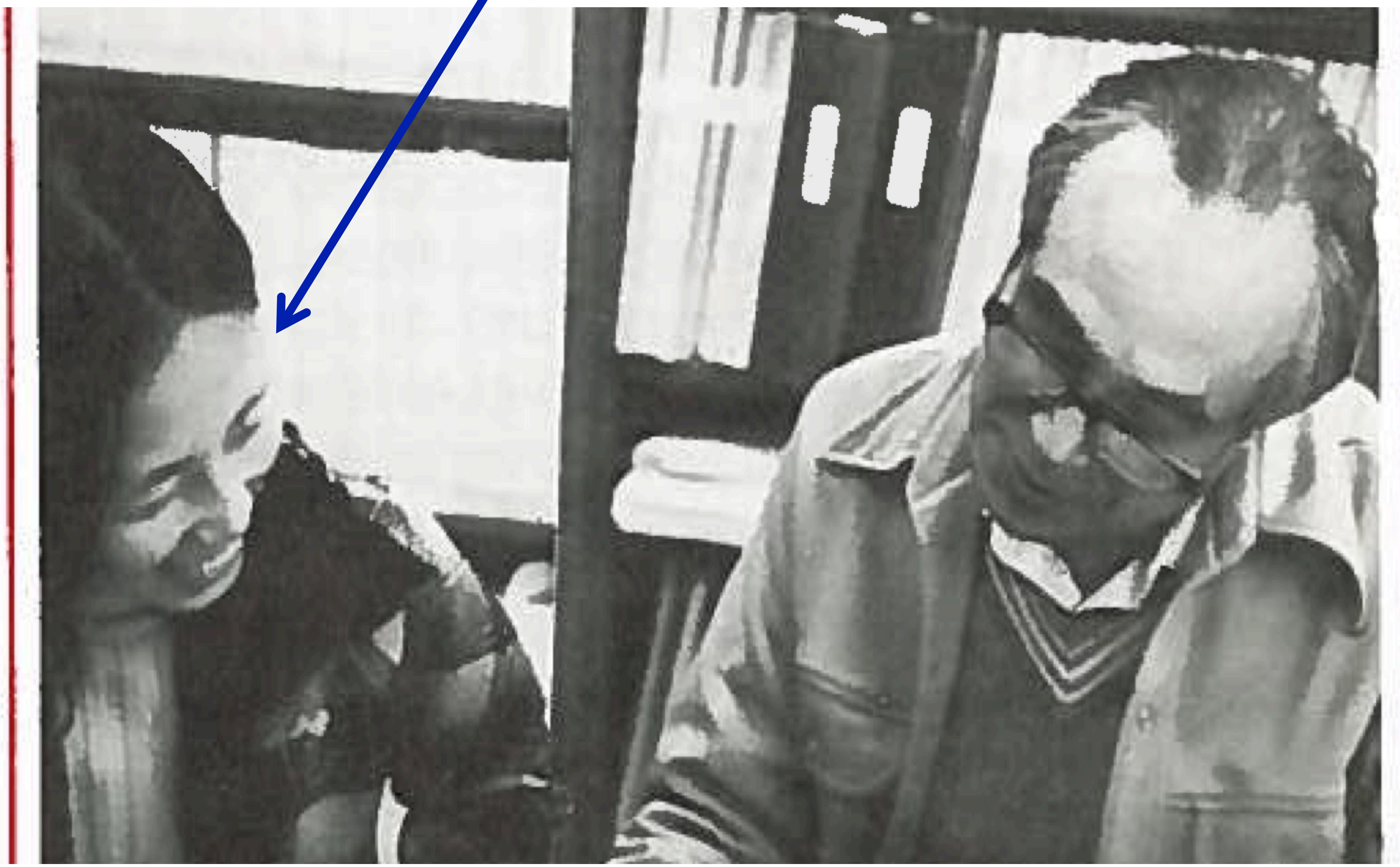
NCAR & CMMAP

(NCAR & CMMAP are sponsored by NSF)

Arakawa's Ph.D. student #10



Outline

- **The basic stuff I learned about the PBL from Arakawa's 151B class.**
- **My Ph.D. work on marine stratocumulus cloud** *(Moeng and Arakawa 1980, JAS)*.
- **My CMMAP work with Arakawa on the PBL under deep convection** *(Moeng and Arakawa 2012, MWR)*.

My favorite class --- 151B

Lim

METEOROLOGY 151 B

Atmospheric Motion II

(Spring 1975, Prof. A. Arakawa)

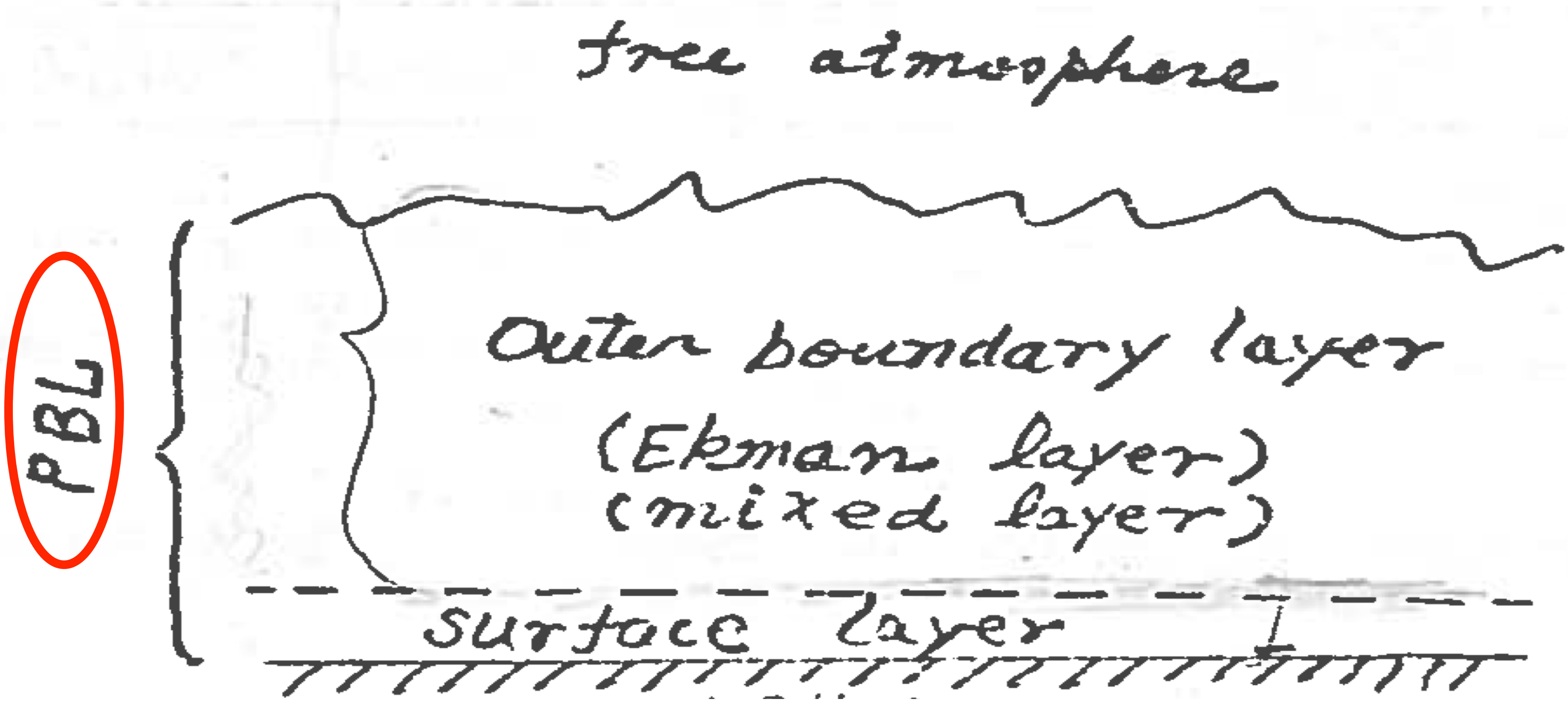
Objective

To study various types of motion in the real atmosphere, with emphasis on their generation, maintenance, and dissipation mechanisms, their mutual interactions, and their roles in weather and climate.

Contents

1. General Circulation of the Atmosphere.
2. Atmospheric Turbulence and Convection.
3. Tropical Circulation Systems.
4. Fronts and Meso-scale Weather Systems in Extratropical Latitudes.
5. Numerical Modeling and Simulation Experiments.

Introduction to the PBL:
a turbulent layer above the surface



How is PBL treated in weather & climate models?

$$\frac{\partial \overline{\mathbb{V}}}{\partial t} + (\overline{\mathbb{V}}\cdot\nabla)\overline{\mathbb{V}} = -2\Omega\times\overline{\mathbb{V}} - \nabla\left(\frac{\delta\bar{p}}{\rho_s}\right) + \frac{\delta\bar{\theta}}{\theta_s} gk + \frac{1}{\rho_s} Div\left(\bar{\mathcal{F}} - \rho_s \overline{\mathbb{V}'\mathbb{V}'}\right). \quad (14)$$

