Understanding cumulus convection through novel diagnostics of cloud-resolving models

Zhiming Kuang

Moist convection is a riddle wrapped in a mystery inside an enigma.

--- After Emanuel 1994 (adapted from Churchill)

Many forms of moist convection

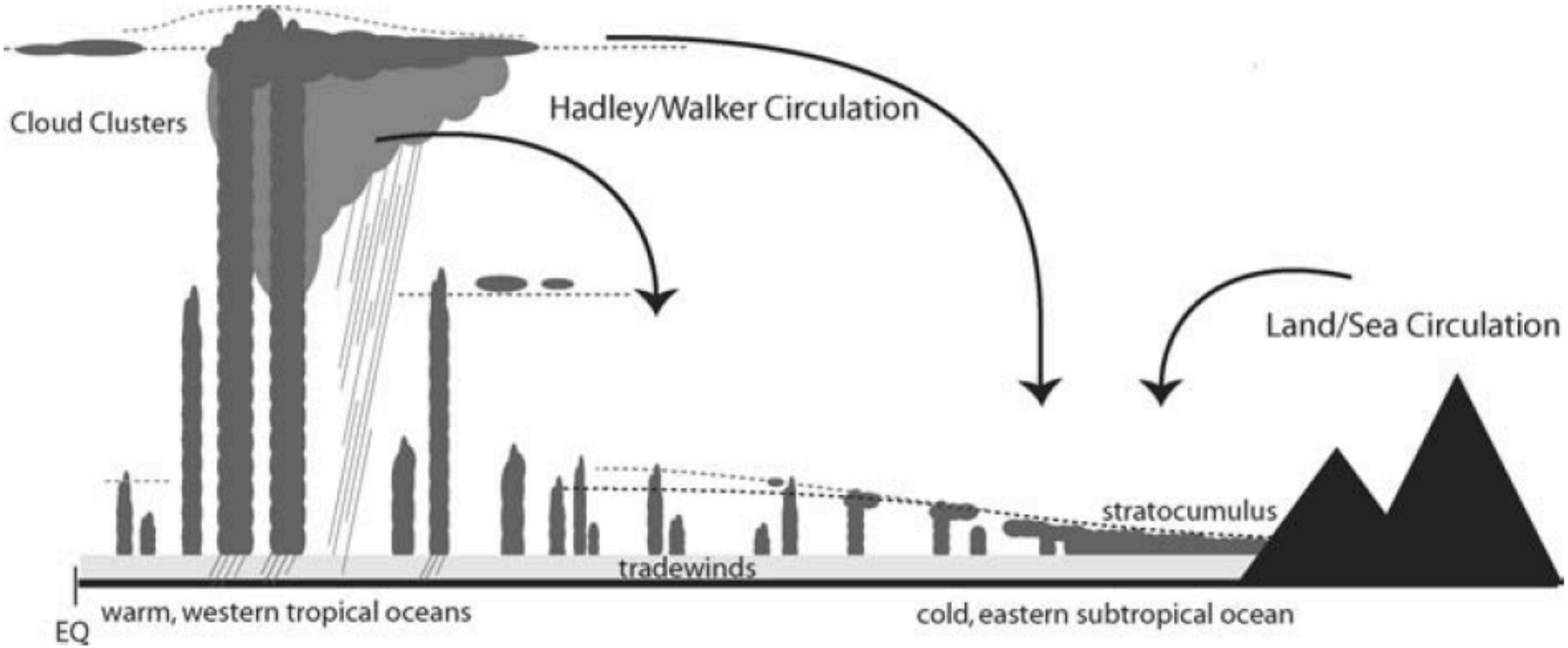
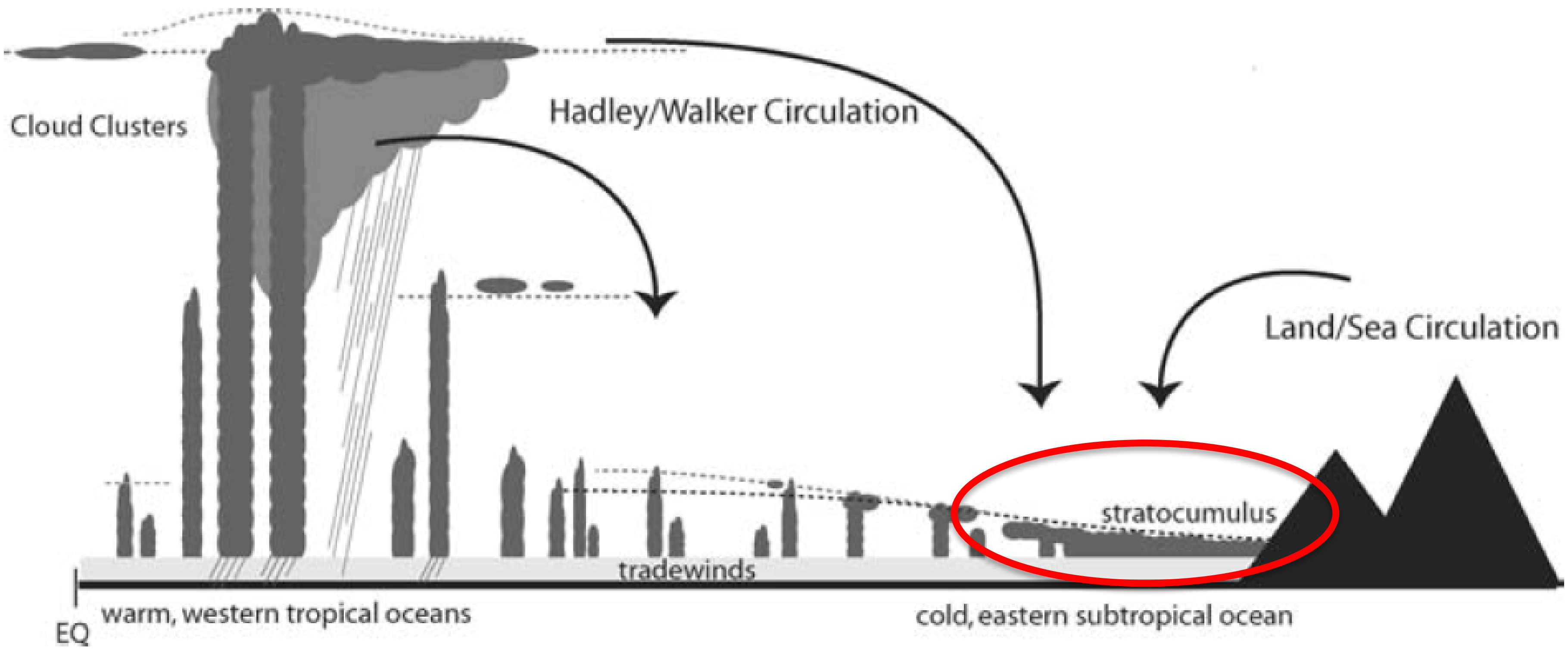


Figure 1 Cloud regimes in thermally direct circulations. Adapted from Arakawa (1975).

Stevens, 2005



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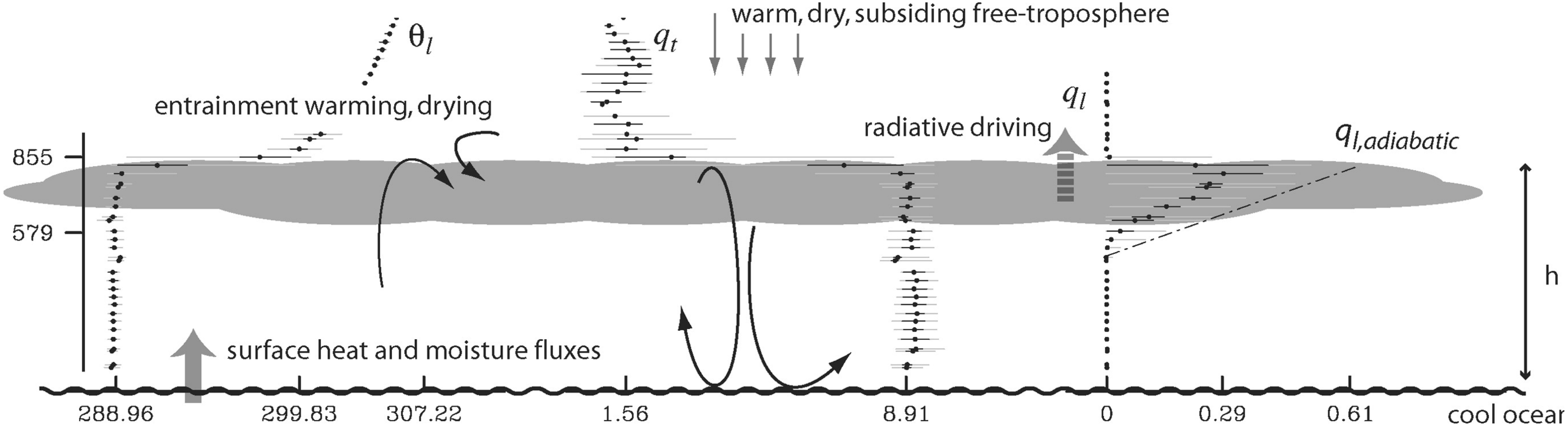
http://cloudappreciationsociety.org/



Stevens, 2005, Annual Review of Earth and Planetary Sciences

Equivalent potential temperature

$$\theta_e \approx \theta \exp\left(\frac{+q_v L_v}{c_{p,d} T}\right)$$

Liquid water potential temperature (conserved only without precipitation)

$$\theta_l \approx \theta \exp\left(\frac{-q_l L_v}{c_{p,d} T}\right)$$

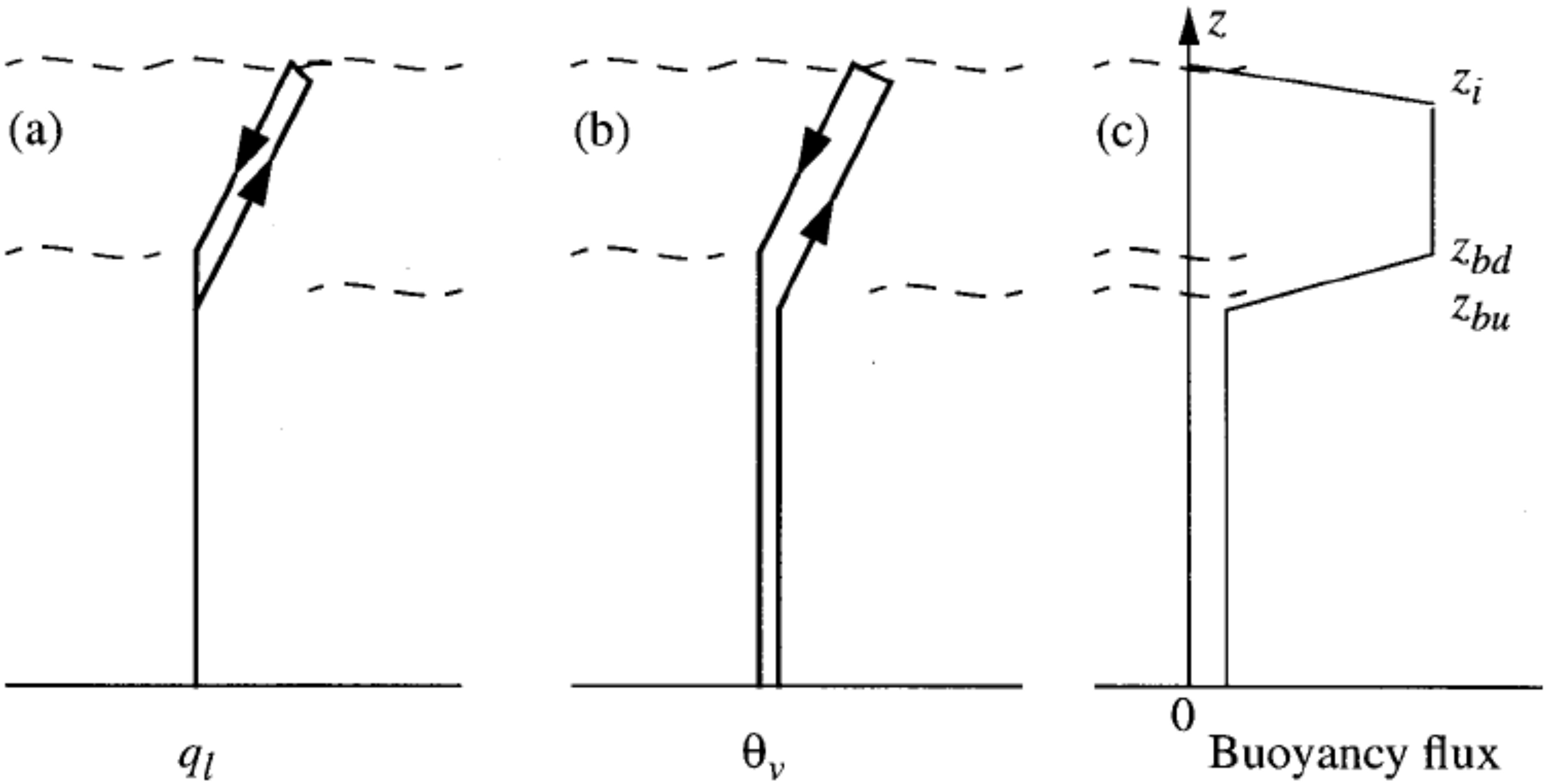
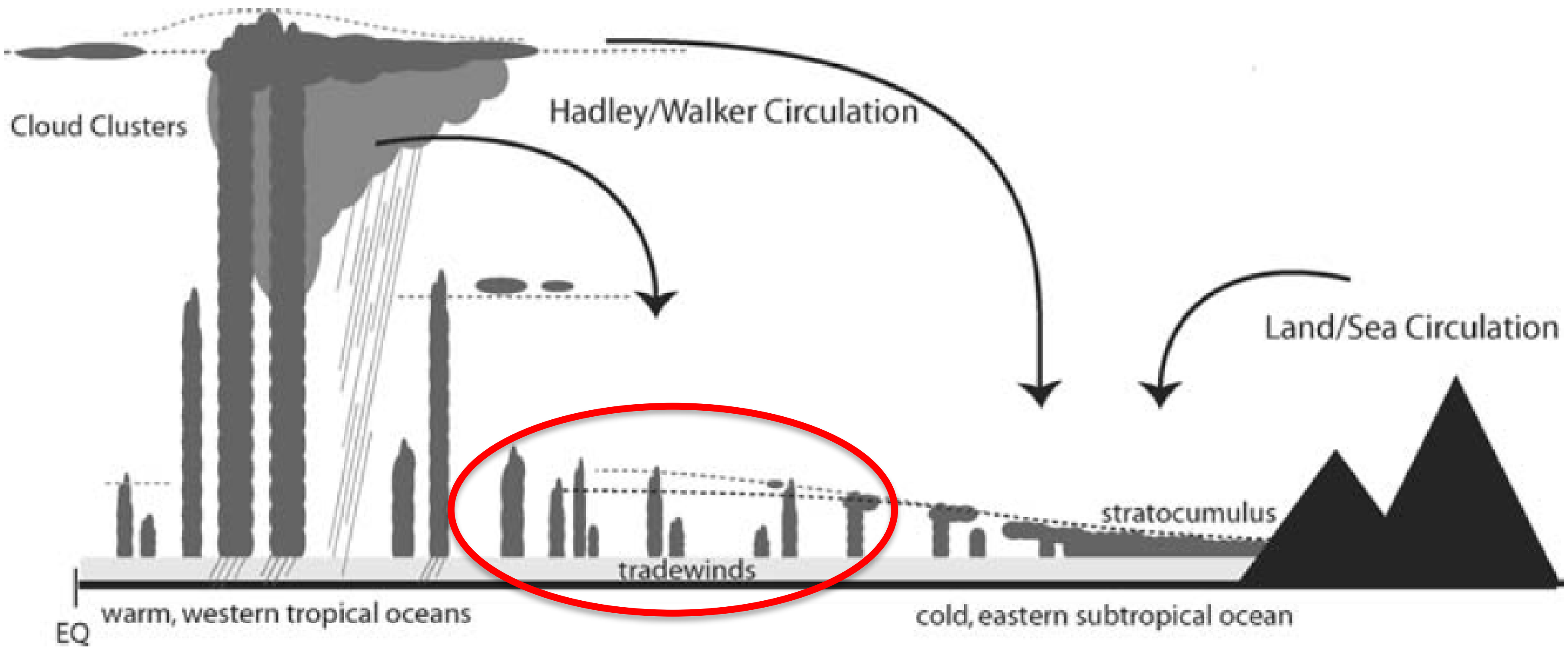


Figure 6. Air parcel properties and buoyancy fluxes in an convective eddy in a well-mixed CTBL. Dashed lines indicate heights of updraft condensation level z_{bu}, downdraft condensation level z_{bd} and inversion z_i. Typical profiles of (a) q_l and (b) θ_v for air parcels cycling through updrafts and downdrafts are shown, along with (c) the resulting buoyancy flux profile.