Eq. (14) is (a version of) the Reynolds* equation. 67

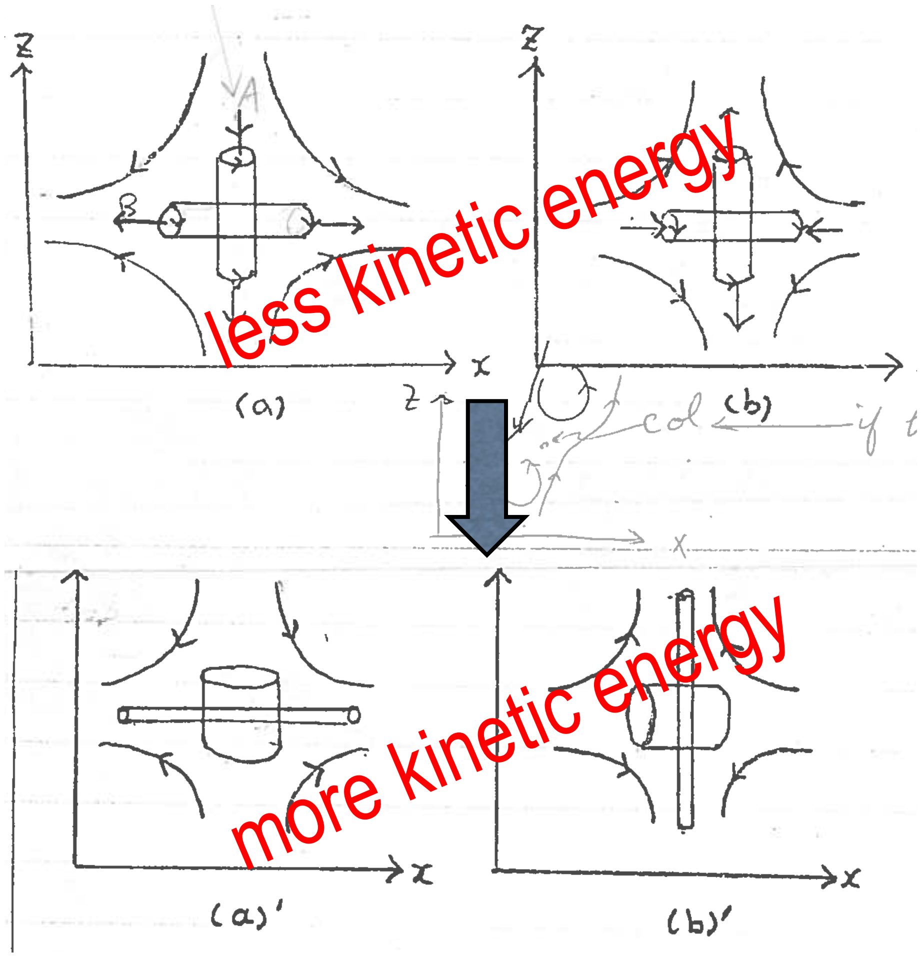
Comparison of (14) with (7) shows that a virtual stress tensor $\bar{\mathcal{F}} - \rho_s \overline{\mathbb{V}'\mathbb{V}'}$ is acting on the mean flow.

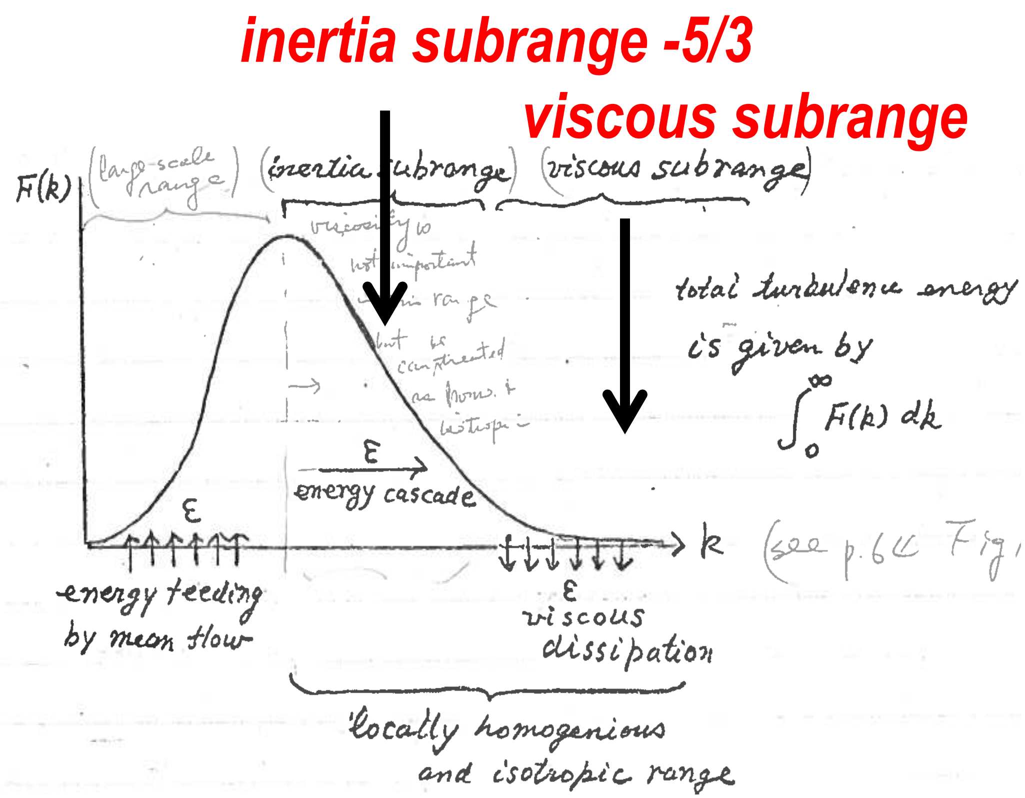
$$-\rho_s \overline{\mathbb{V}'\mathbb{V}'} = \begin{pmatrix} -\rho_s \overline{u'u'}, & -\rho_s \overline{v'u'}, & -\rho_s \overline{w'u'} \\ -\rho_s \overline{u'v'}, & -\rho_s \overline{v'v'}, & -\rho_s \overline{w'v'} \\ -\rho_s \overline{u'w'}, & -\rho_s \overline{v'w'}, & -\rho_s \overline{w'w'} \end{pmatrix} \quad (15)$$

is called the Reynolds stress or eddy stress. The

All turbulent motions are represented by this term!

The origin of turbulence--shear instability

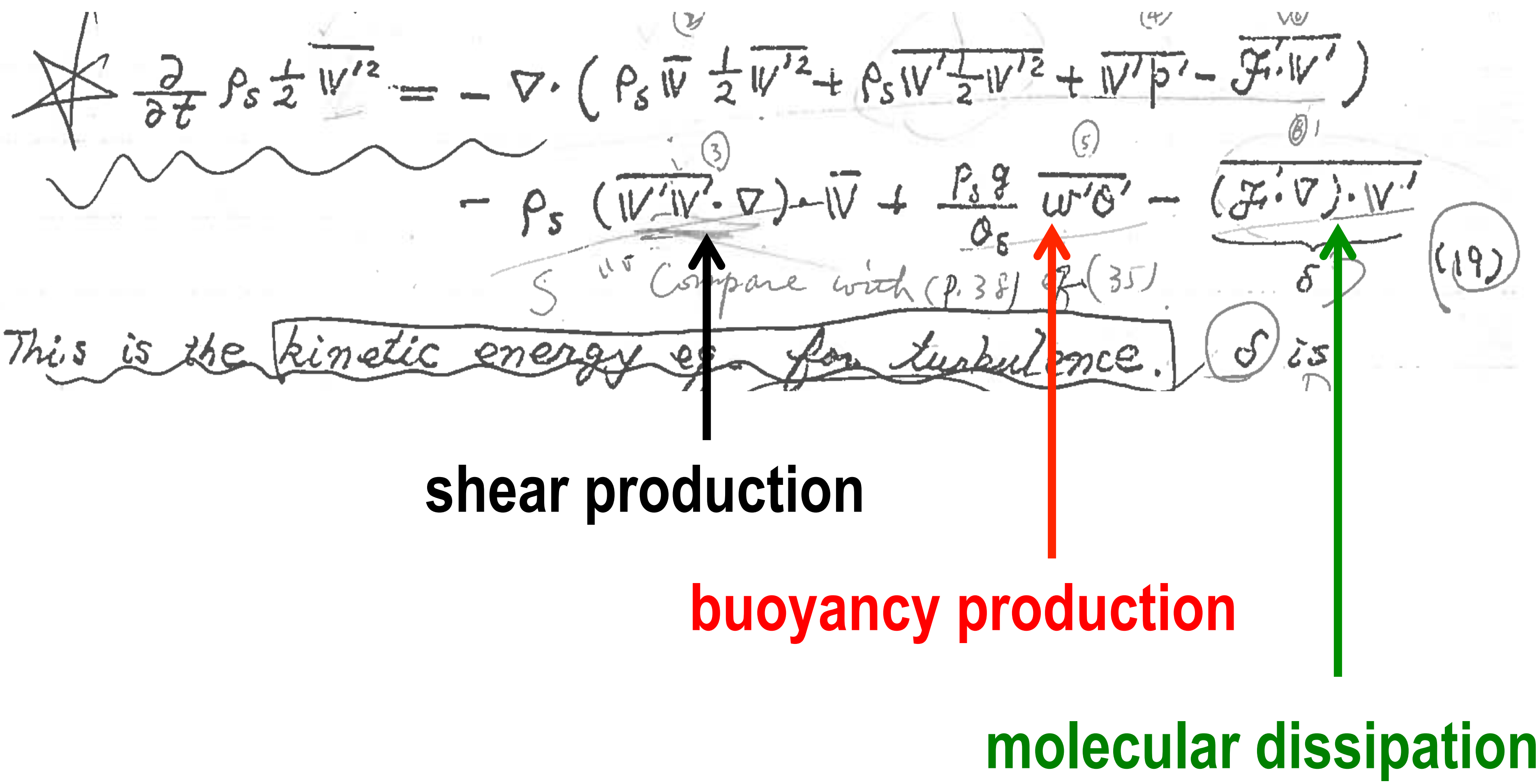




deformation ➡ vortex stretching ➡ turbulence

nonlinear scrambling ➡ energy cascade ➡ dissipation

Sources & sinks of turbulence kinetic energy



$$\frac{\partial}{\partial t}\rho_s \frac{1}{2}\overline{\mathbb{V}'^2} = -\nabla\cdot\left(\rho_s \overline{\mathbb{V}}\,\frac{1}{2}\overline{\mathbb{V}'^2} + \rho_s \overline{\mathbb{V}'\frac{1}{2}\mathbb{V}'^2} + \overline{\mathbb{V}'p'} - \overline{\mathcal{F}'\cdot\mathbb{V}'}\right) - \rho_s\left(\overline{\mathbb{V}'\mathbb{V}'}\cdot\nabla\right)\cdot\overline{\mathbb{V}} + \frac{\rho_s g}{\theta_s}\overline{w'\theta'} - \overline{(\mathcal{F}'\cdot\nabla)\cdot\mathbb{V}'} \qquad (19)$$

Compare with (p.38) eq.(35)

This is the kinetic energy eq. for turbulence. δ is

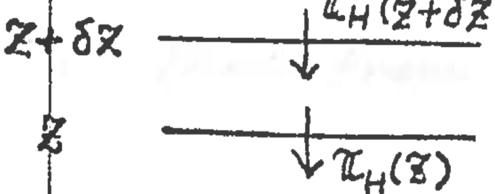
The surface layer
also known as the “constant flux layer”

A common misconception:

“Flux is constant in the constant flux layer”

$$\rho_s \mathbb{k}\times(\mathbb{V}_H - \mathbb{V}_g)\,\delta z = \tau_H(z+\delta z) - \tau_H(z) \qquad (6)$$

$$\rightarrow 0 \quad \text{as } \delta z \rightarrow 0.$$



$$\tau_H(z+\delta z) \doteqdot \tau_H(z) + \frac{\partial \tau_H}{\partial z}\delta z$$

This means that the stress can be considered as approximately constant within the thin layer.

Note that the approximate constancy is due to small δz but not due to small $\partial\tau_H/\partial z$.

Similarity analysis & Monin-Obukhov theory for the surface layer

We obtain only one combination of u_*, z, and $\frac{g}{\theta_s}\overline{w'\theta'}$ which is non-dimensional. That is

buoyancy flux

$\left(\frac{g}{\theta_s}\overline{w'\theta'}\right)/\left(\frac{u_*^3}{z}\right)$. If we define L by

$$L \equiv -\frac{u_*^3}{k\frac{g}{\theta_s}\overline{w'\theta'}}. \quad (12)$$

Then z/L is non-dimensional. Then, instead of (10)', we have

$$\frac{kz}{u_*}\frac{\partial u}{\partial z} = \phi_m\left(\frac{z}{L}\right), \quad (13)$$

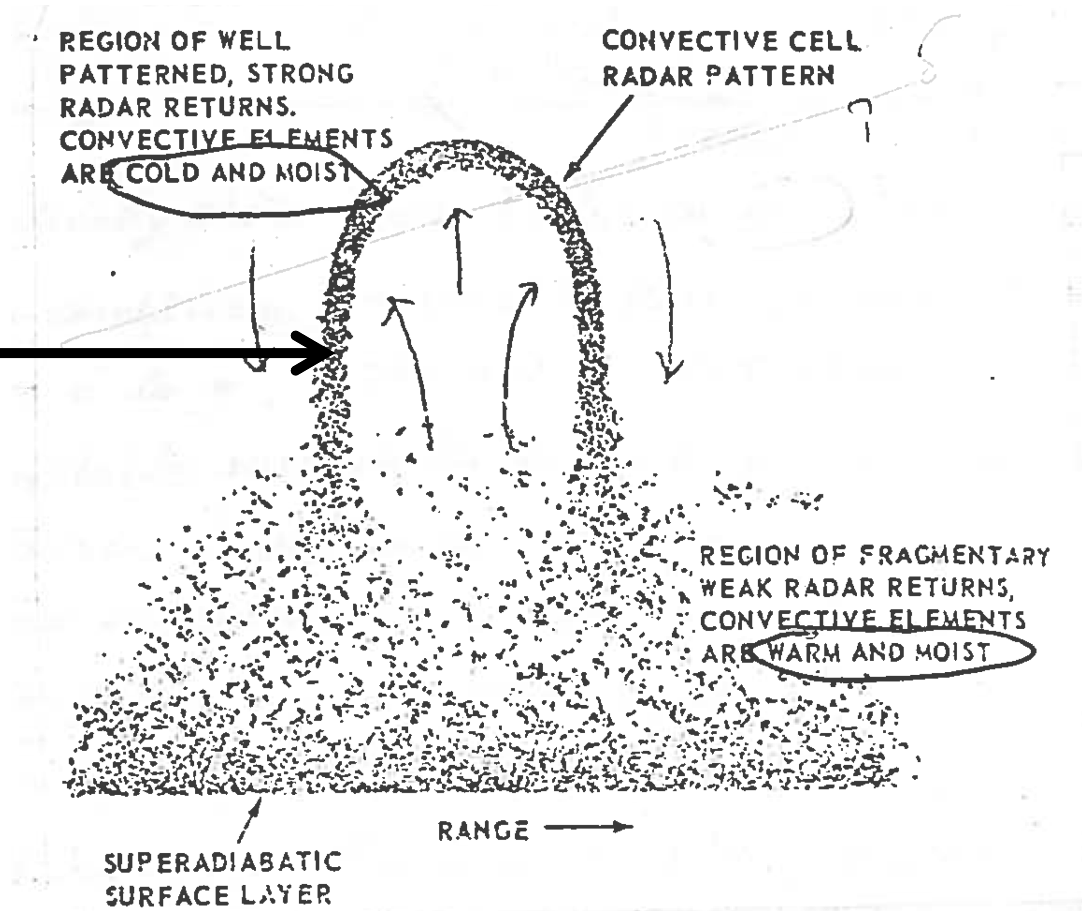
= non-dimensional

for wind shear in sfc layer

where ϕ_m is a universal function. L is called Monin-Obukhov* (stability) length. When $\overline{w'\theta'} < 0$

First time I saw a "large eddy".

a thermal
(large eddy)



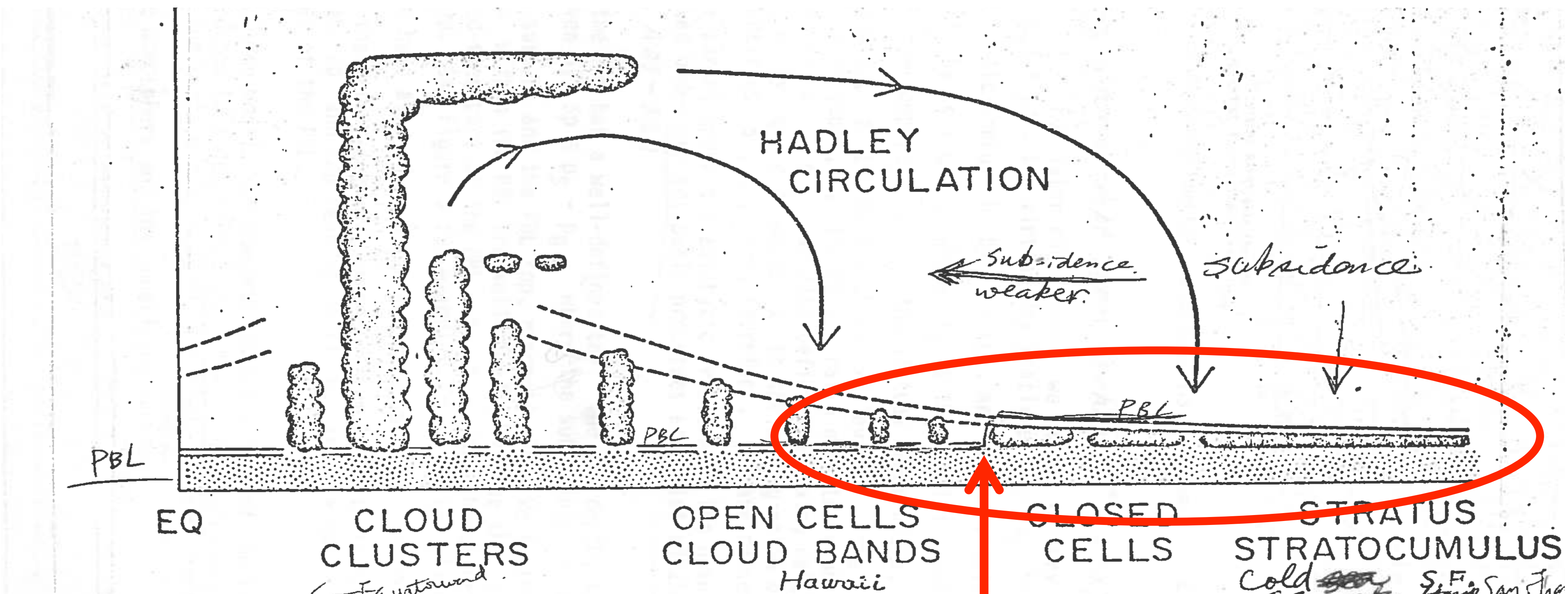
"Large eddies" contain most of the energy & are responsible for most of the transport---

basis for LES.

Two important roles of the PBL

1. **Carry heat, moisture, pollutants…**
   from the Earth's surface to the atmosphere.

2. **Regulate the Earth radiation budget via**
   low clouds in the PBL.



What causes the transition from ~100% cloudiness to < 10%?