Bretherton 1997



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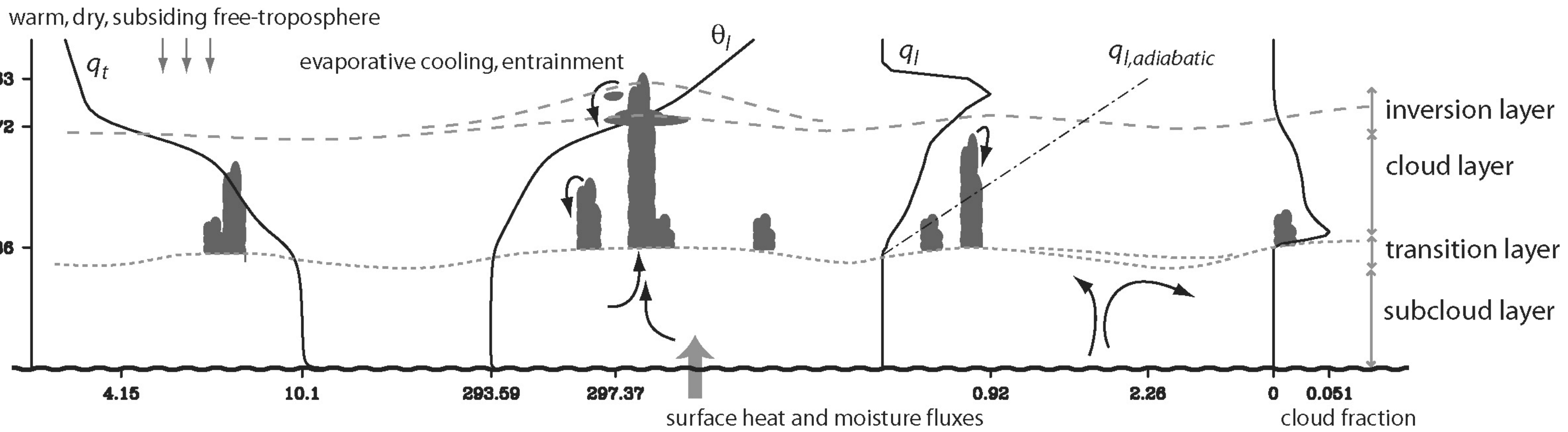


Stevens, 2005

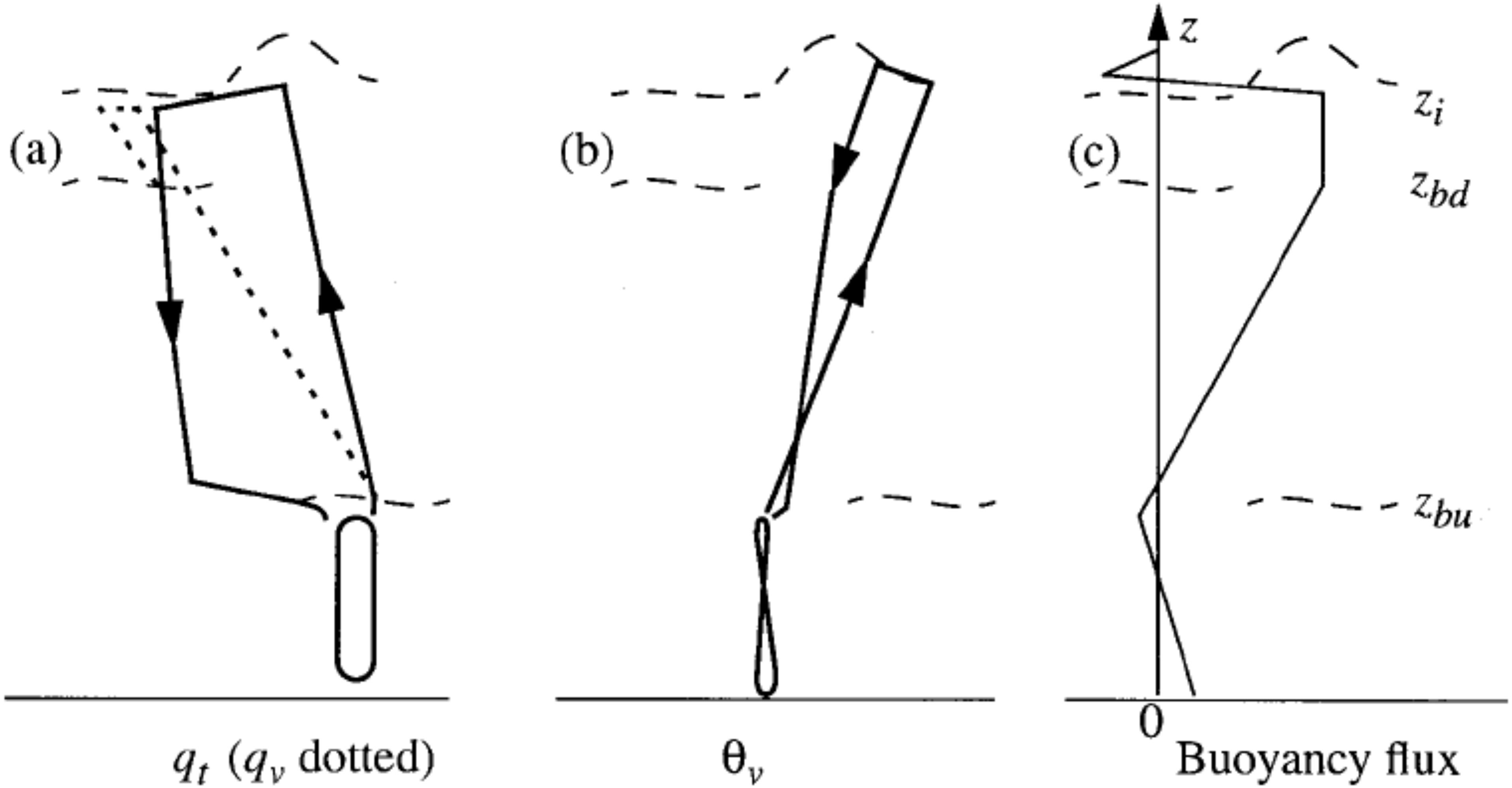
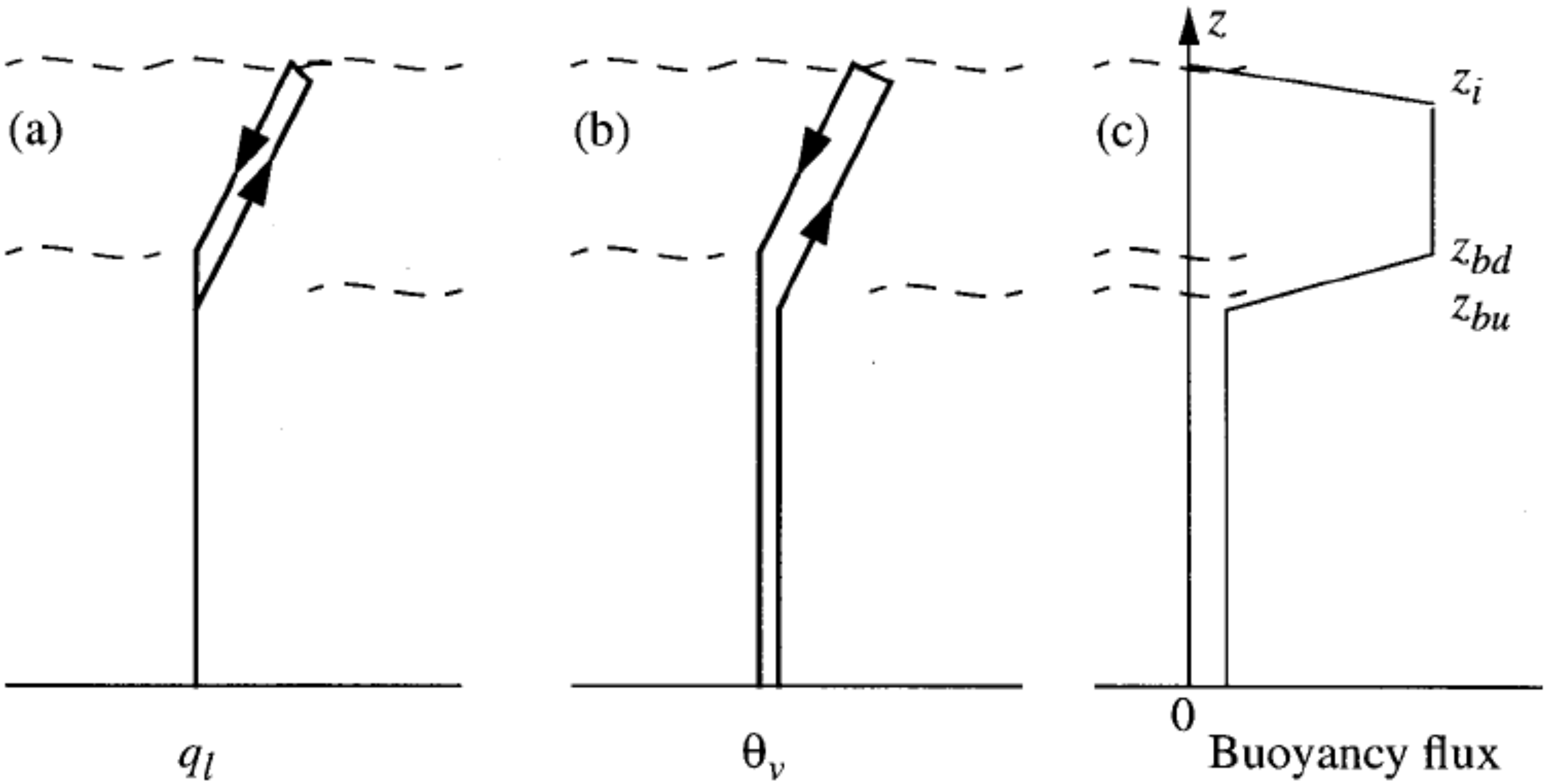


Figure 7. Air parcel paths and buoyancy fluxes in an convective eddy in a decoupled CTBL with cumulus rising into stratocumulus. Dashed lines indicate heights of cumulus base (updraft condensation level) z_{bu}, stratocumulus cloud base (downdraft condensation level) z_{bd} and inversion z_i. Typical profiles of (a) q_t amd q_v and (b) θ_v for air parcels cycling through updrafts and downdrafts are shown, along with (c) the resulting buoyancy flux profile. Note that all but a few percent of subcloud layer eddies (closed circuits) do not form cumuli. See text for more discussion.

Bretherton 1997



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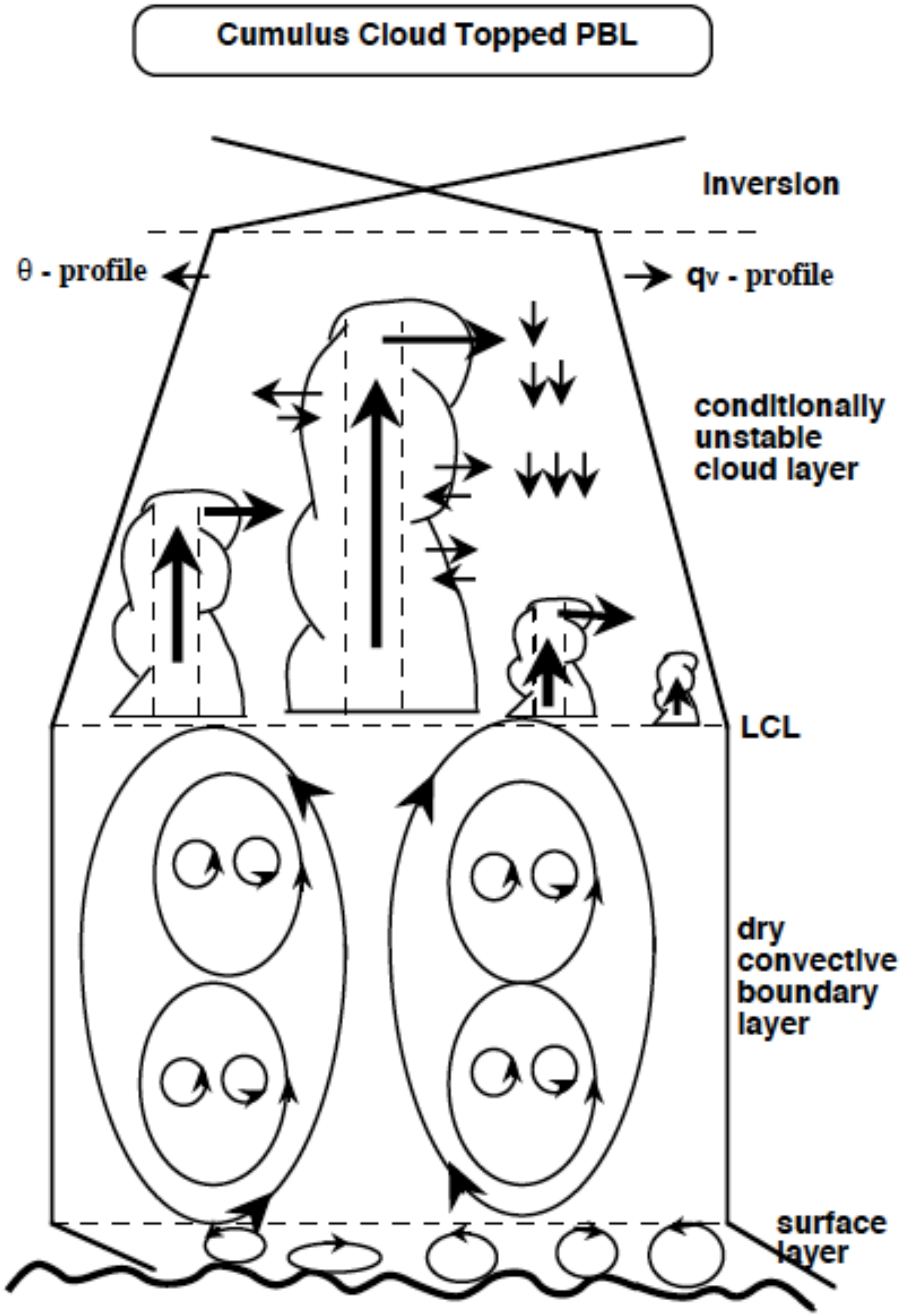


Siebesma, 1998

Figure 4. Cartoonlike view of the dynamics of the cumulus topped boundary layer.