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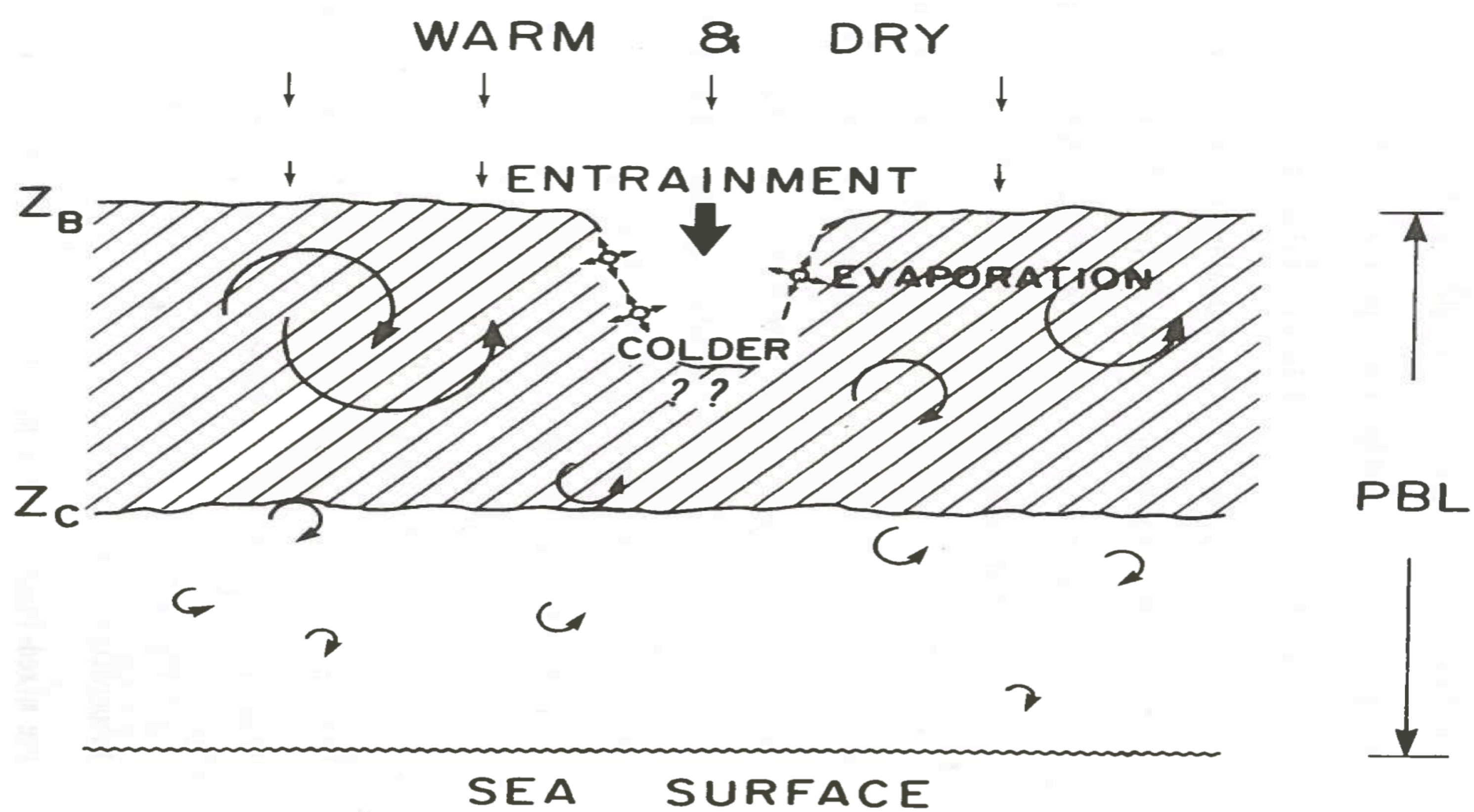
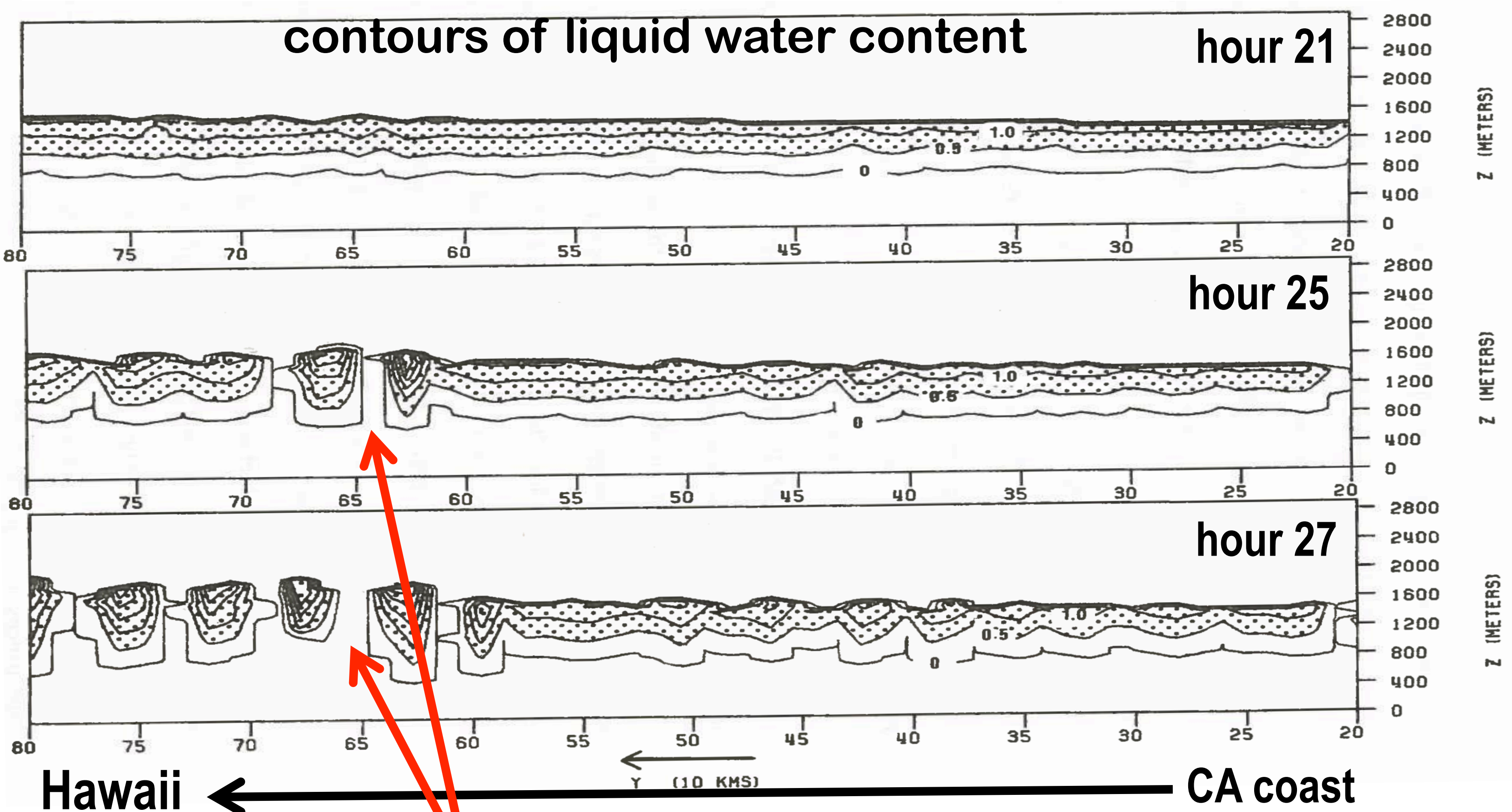
Cloud-Top Entrainment Instability (CTEI)

Randall (1980) & Deardorff (1980) proposed CTEI as a mechanism that breaks up the solid stratus cloud deck into scattered cumuli.



Built a 2D cloud model
(using a higher-order closure turbulence scheme)
to show CTEI at work.



Under the CTEI condition, cloud deck breaks up…

(Moeng and Arakawa 1980)