Imaged from the International Space Station

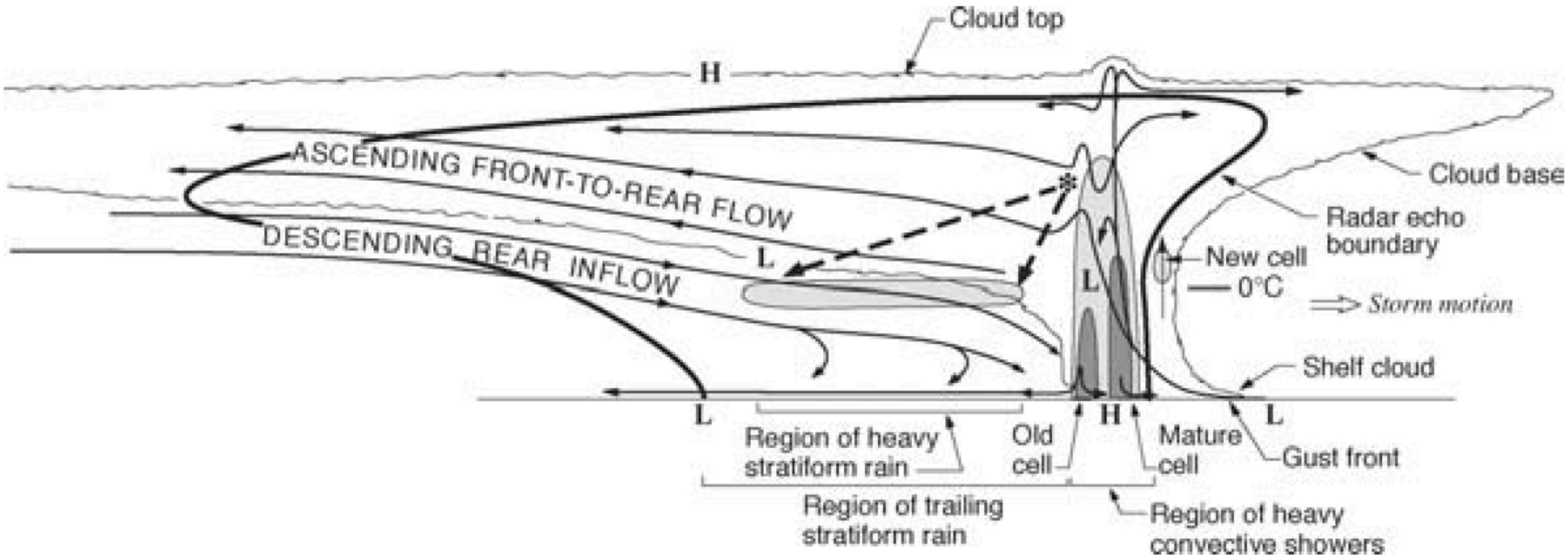
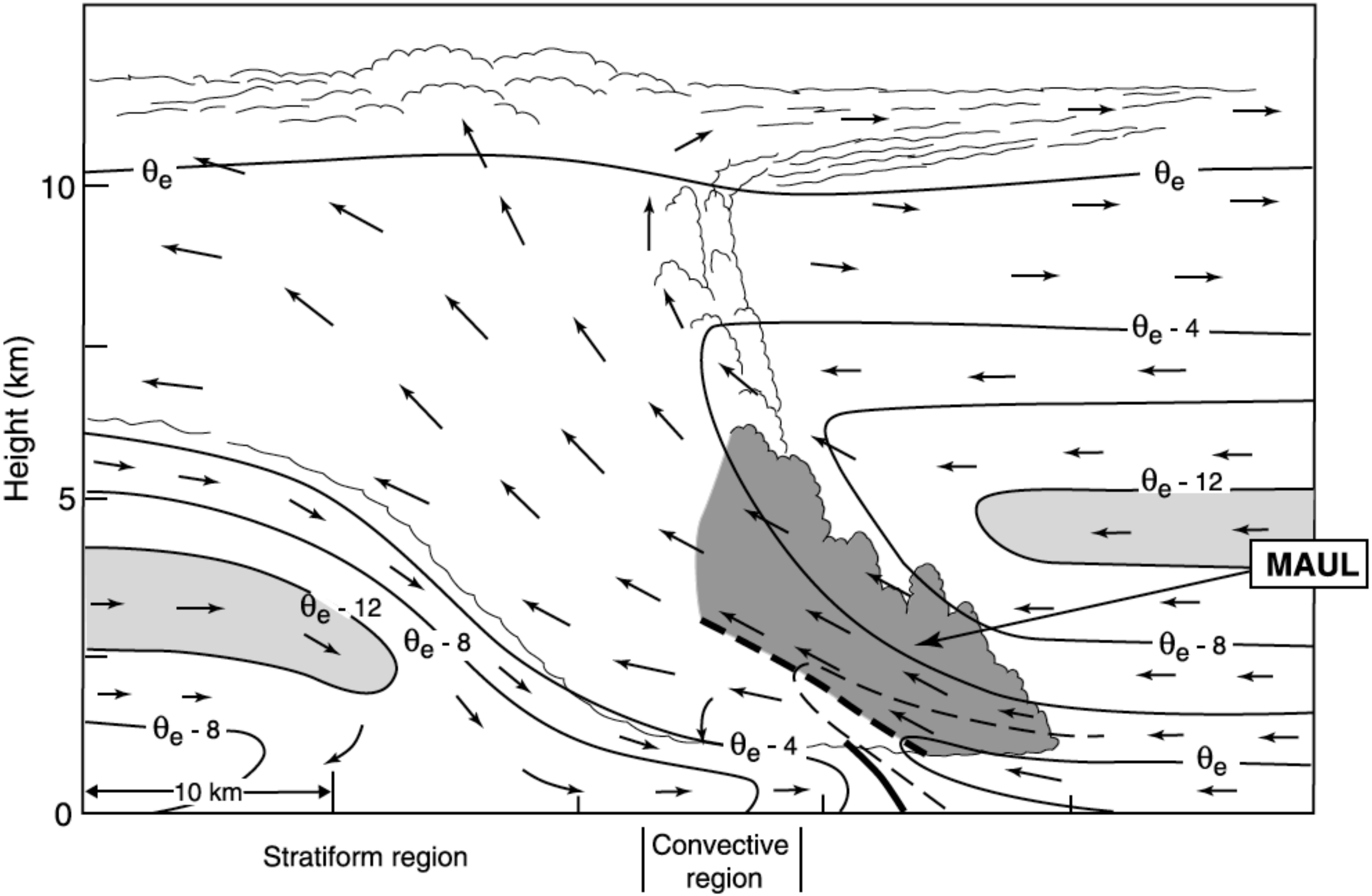


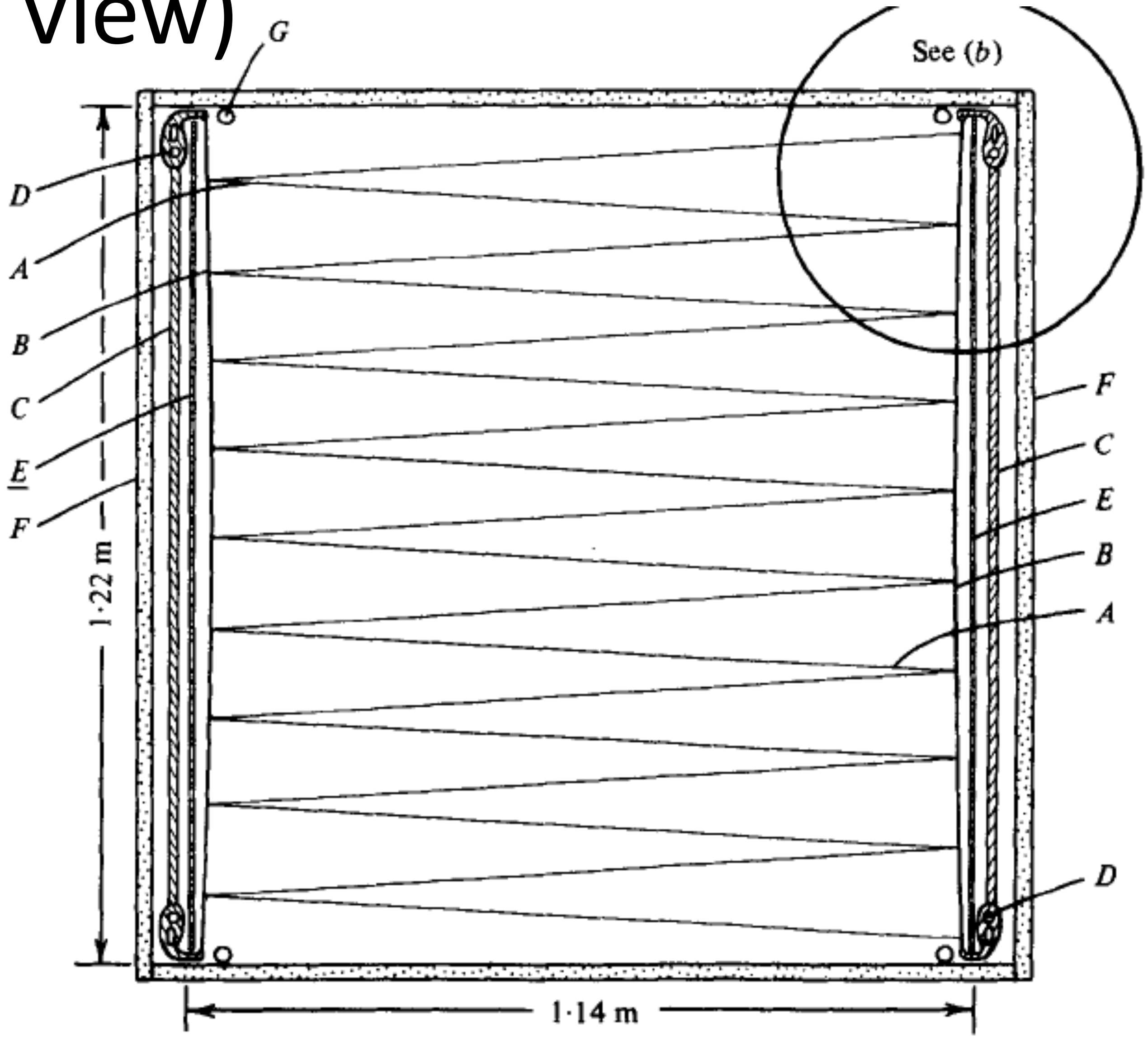
Figure 11 Example of a prototypical mesoscale convective system, a squall line. Taken from Houze (1989).



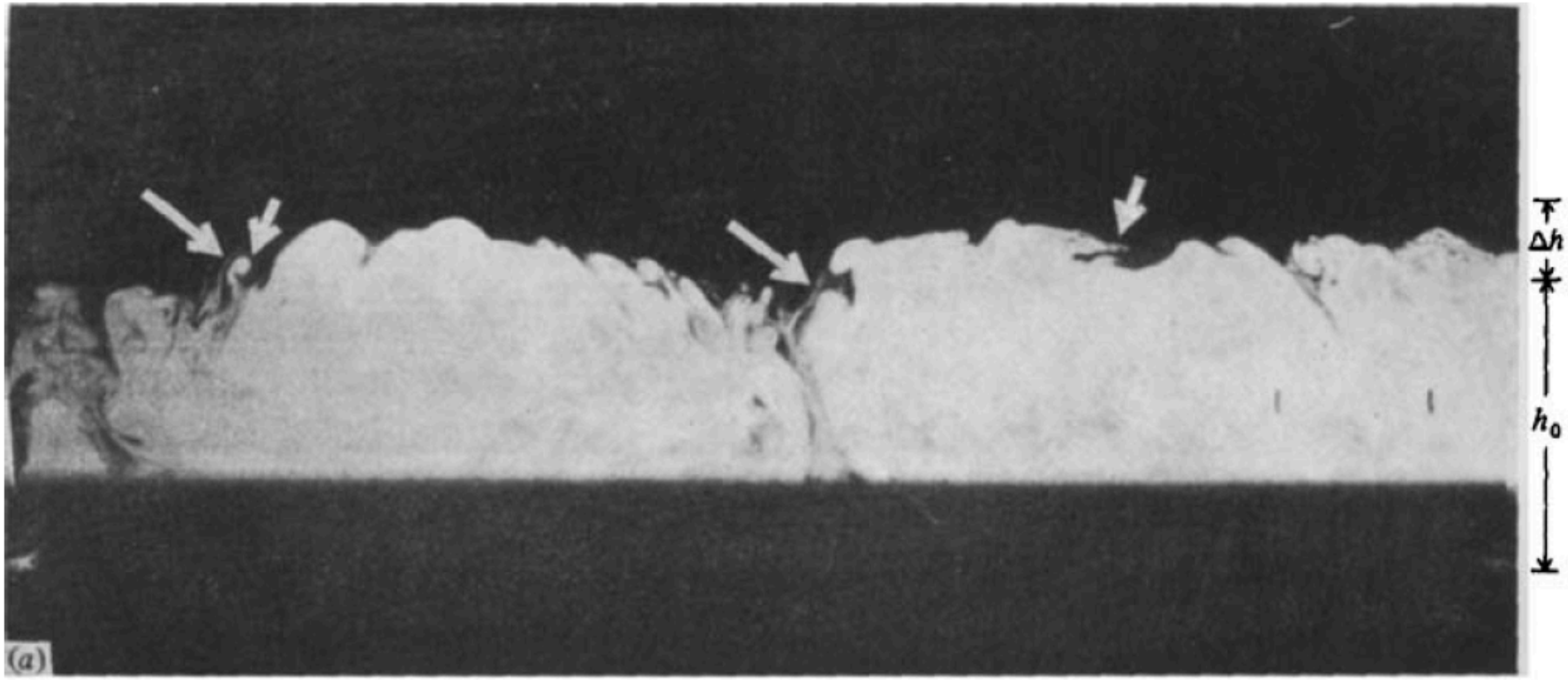
Houze (2004) adapted from Bryan and Fritsch (2000)