But nature is a lot more complicated…

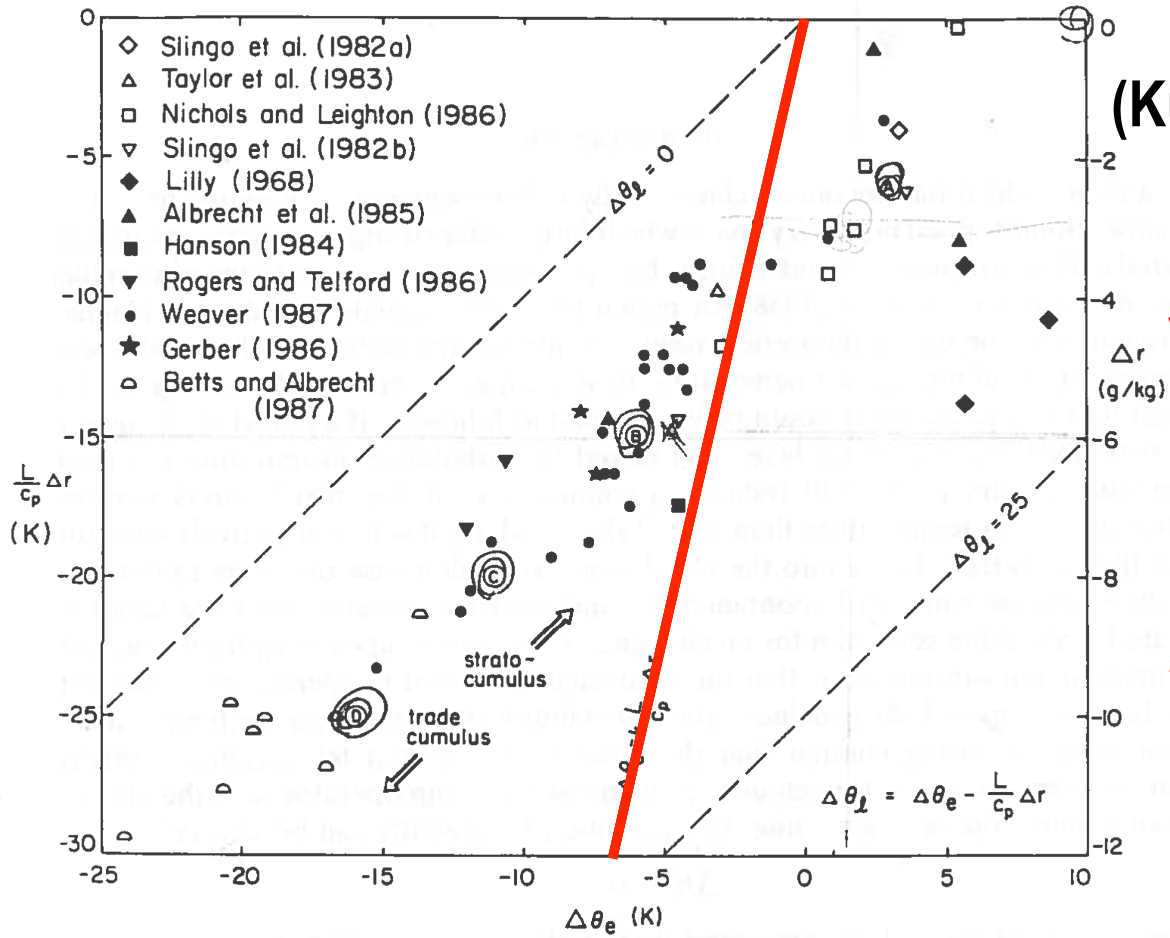


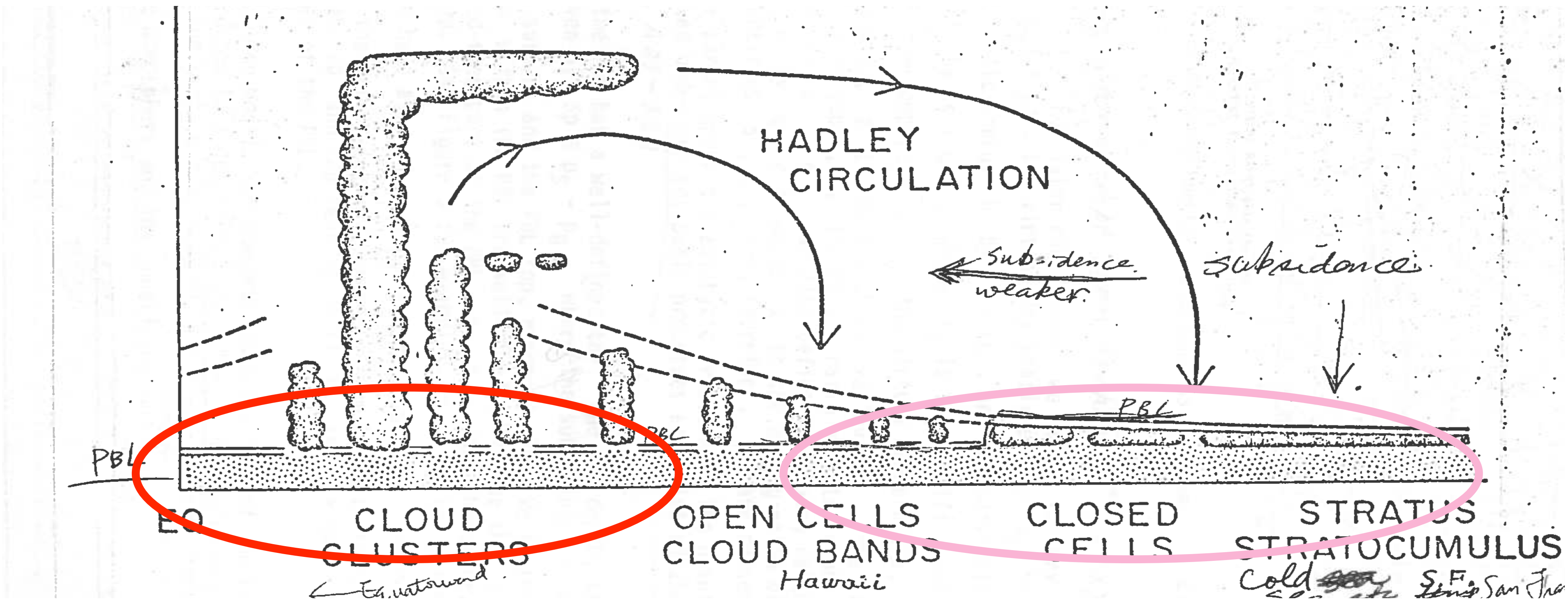
Figure 1. The $(\Delta\theta_e, \Delta r)$ plane, with the critical thermodynamic instability curve $(\Delta\theta_e = k(L/c_p)\Delta r)$. Observational data are indicated by the coded symbols, with open symbols for mid-latitude cases, solid symbols for subtropical cases and 'cumulus symbols' for trade cumulus cases. Two thirds of the stratocumulus observations lie to the left of the critical curve and hence are at odds with the predictions of the thermodynamic theory of cloud top entrainment instability.

(Kuo and Schubert 1988)

"Two thirds of the stratocumulus observations lie to the left of the critical curve and hence are at odds with…" CTEI.

CTEI "remains as a theory until it is proven wrong." says D. Randall.

At CMMAP, I shifted my research focus to tropical deep convection & cloud-resolving modeling (CRM)



How does the PBL feed moisture into deep clouds?

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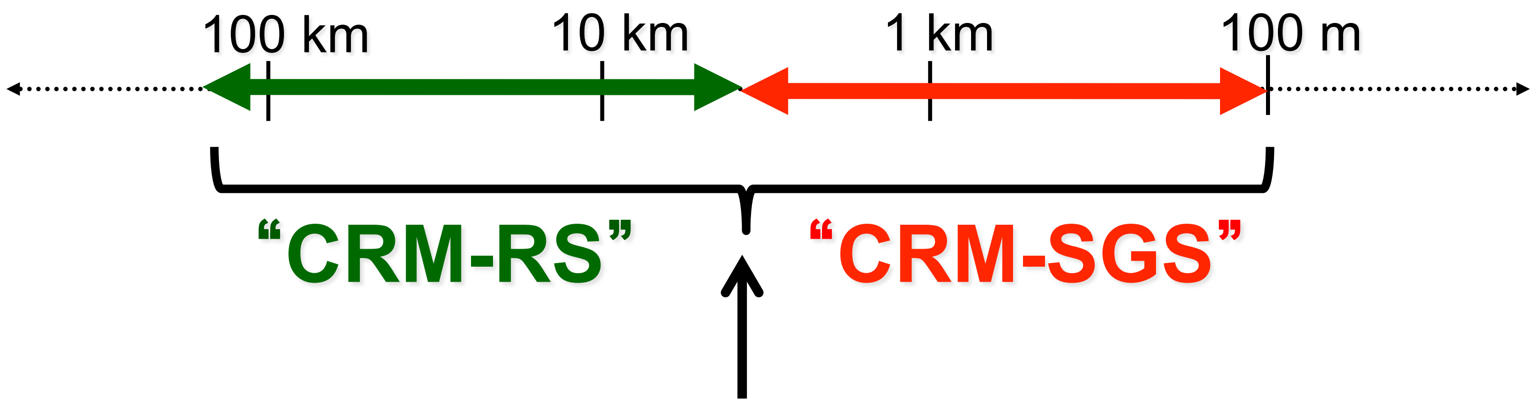
Are conventional PBL schemes good for km-grid CRMs?

Do we need to treat the PBL differently in km-grid CRMs?

Split the Giga-LES flow field into CRM-RS & CRM-SGS:



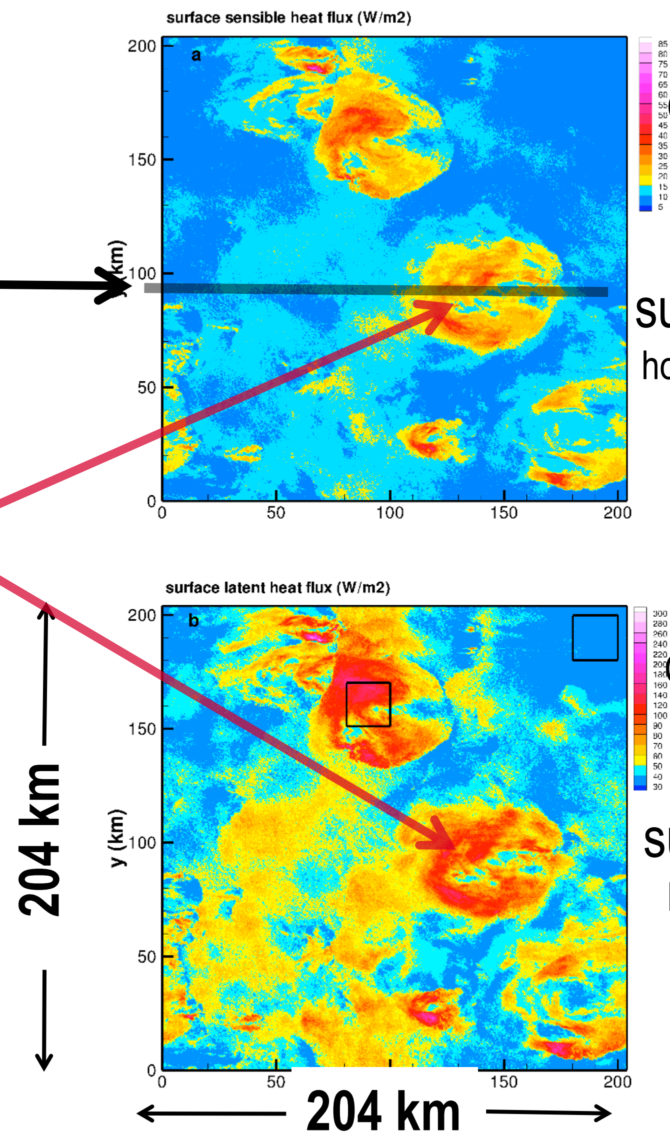
cutoff scale ~ a typical CRM grid size O(km)

In PBL, almost all fluxes are carried by CRM-SGS.

Spatial distribution of surface heat fluxes: the PBL highly inhomogeneous

Next: show a vertical cross-section of the "PBL" through a cold pool

strong positive sfc buoyancy flux in cold pool areas!



Color range: 5 -- 85 W/m2

surface sensible heat flux

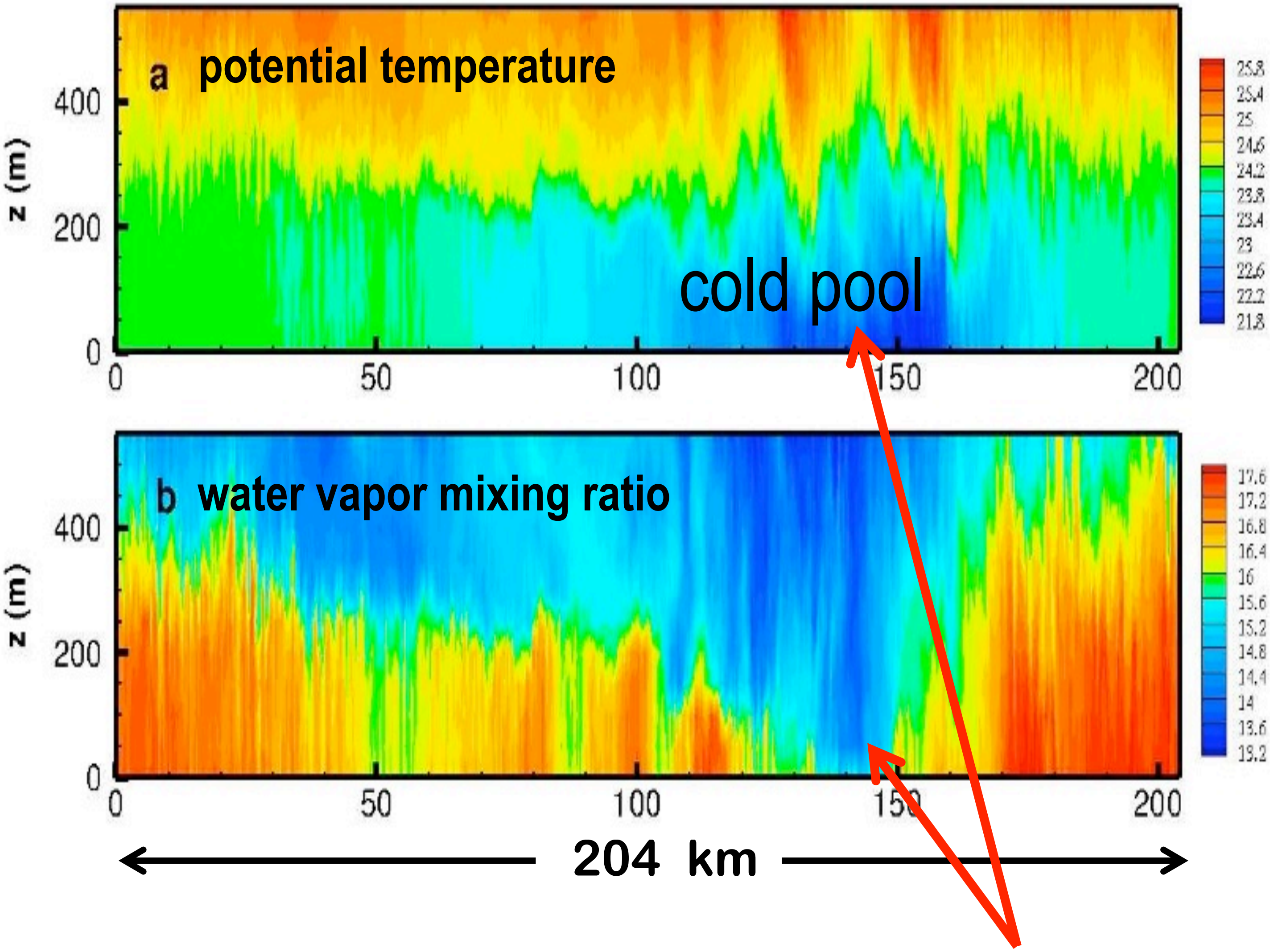
horizontal mean ~ 12 W/m2

Color range: 30 – 300 W/m2

surface latent heat flux

horizontal mean ~ 55 W/m2

The "PBL" under a deep convection system



Stably stratified & dry where sfc B-flx is strong.