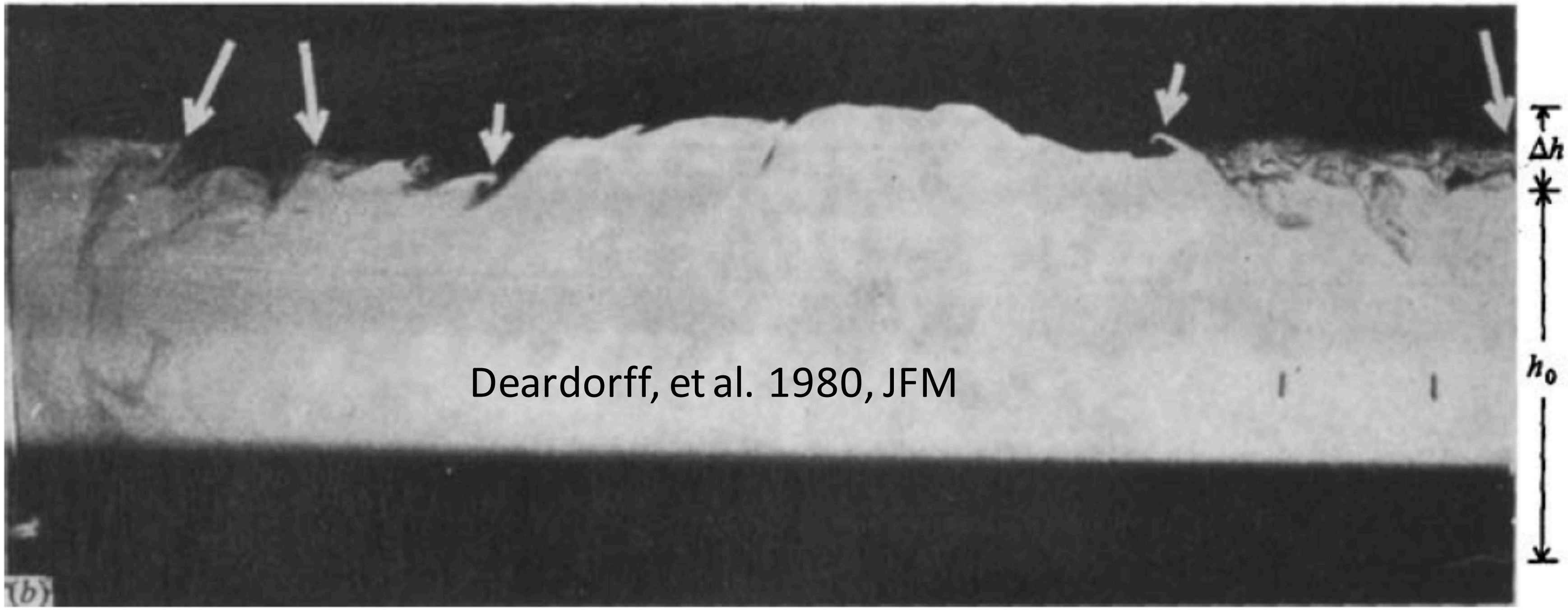
Laboratory experiments

Water tank experiments of CBL (Top-down view)



Deardorff, et al. 1980, JFM





Deardorff, et al. 1980, JFM

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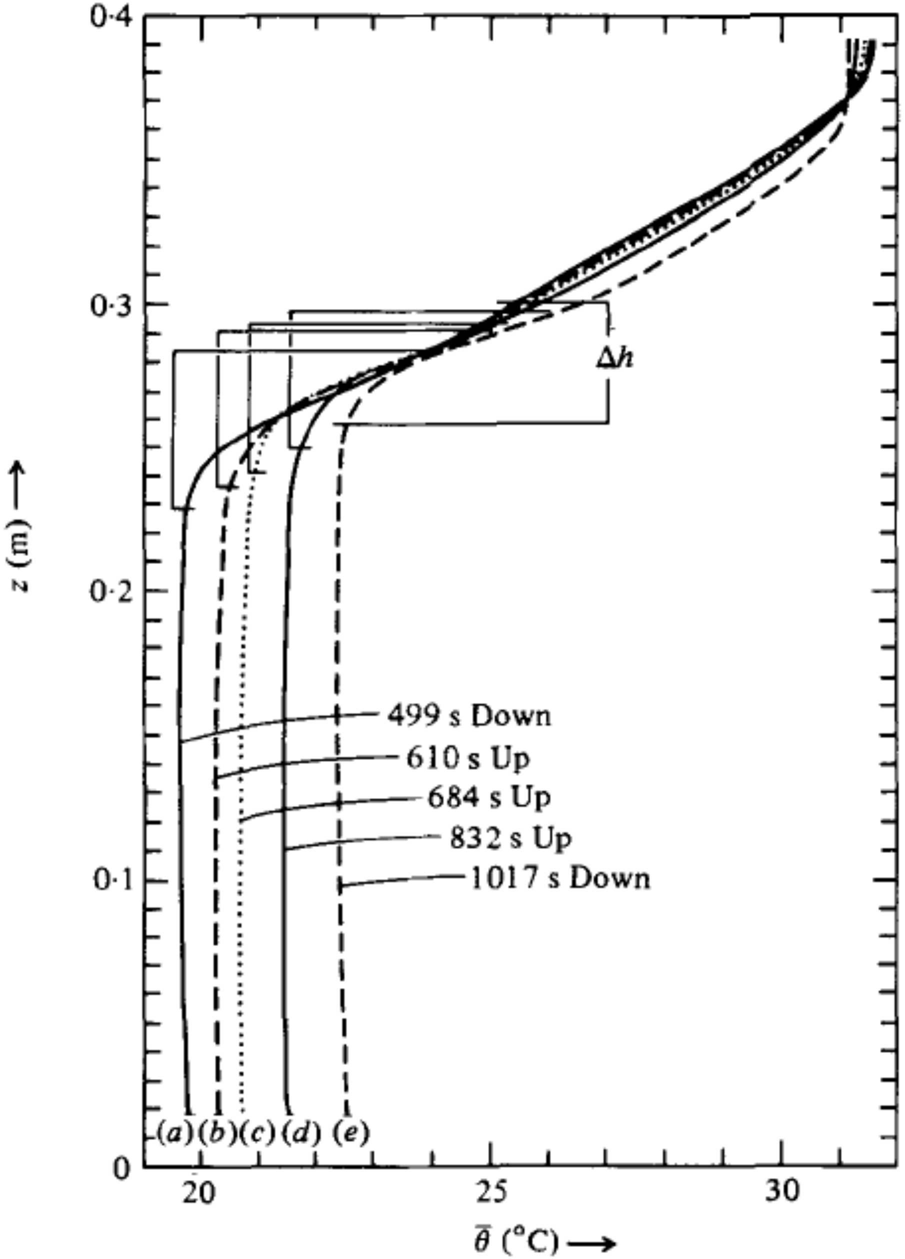
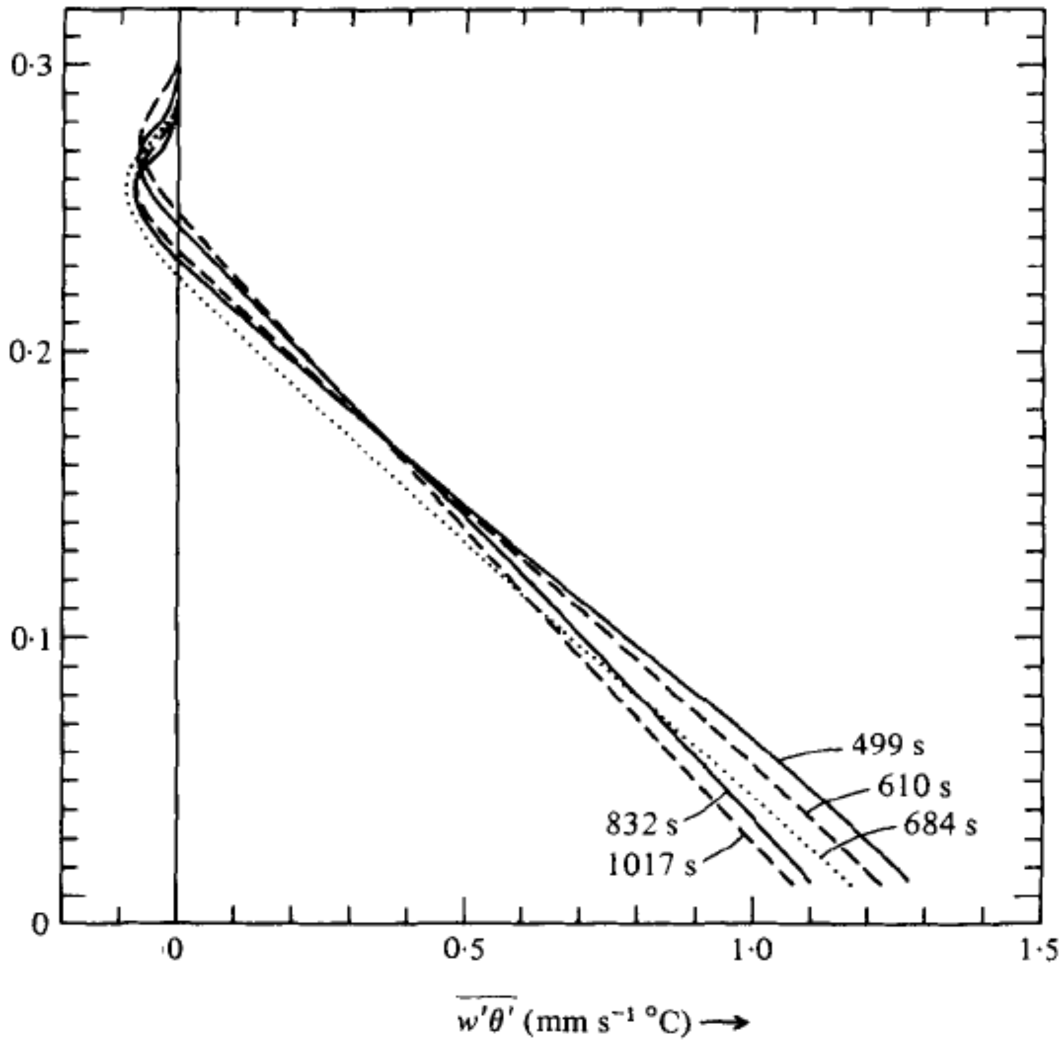
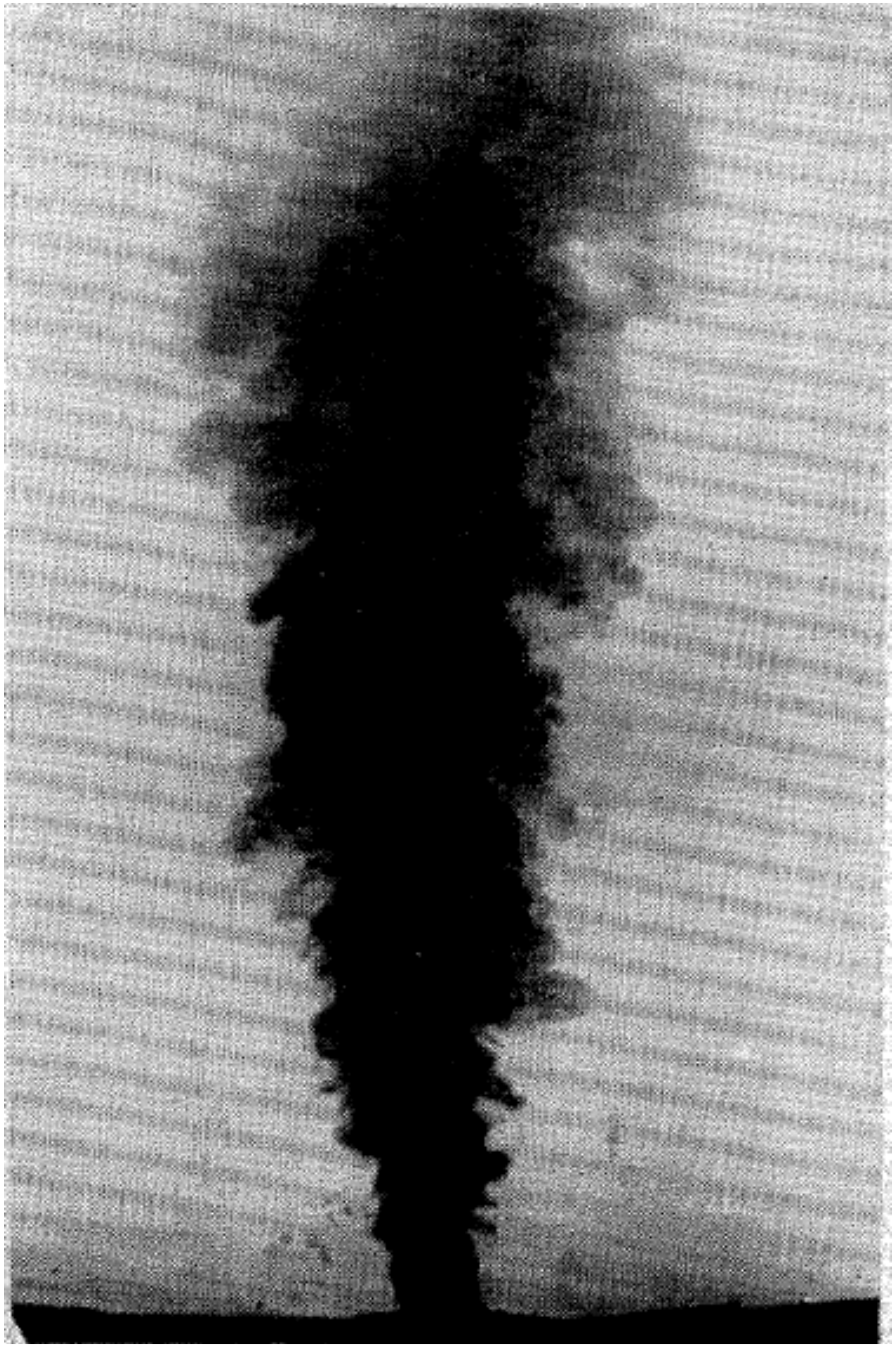
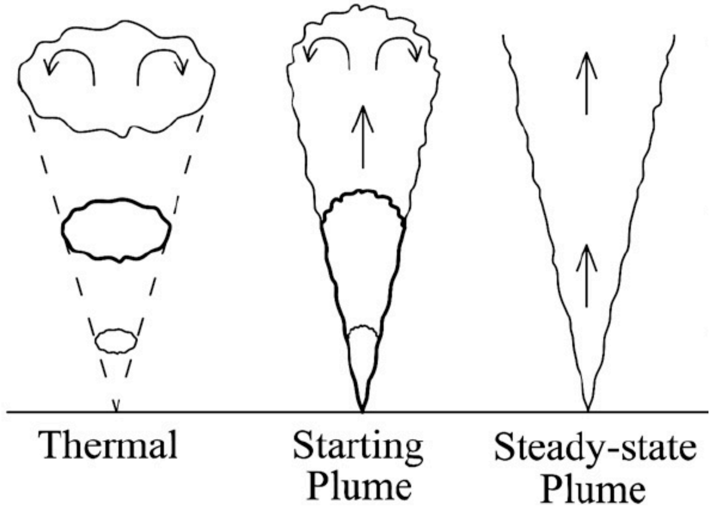






Entraining similarity plume

Morton et al., 1956, JFM



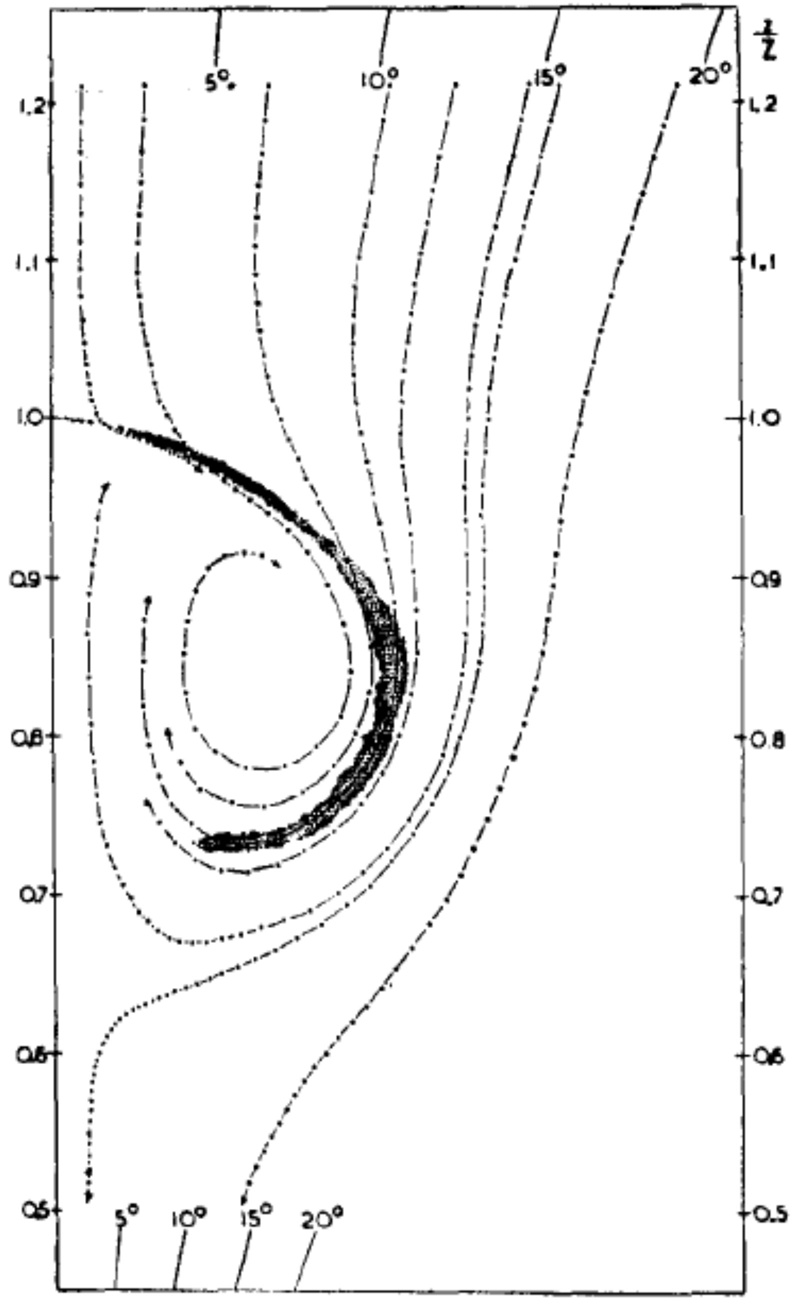
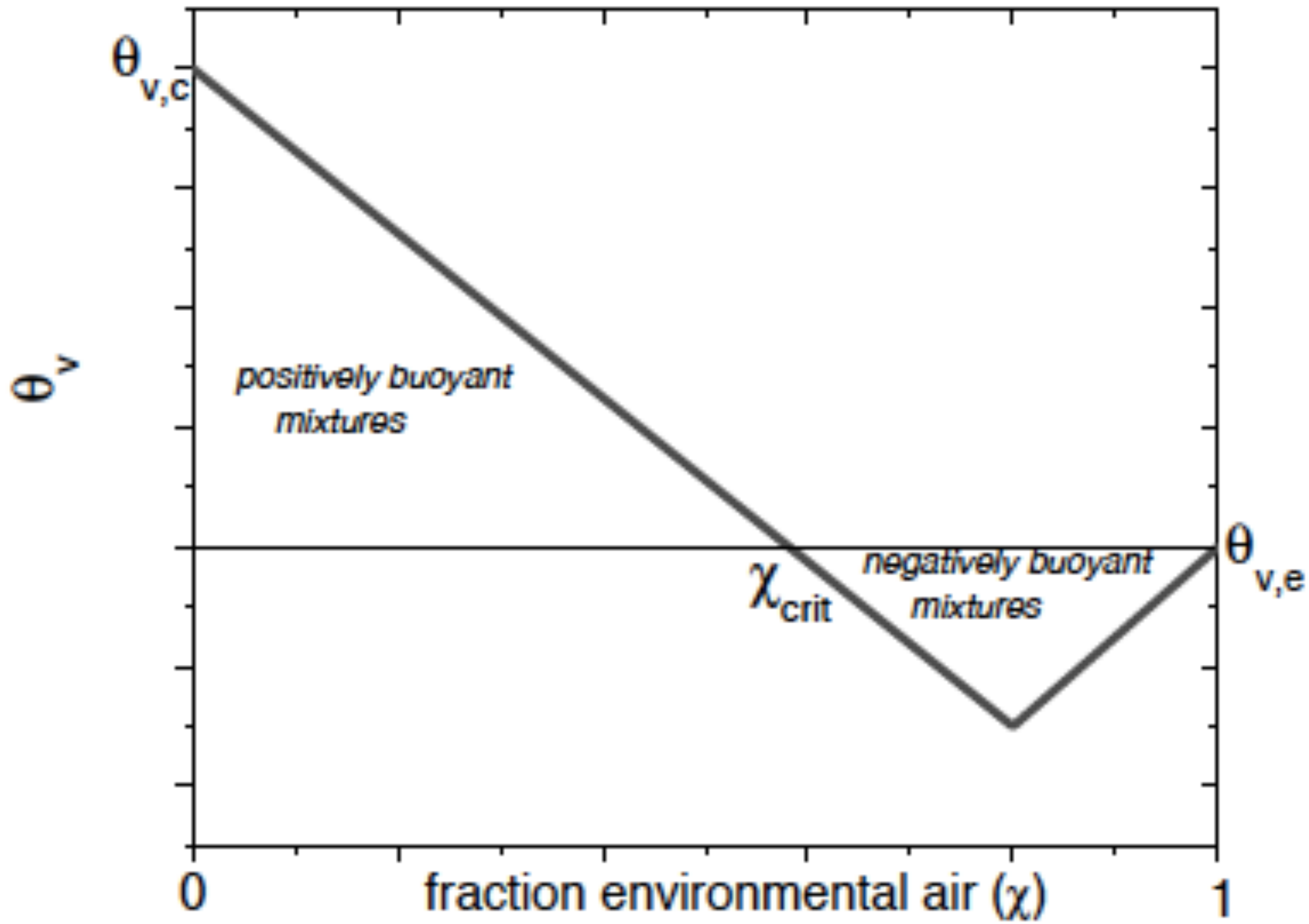


Figure 4. Paths of particles of fluid relative to the thermal and computed from the average velocities presented in Fig. 2.

Streamlines in a thermal

Woodward 1959 QJ

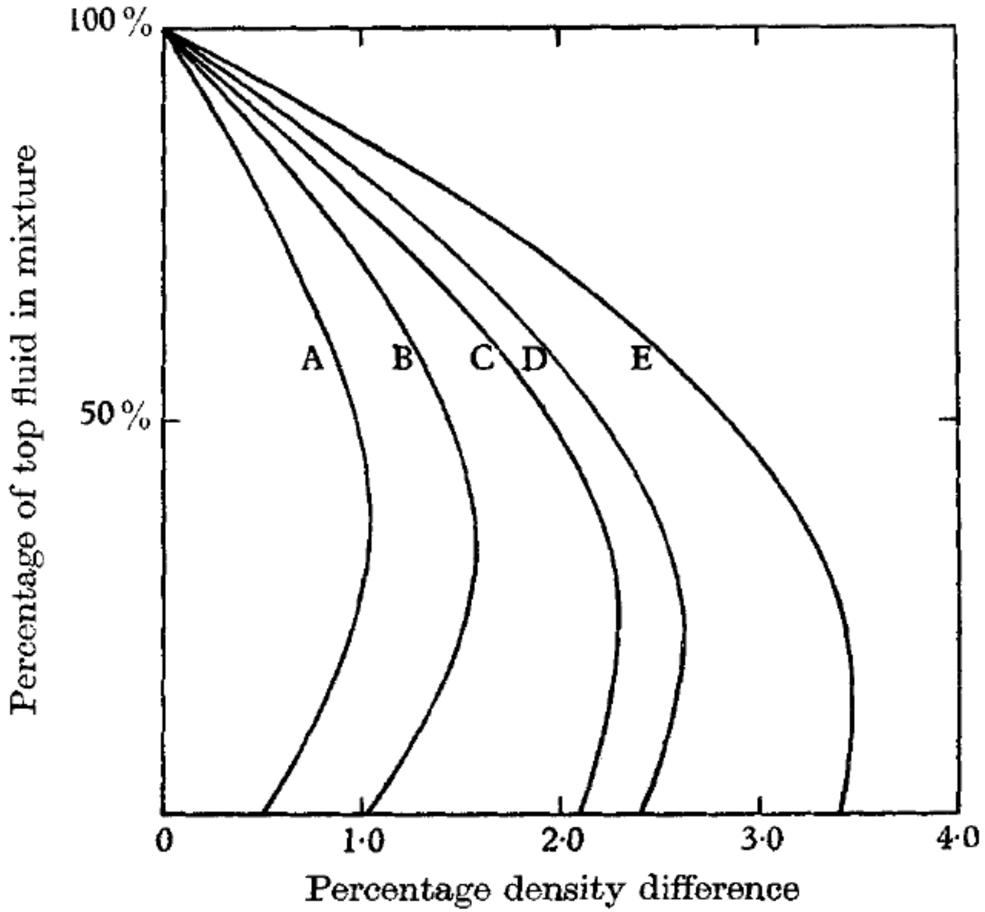
Clouds are different



Cloud air

Environmental air

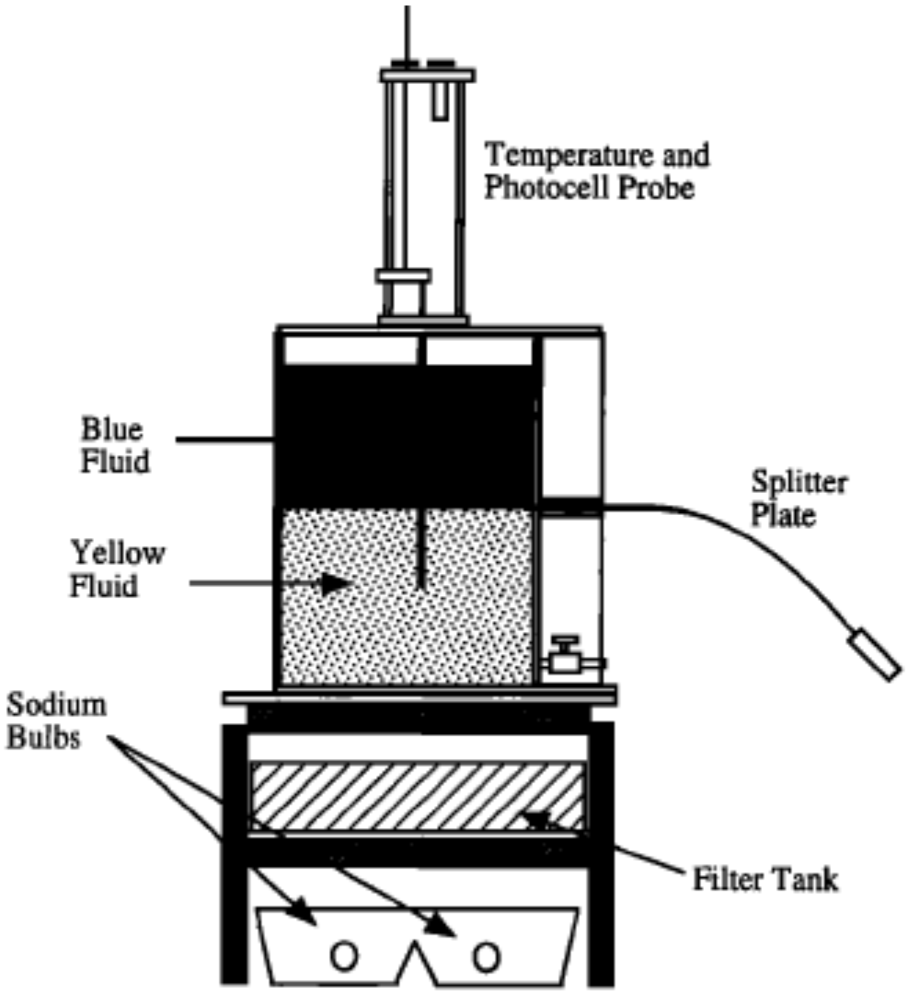
Alcohol with ethylene glycol in various proportions mixing with water

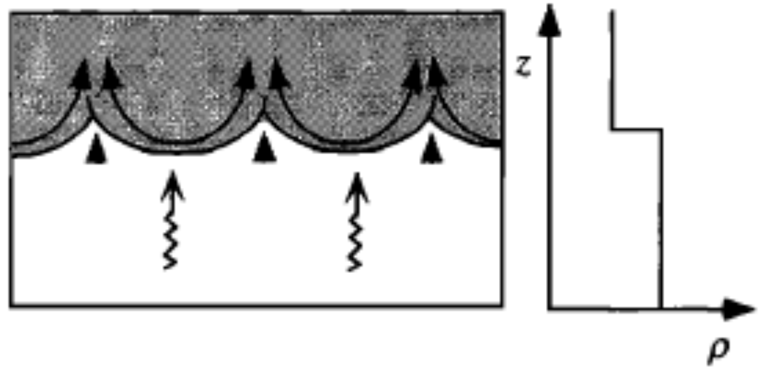


Turner and Yang, 1963, JFM

FIGURE 2. The measured density behaviour of mixtures of the 'non-linear' fluids used in our experiments. The curves have been plotted for clarity with respect to the density of the top layer, although in practice both densities were varied by a few percent to obtain the desired behaviour.