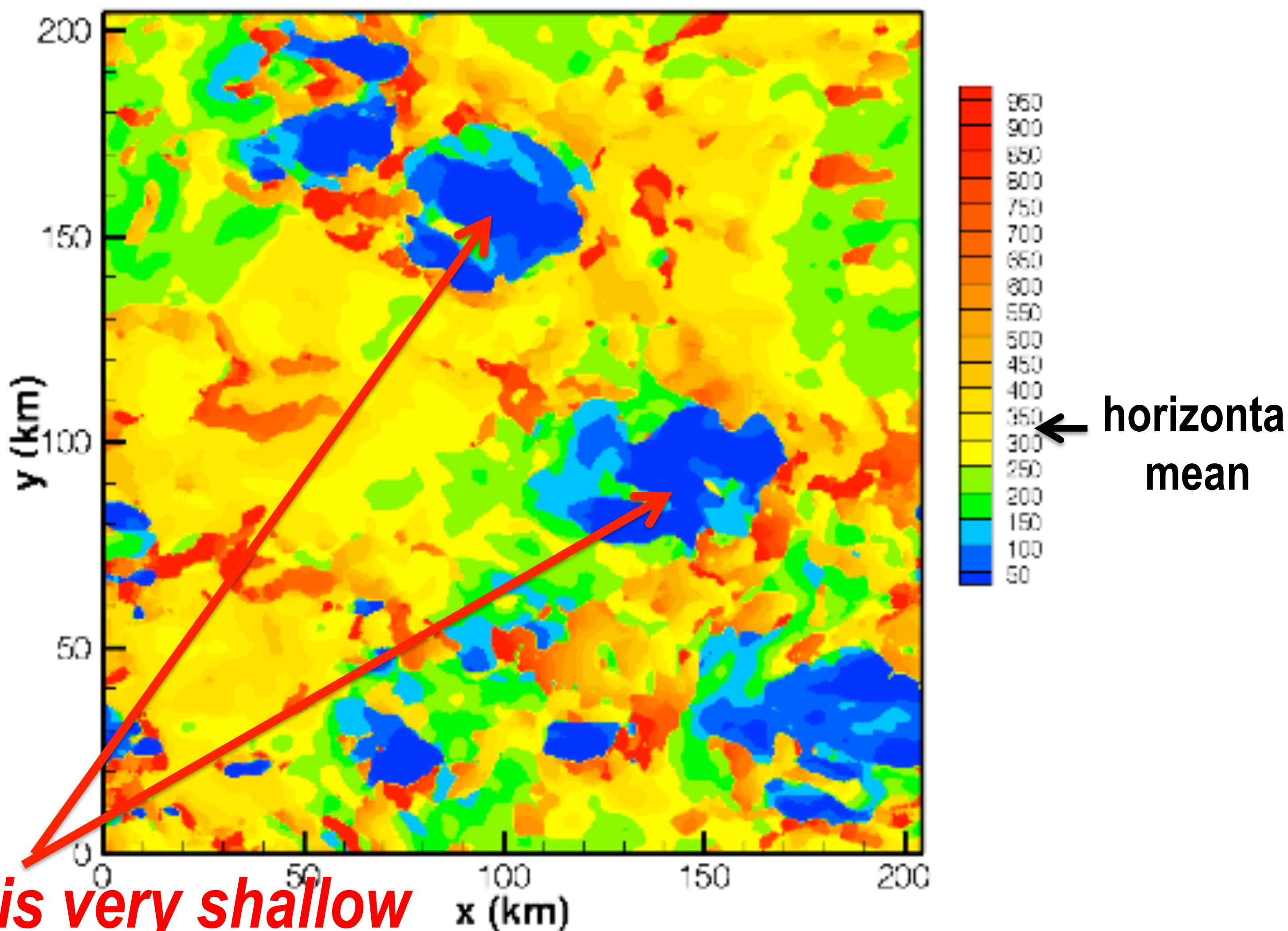
***** Not a "typical" convective PBL.***

Can't be treated with "typical" PBL schemes.

Find the PBL height *(based on the CRM-RS field)*

distribution of the inversion (PBL) height

1. **Search for max $\partial\theta_\ell / \partial z$ and min $\partial q / \partial z$ below 1 km.**
2. **Choose the min. of the two.**

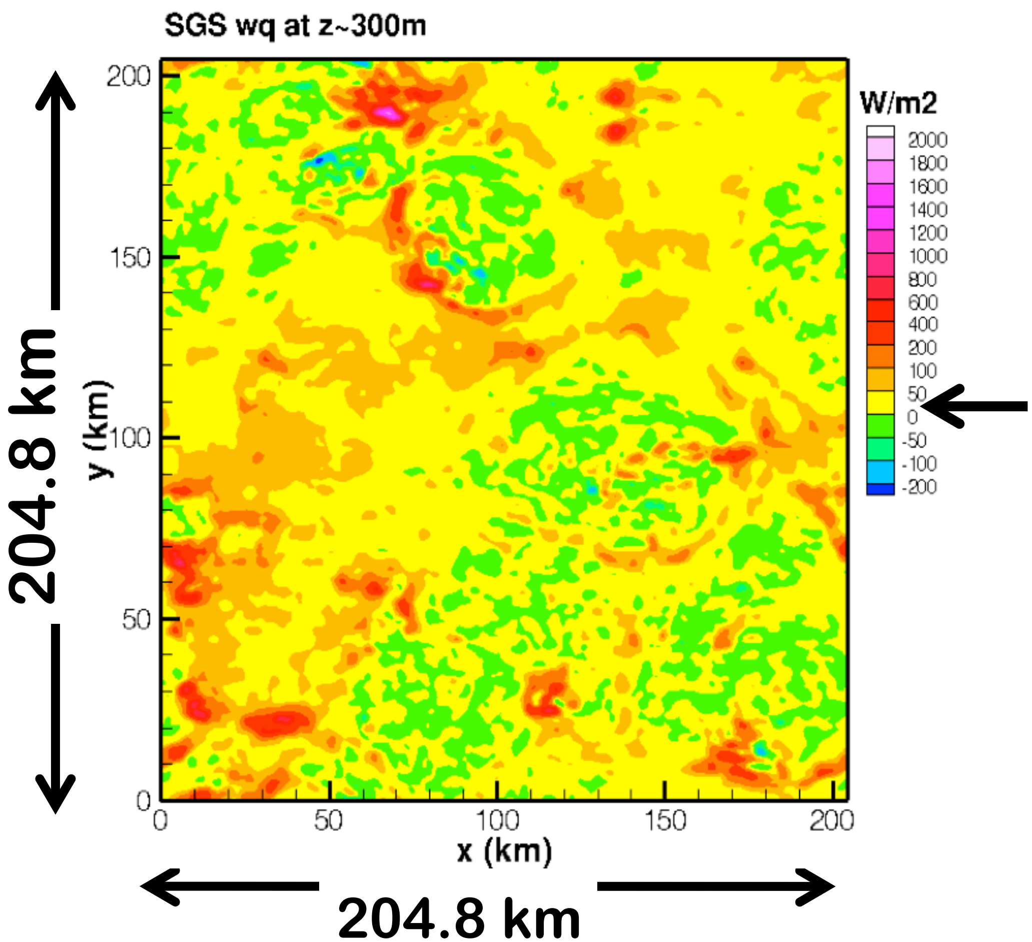


***** The PBL is very shallow where sfc b-flux is very positive!***

(Moeng and Arakawa 2012; MWR)

Horizontal distribution of SGS q-flux at z ~ 300 m

(retrieved from Giga-LES with a 4 km grid cutoff)



The PBL q-fluxes vary all over the place

[-200 ; +2000] W/m^2.

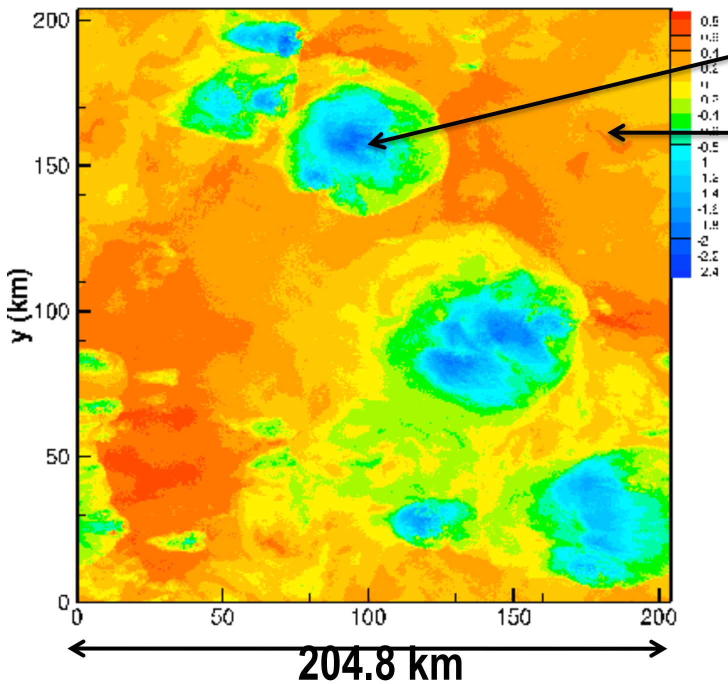
Horizontal (ensemble) mean cannot represent local fluxes in CRMs.