Cloud-top radiative cooling





Sayler and Breidenthal, 1998, JGR

Condensational heating represented through Ohmic dissipation

Narasimha et al., PNAS, 2011

Aircraft Observations

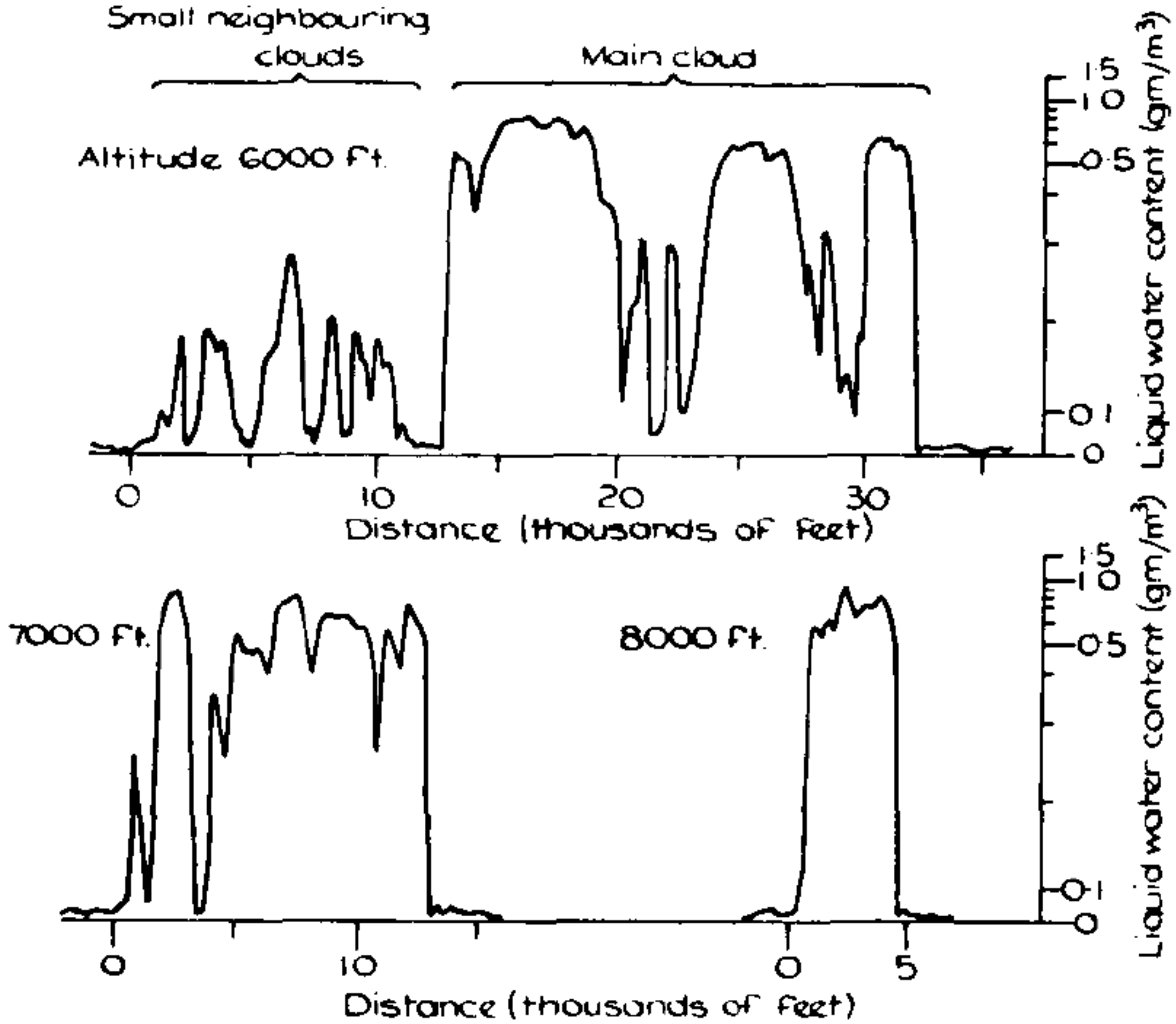
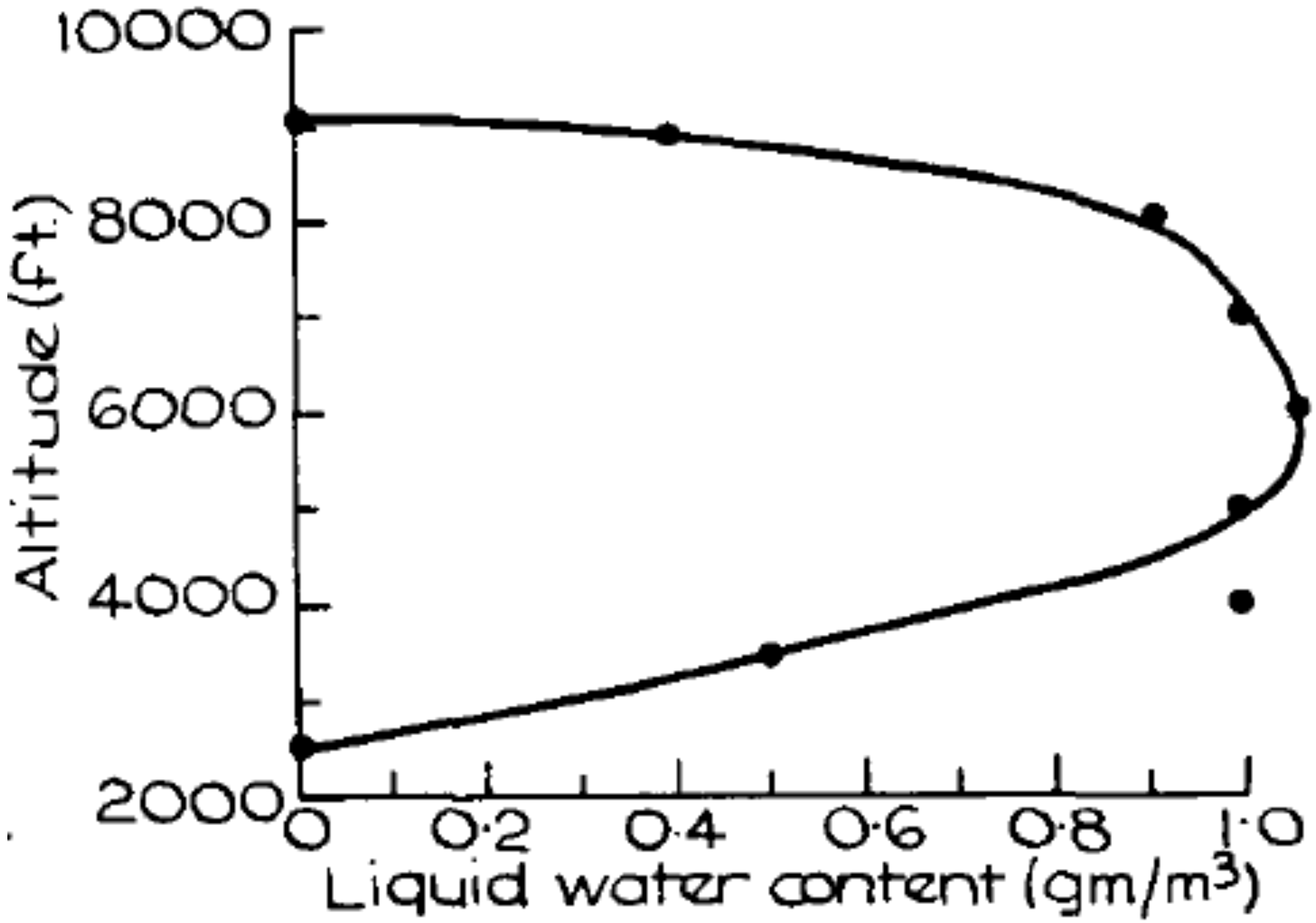
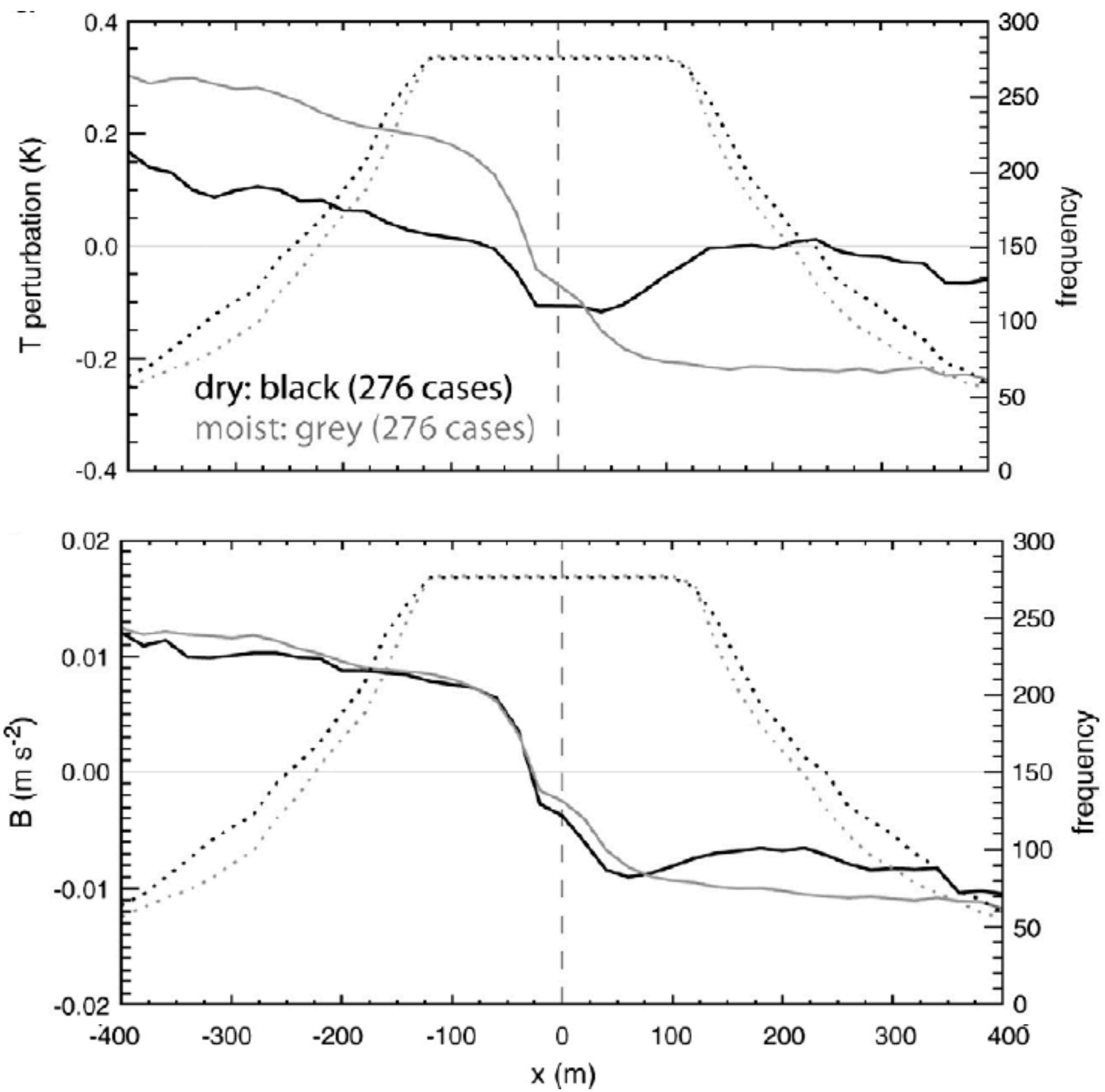


Fig. 3. Successive traverses through cumulus cloud at 6,000, 7,000 and 8,000 ft. Cloud base 3,000 ft, temperature 18·3° C; top 9,300 ft, 7·2° C.

Warner 1955

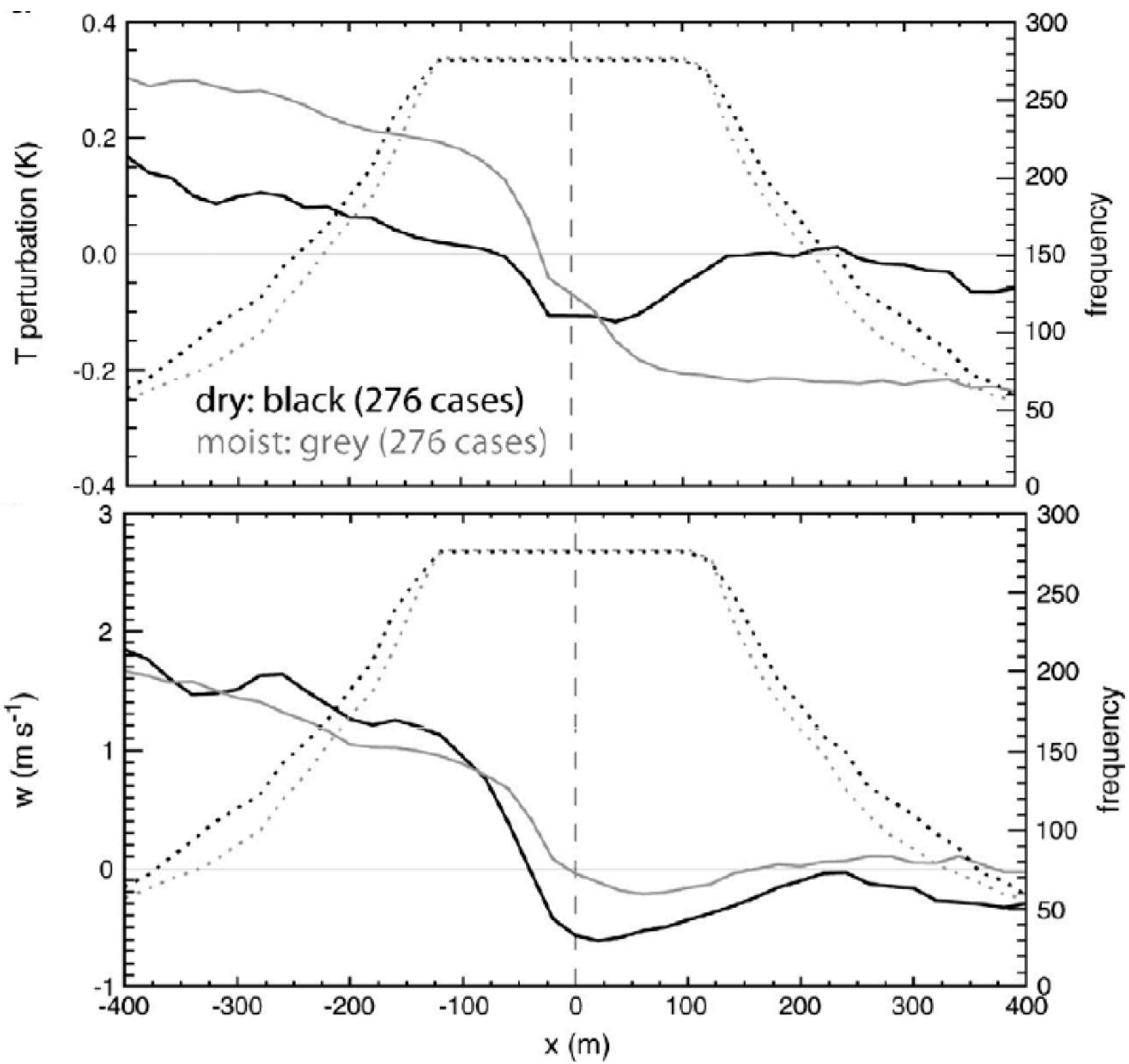

10000
8000
6000
4000
2000
Altitude (ft.)
0
0·2
0·4
0·6
0·8
1·0
Liquid water content (gm/m3)

Warner 1955



A more recent example from RICO

Wang and Geerts, 2010



A more recent example from RICO

Wang and Geerts, 2010

Flights through cumulonimbus

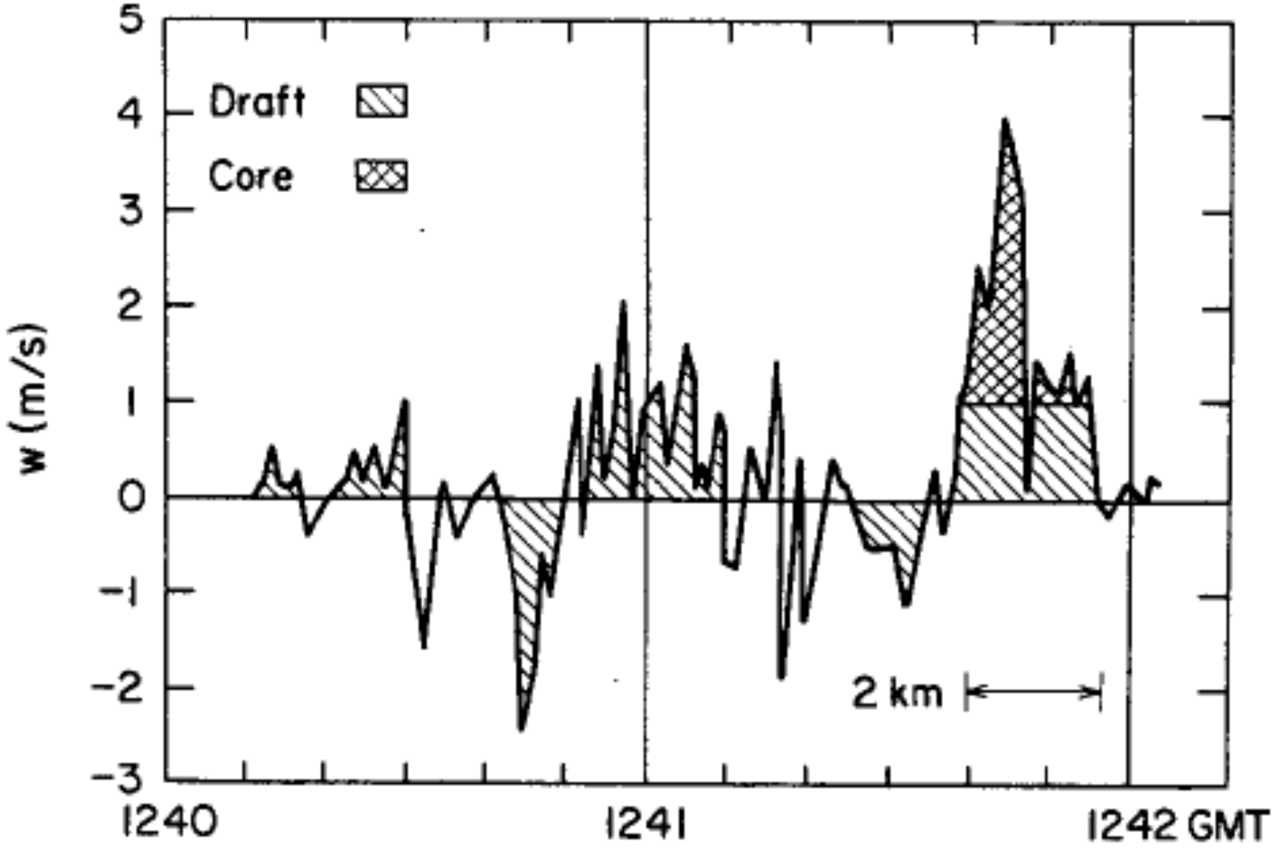
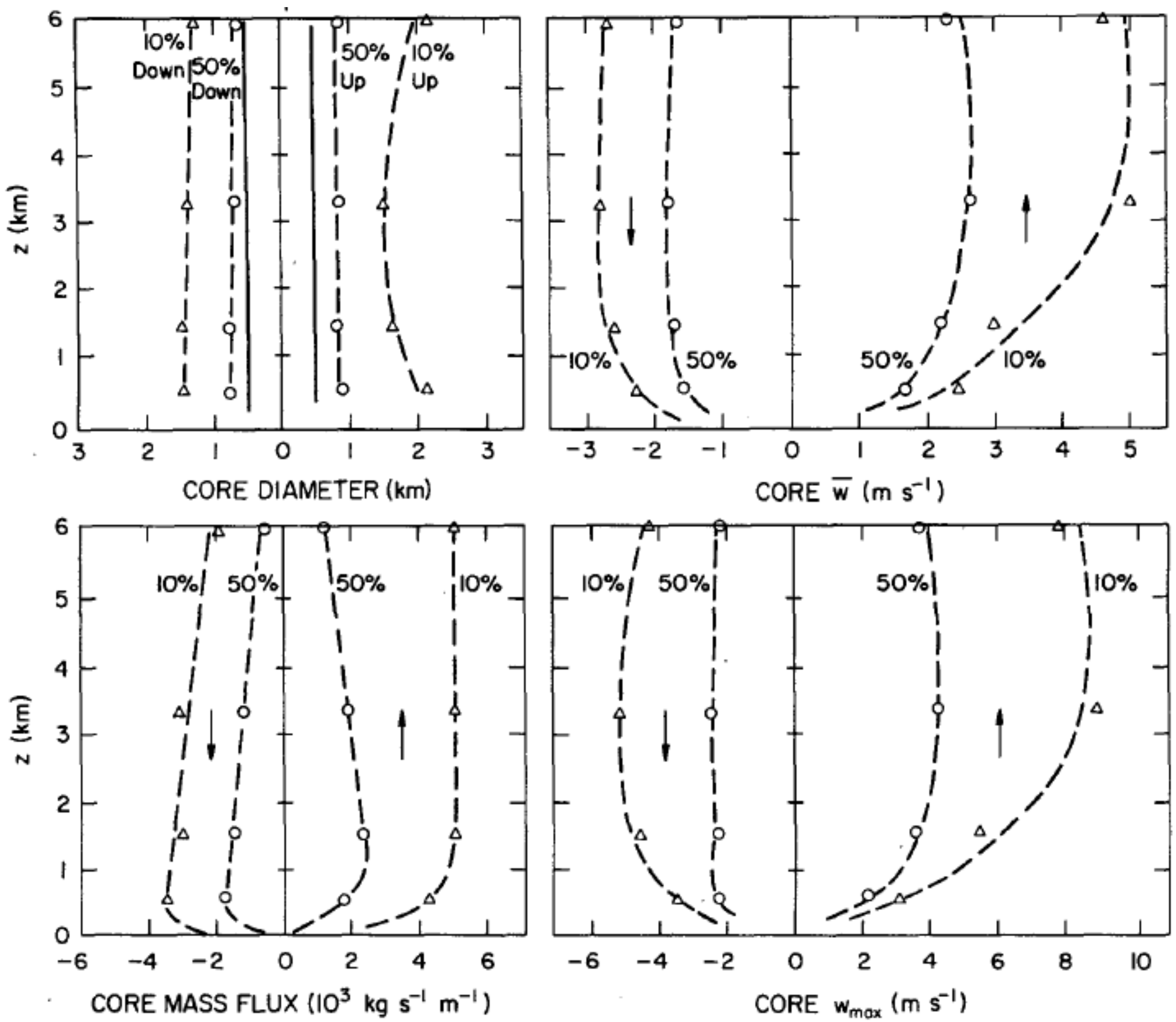


FIG. 2. Time series illustrating definition of drafts and cores, adapted from US C-130 at 5471 m, Day 257. An updraft has to reach 0.5 m s^{-1} and be positive for 0.5 km (~5 s) or more; a core has to have w of at least 1 m s^{-1} for 0.5 km or more. Downdrafts and downdraft cores are defined in the same way. Note that the draft at the right has two cores.

Lemone and Zipser, 1980



Lemone and Zipser, 1980

FIG. 5. Variation with altitude of median (50%) and 10% level (stronger than 90% of the population) updraft and downdraft cores, with respect to core diameter, mean vertical velocity of cores, maximum 1 s vertical velocity within core, and core mass flux.

Stith, 1992, JAS

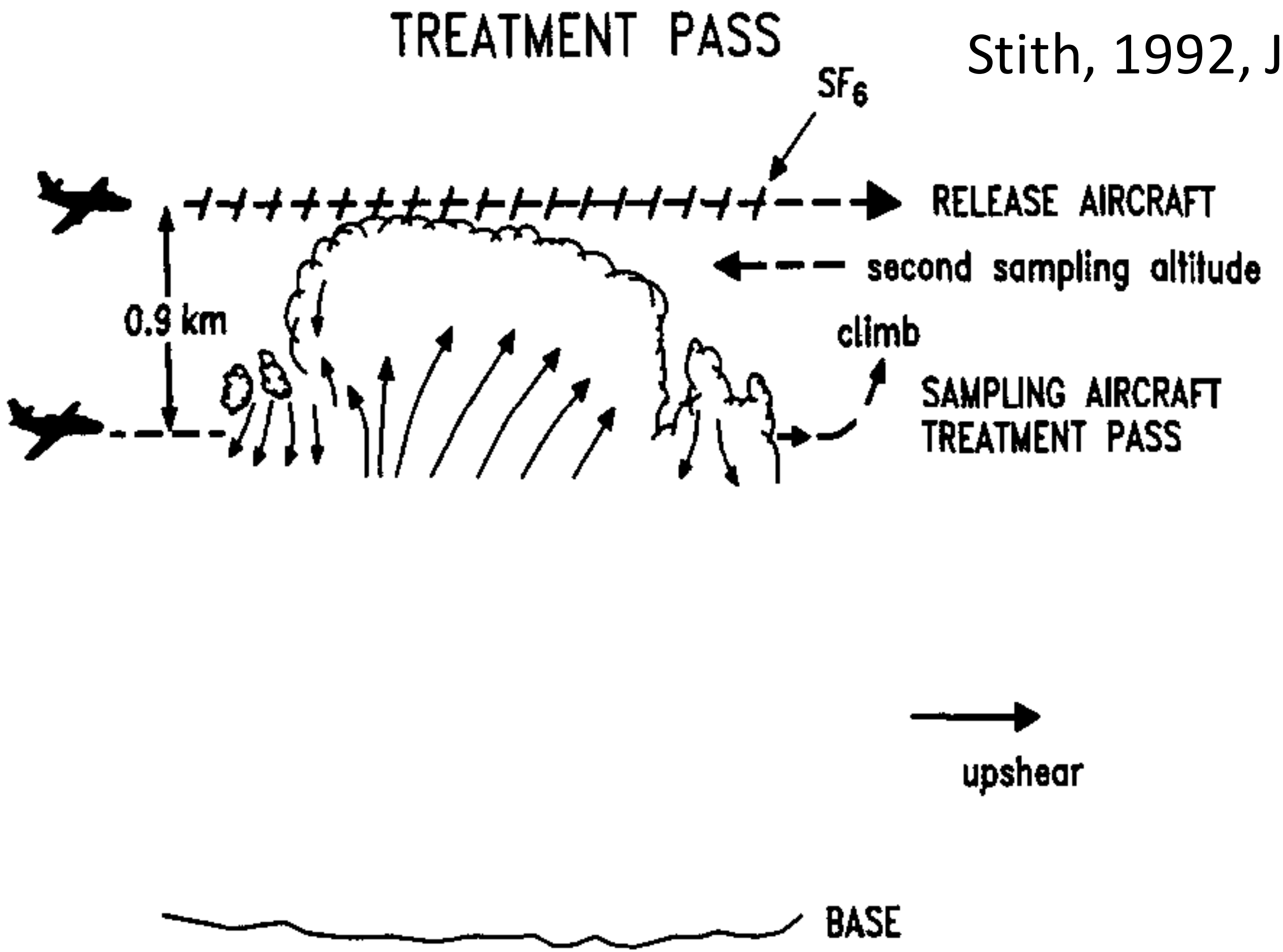
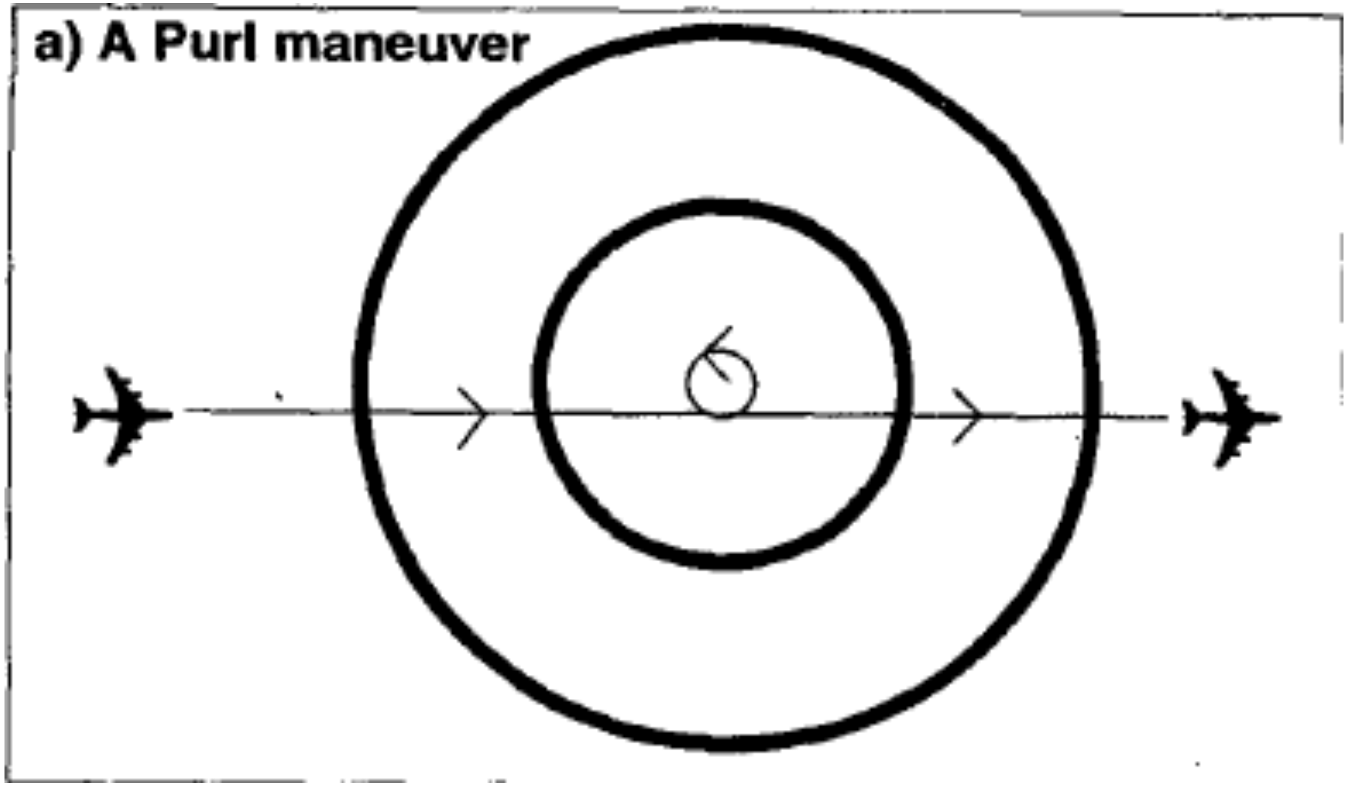


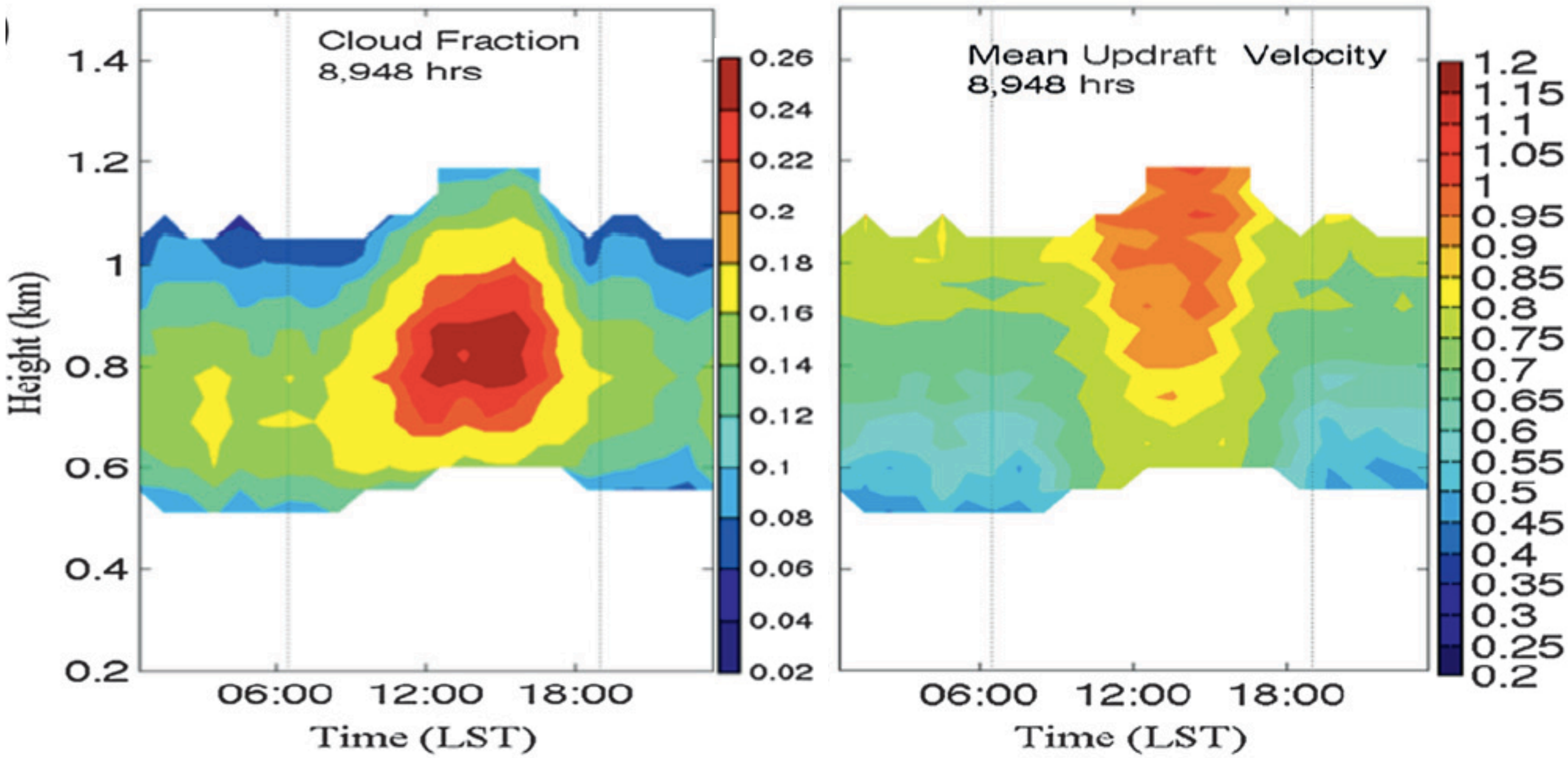
FIG. 1. Diagram of the aircraft sampling and treatment experiment as applied to the cloud on 22 June 1989. See text for more details.