** Conventional ensemble PBL schemes may not be applicable for CRMs.

Where does the PBL feed moisture into the deep convection system?

Select & study six PBL regimes

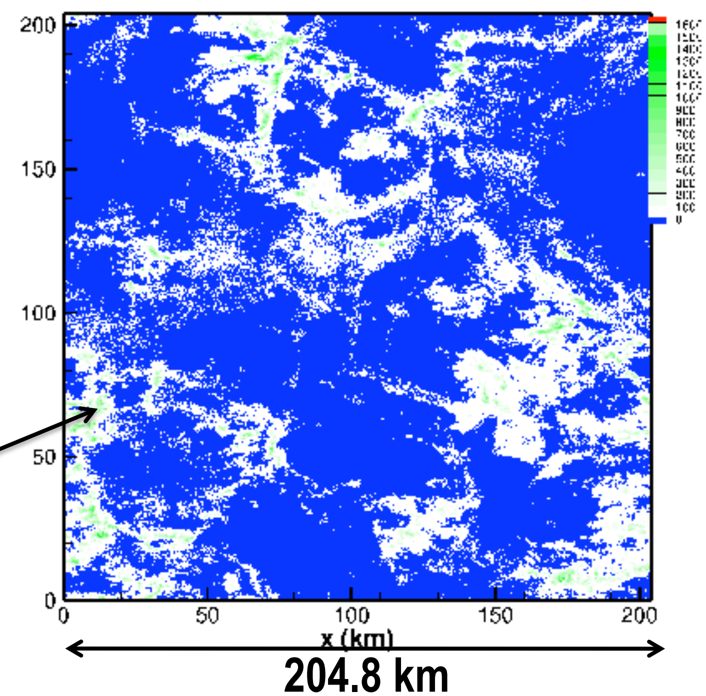
near-surface temperature



1. PBL-cold

2. PBL-envr

vertically-integrated condensed water



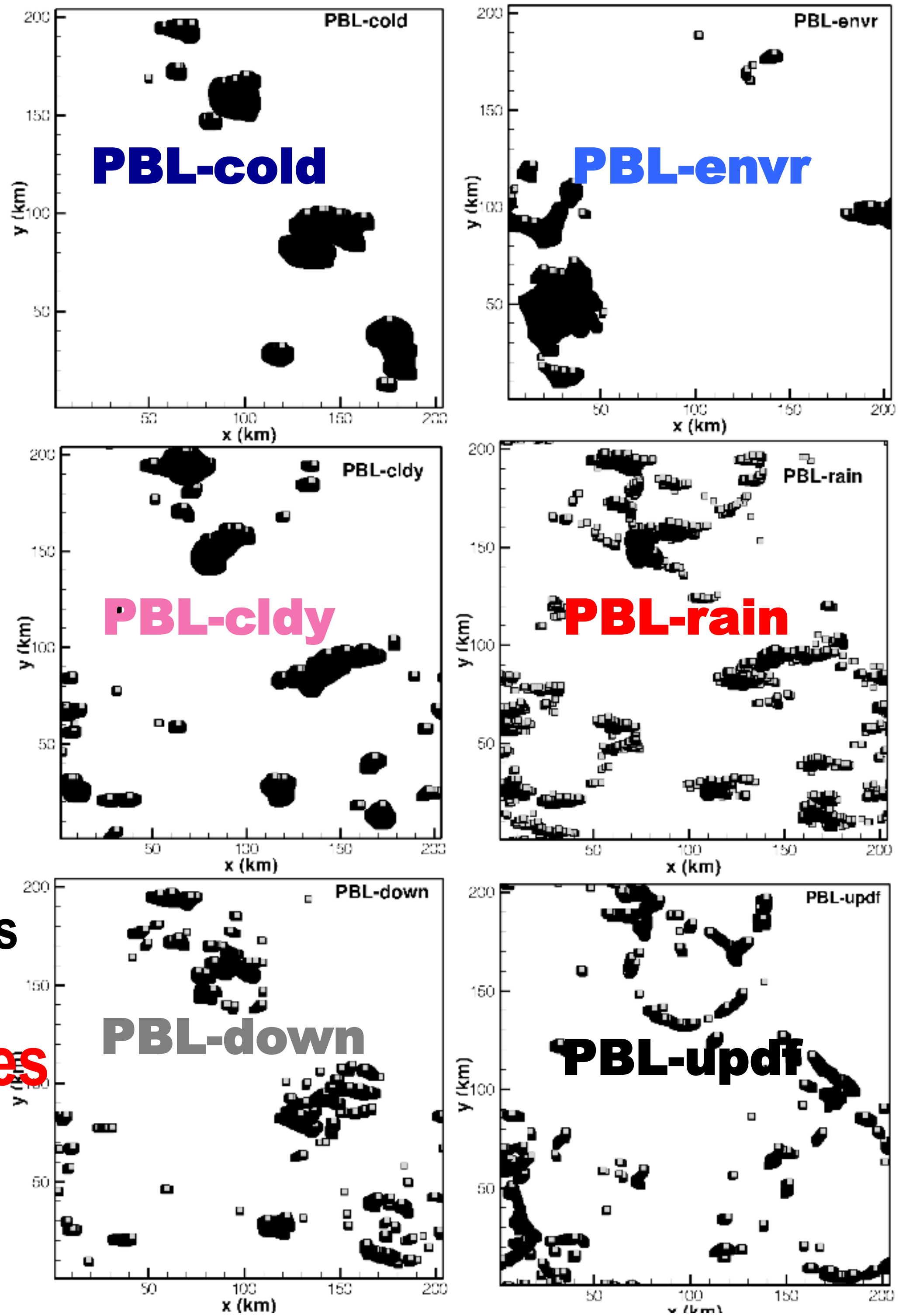
3. PBL-cldy

4. PBL-rain

5. PBL-updf

6. PBL-down

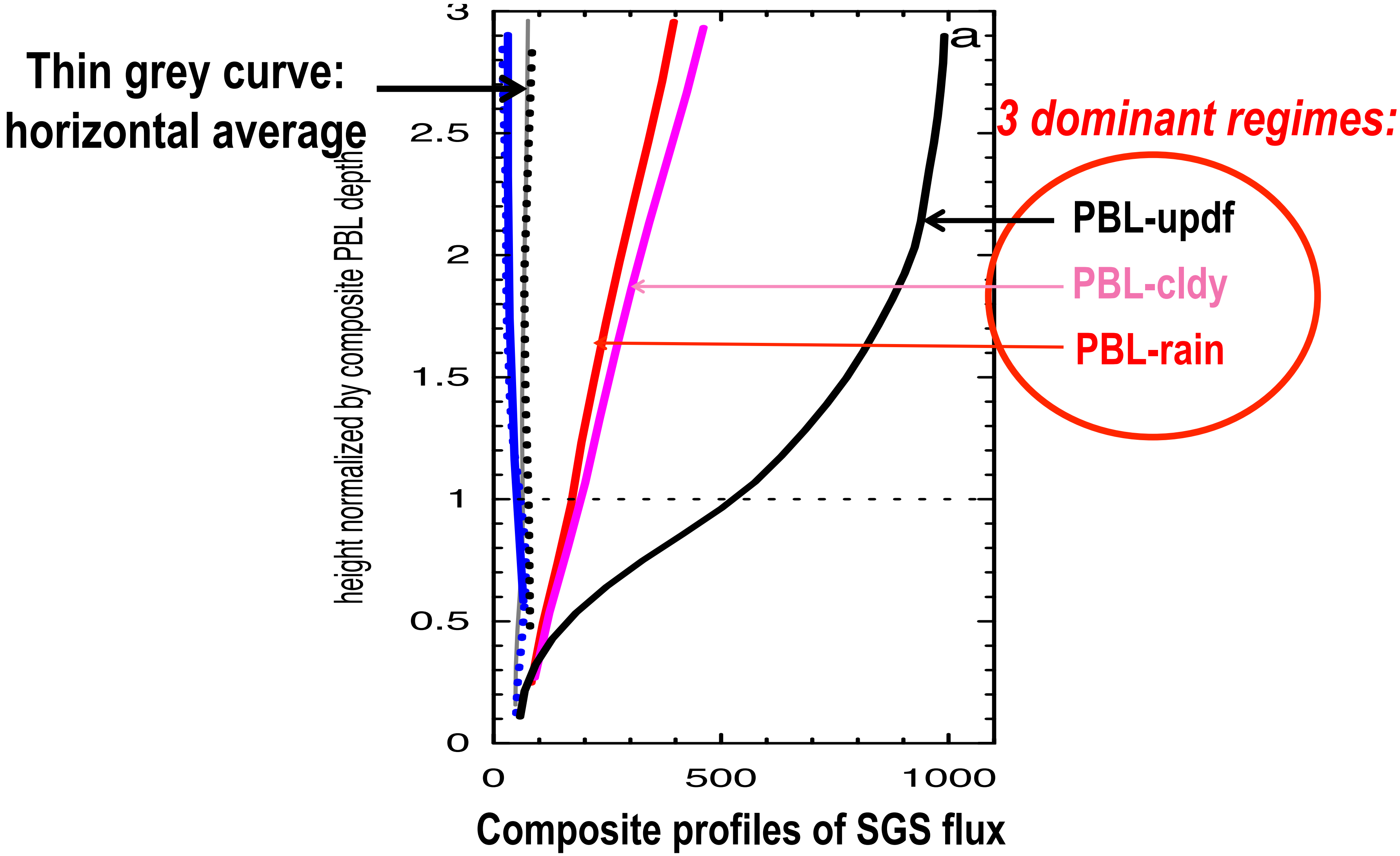
Grid locations of the 6 PBL regimes



**Sample sizes range:
140,000 - 220,000 LES grid points**

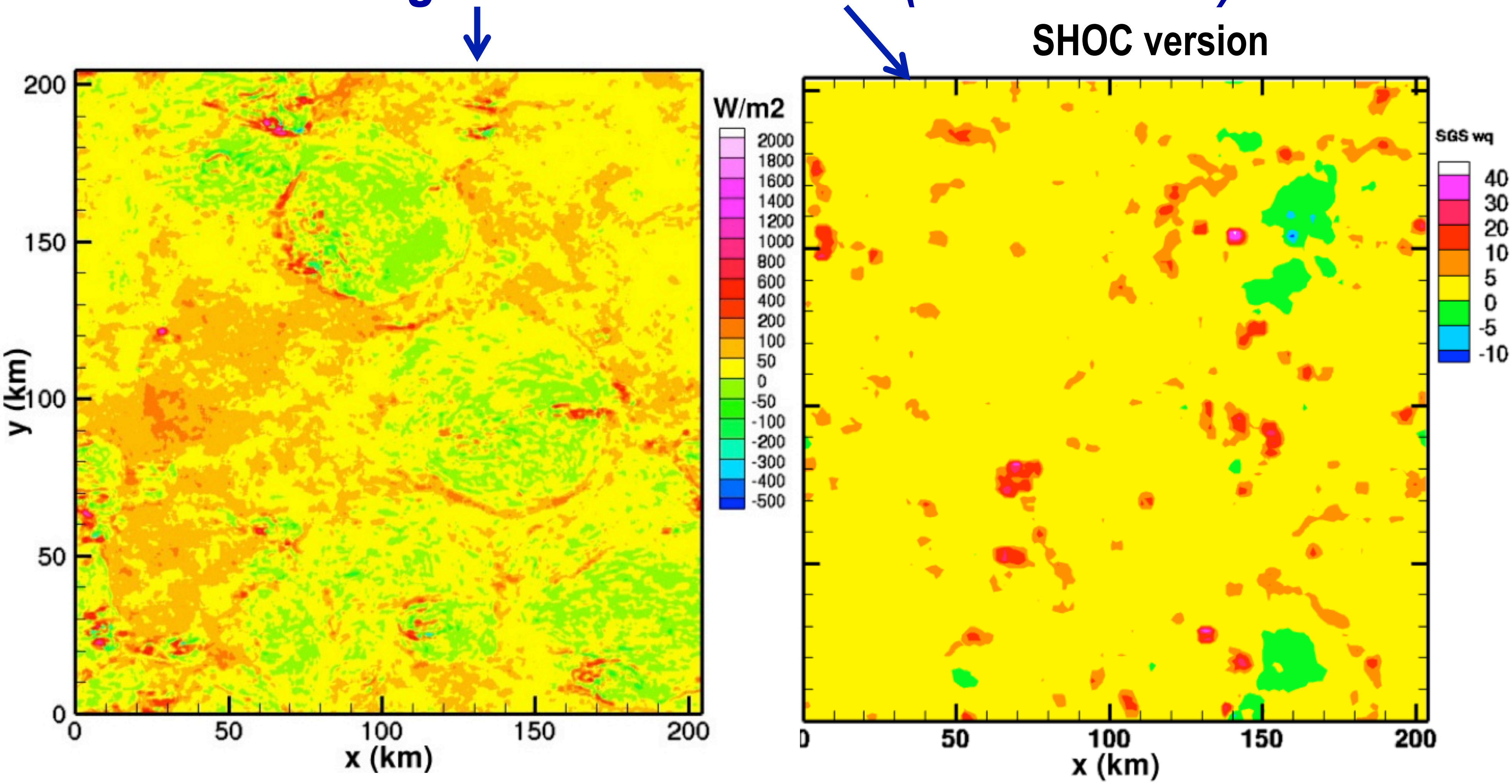
Next: Find their composites

The composite profiles of SGS q-fluxes



Large SGS fluxes occur at areas with low-level updrafts & clouds & rain.

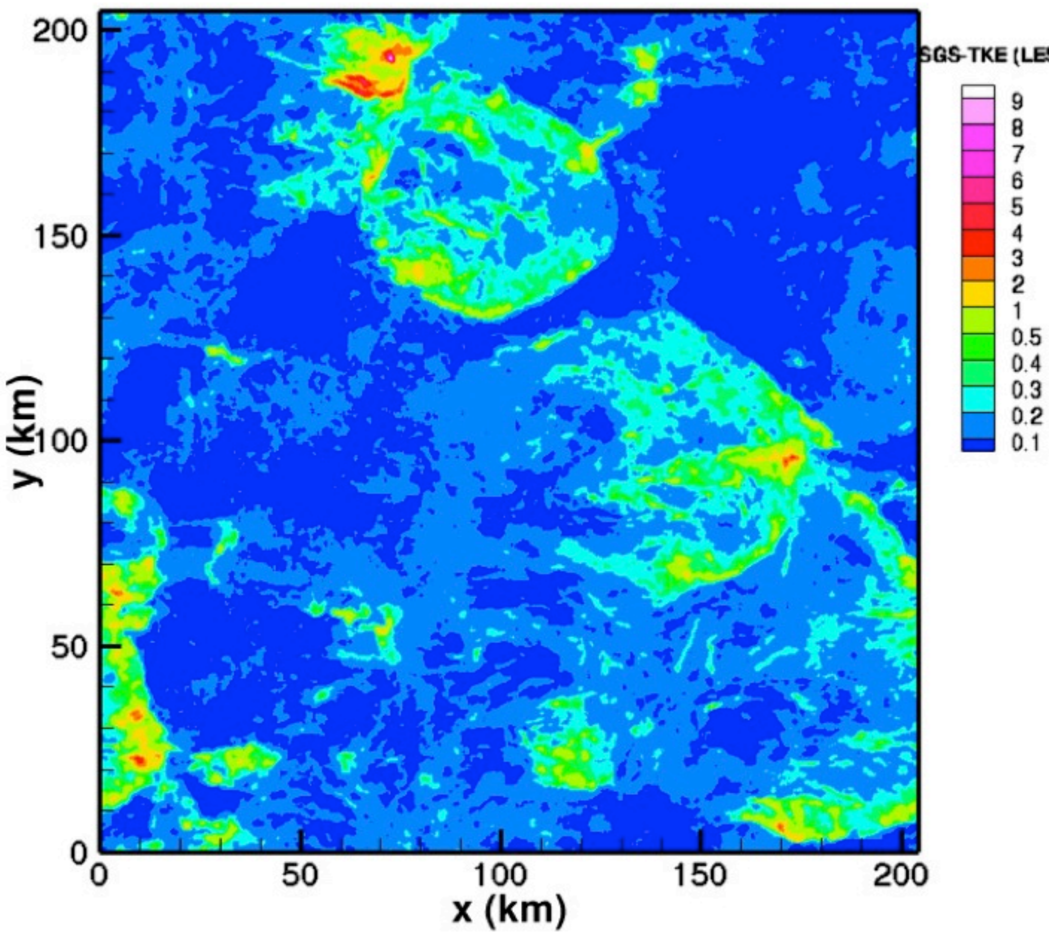
Comparing SGS q-flux distributions at z~ 300 m between Giga-LES & SAM-CRM (for Δ=1.6 km)



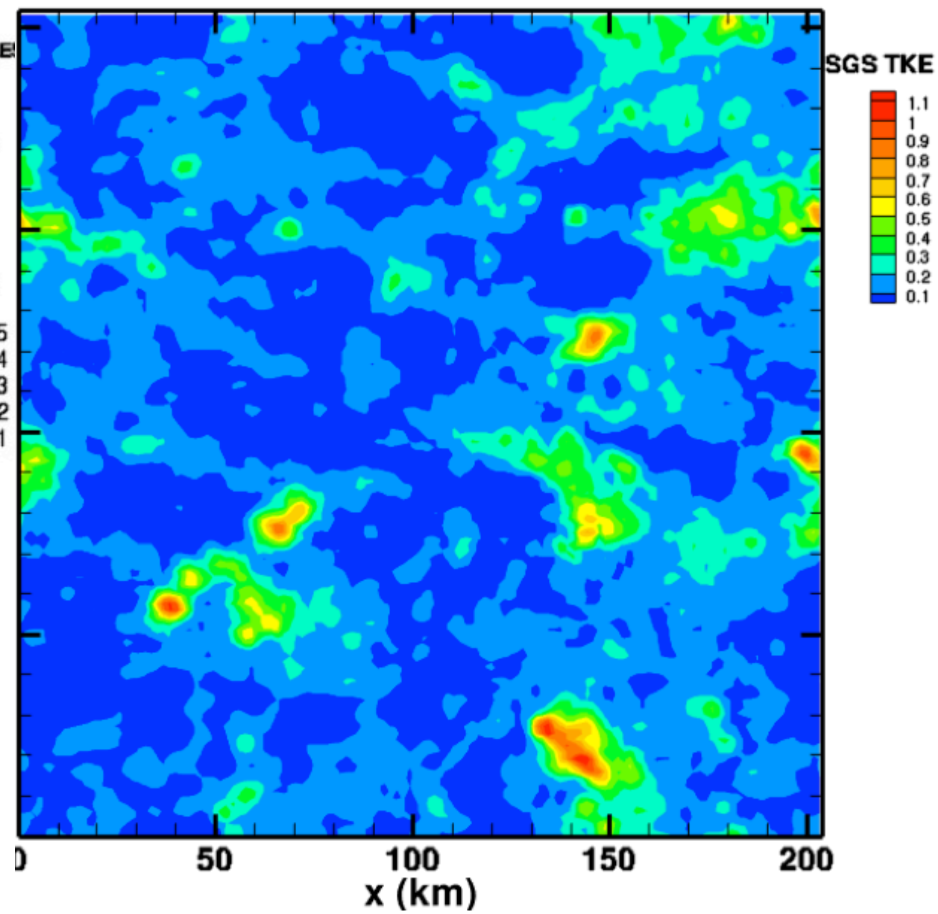
[-500 to 2000 W/m^2] vs. [-10 to 40 W/m^2]

SAM underestimates flux variation & extrema.

Comparing SGS TKE distributions at z~ 300 m between Giga-LES & SAM-CRM (for Δ=1.6 km)



SHOC version



max ~ 9 m^2/s^2 max ~ 1 m^2/s^2

SAM underestimates extreme events.

Future work

- How the PBL transport impacts the development of deep convection.
- Improve the representation of PBL transport in CRMs.
- Hope my PBL study could help hurricane research.

Professor Arakawa:

Thank you for great teaching & mentoring, & bringing me into the exciting field of the PBL.