Use divergence theorem

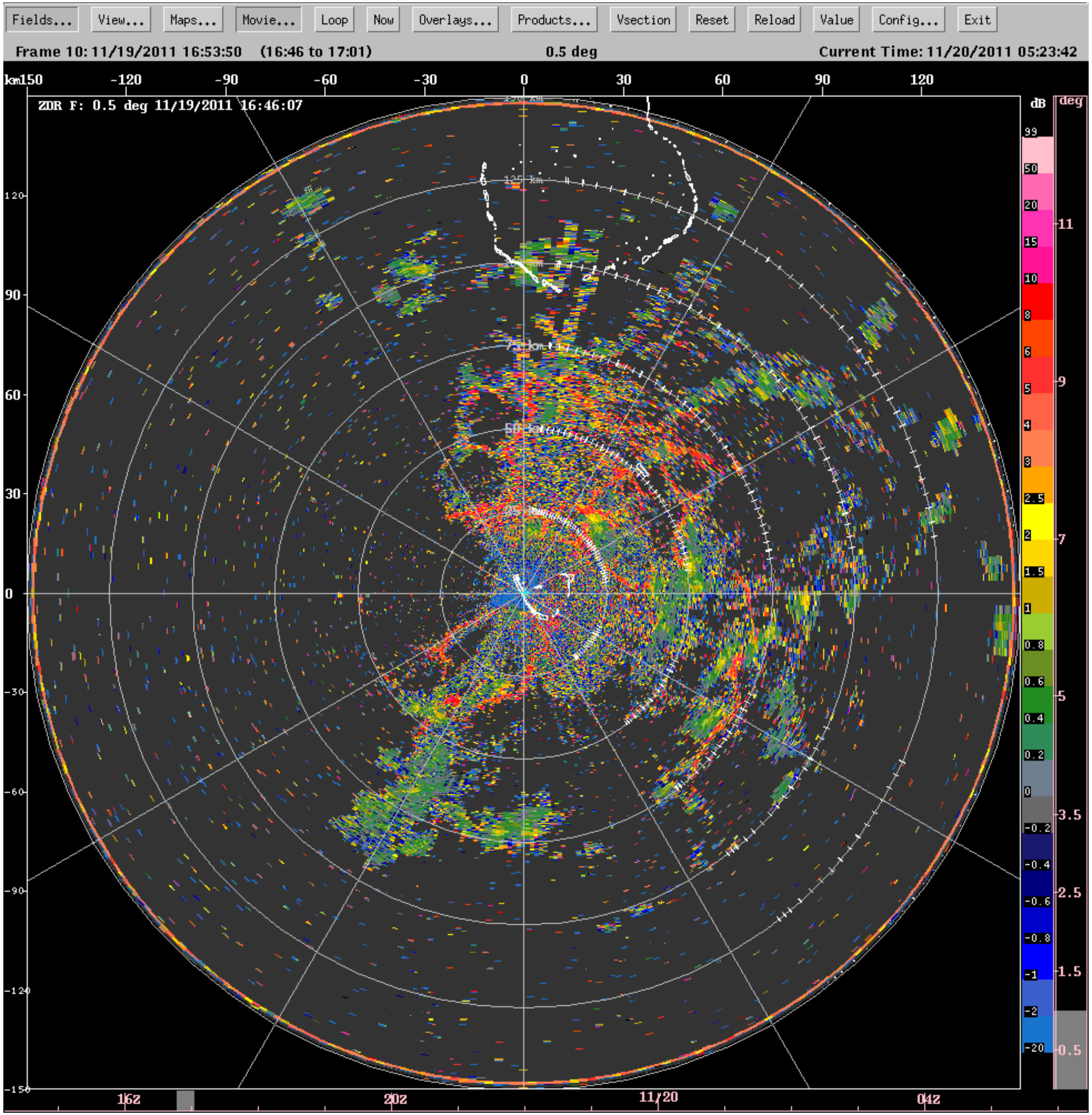
(Mapes and Houze 1995)



Profiling cloud radar



Kollias and Albrecht, 2010



Fields...
View...
Maps...
Movie...
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Now
Overlays...
Products...
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Reset
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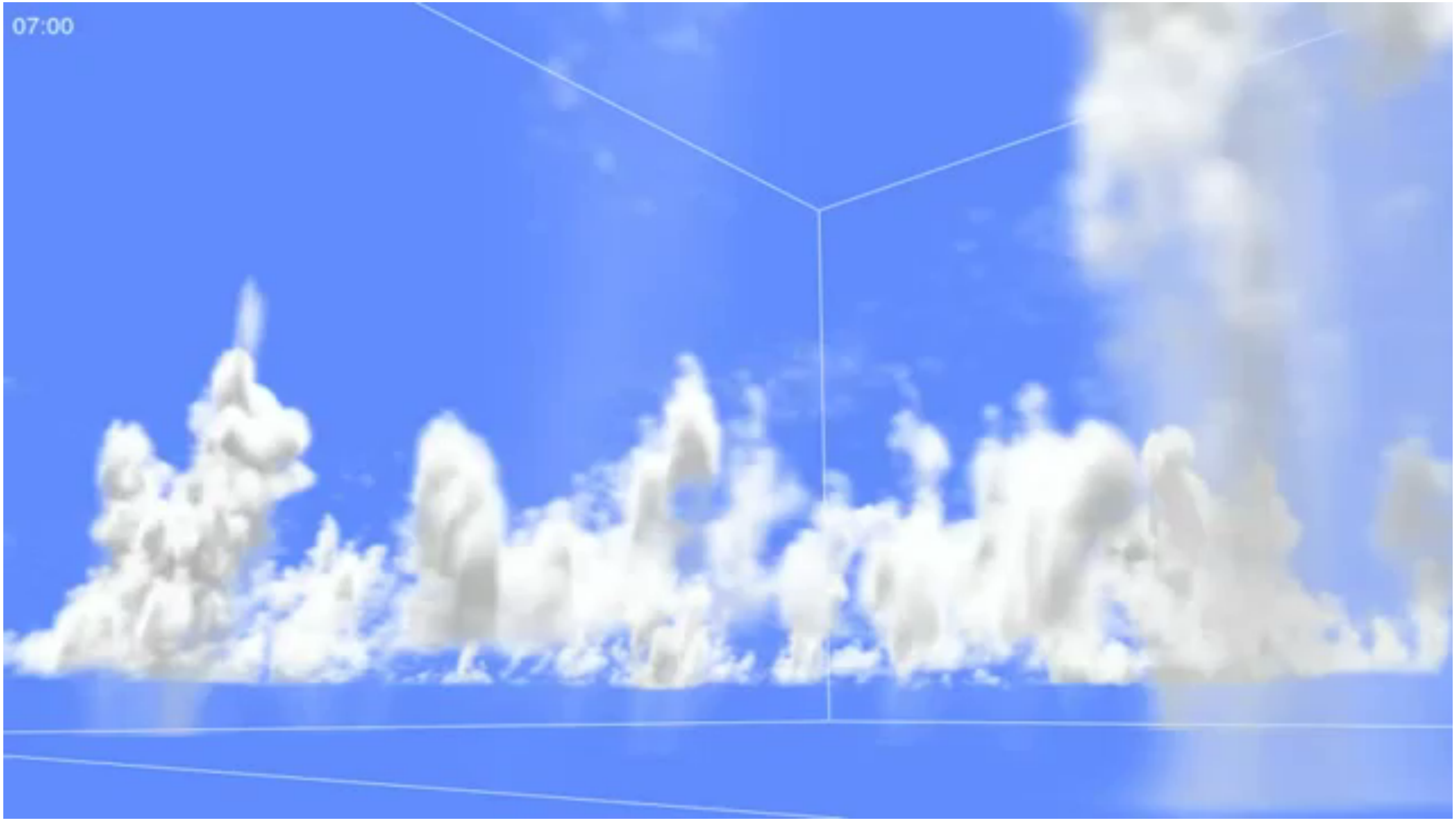
Value
Config...
Exit
Frame 10: 11/19/2011 16:53:50 (16:46 to 17:01)
0.5 deg
Current Time: 11/20/2011 05:23:42
ZDR F: 0.5 deg 11/19/2011 16:46:07
km
dB
deg
16Z
20Z
11/20
04Z

Cloud-resolving models



Credit: P. Siebesma, Delft U. Technology, Netherlands, computation done on a GPU

Supercell

- The models, though very impressive, are not perfect.
- Even if they were, how to make sense of the huge amount of data?
- If all I get is a movie, I would prefer watching clouds from a sunny beach

Blyth et al., 1988

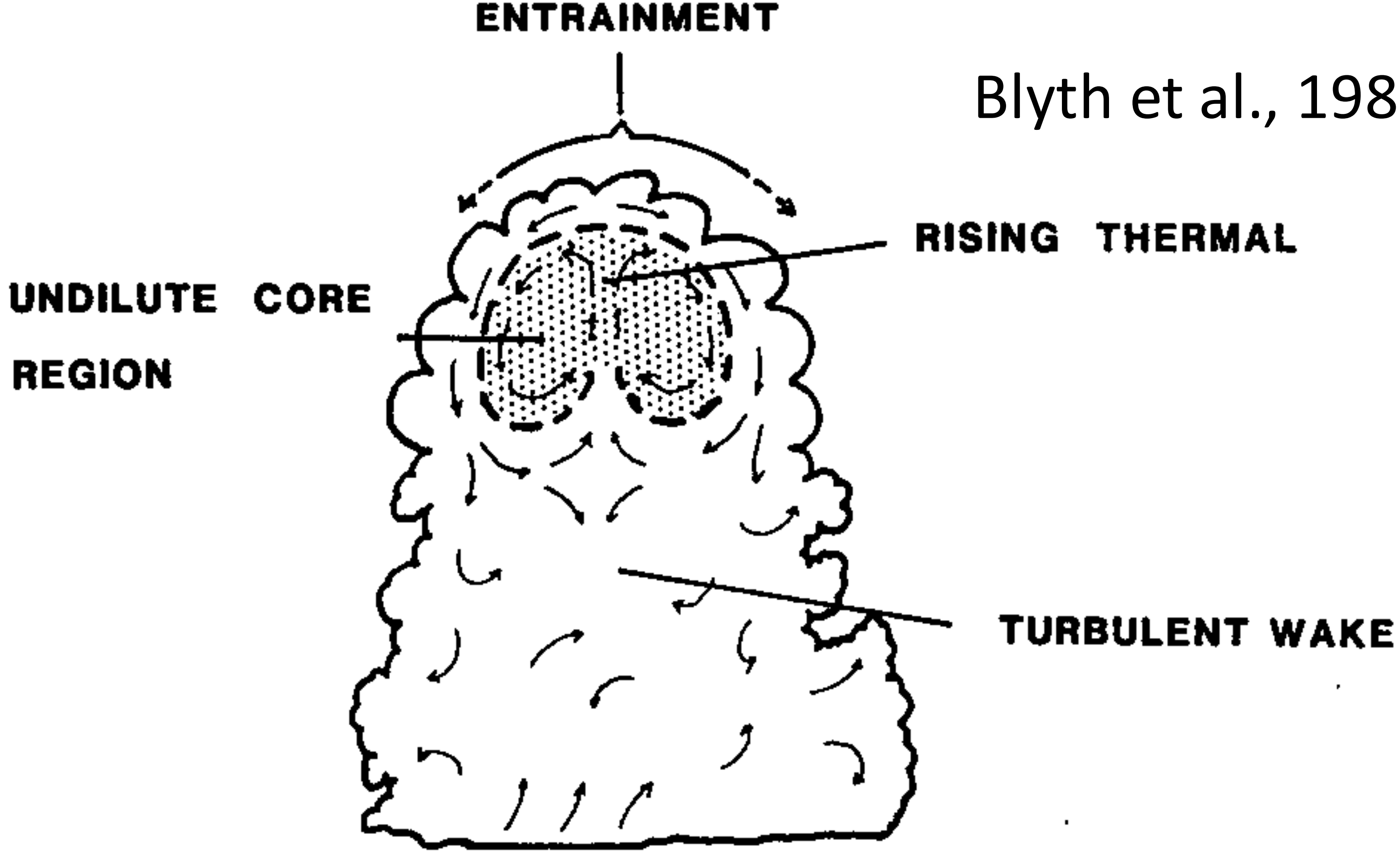
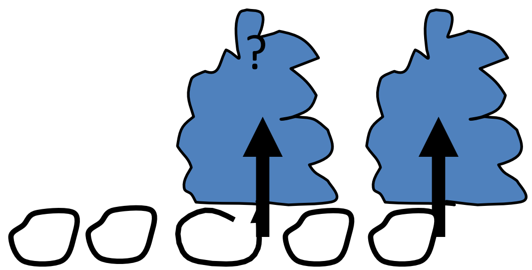


FIG. 14. Schematic model of a cumulus cloud showing a shedding thermal that has ascended from cloud base. Continuous entrainment into the surface of the thermal erodes the core, and the remaining undiluted core region continues its ascent, leaving a turbulent wake of mixed air behind it. See text for further discussion.

How to represent an ensemble of cumulus clouds? (a.k.a. cumulus parameterization)

Ingredients of mass flux schemes:

1. Trigger
2. Cloud base properties
3. Cloud model (depth, mixing dynamics, microphysics)
4. Mass-flux closure
5. Precipitation-driven downdrafts
6. Mesoscale organization
7. Stratiform microphysics



Despite 40 years evolution, all are controversial.

Shallow cumulus convection

- Shallow Cu are best starting point for Cu parameterization.
- They are well studied from a sunny beach

- No rain, nasty mesoscale stuff or mysterious ice processes

…just the pure joy of moist turbulence.

Slide by Chris Bretherton

Statistical closure v.s. deterministic cartoon

Statistical closure

$$\left(\frac{\partial \bar{a}}{\partial t}\right)_{\text{turb}} = -\frac{\partial}{\partial z}\left(\overline{w'a'}\right)$$

$$\frac{\partial}{\partial t}\left(\overline{w'a'}\right) = -\overline{w'w'}\frac{\partial \bar{a}}{\partial z} - \frac{\partial}{\partial z}\overline{w'w'a'} + \overline{a'b'} - \frac{1}{\rho}\overline{a'\frac{\partial p'}{\partial z}}$$

……

Parameterize high-order terms in terms of low order terms

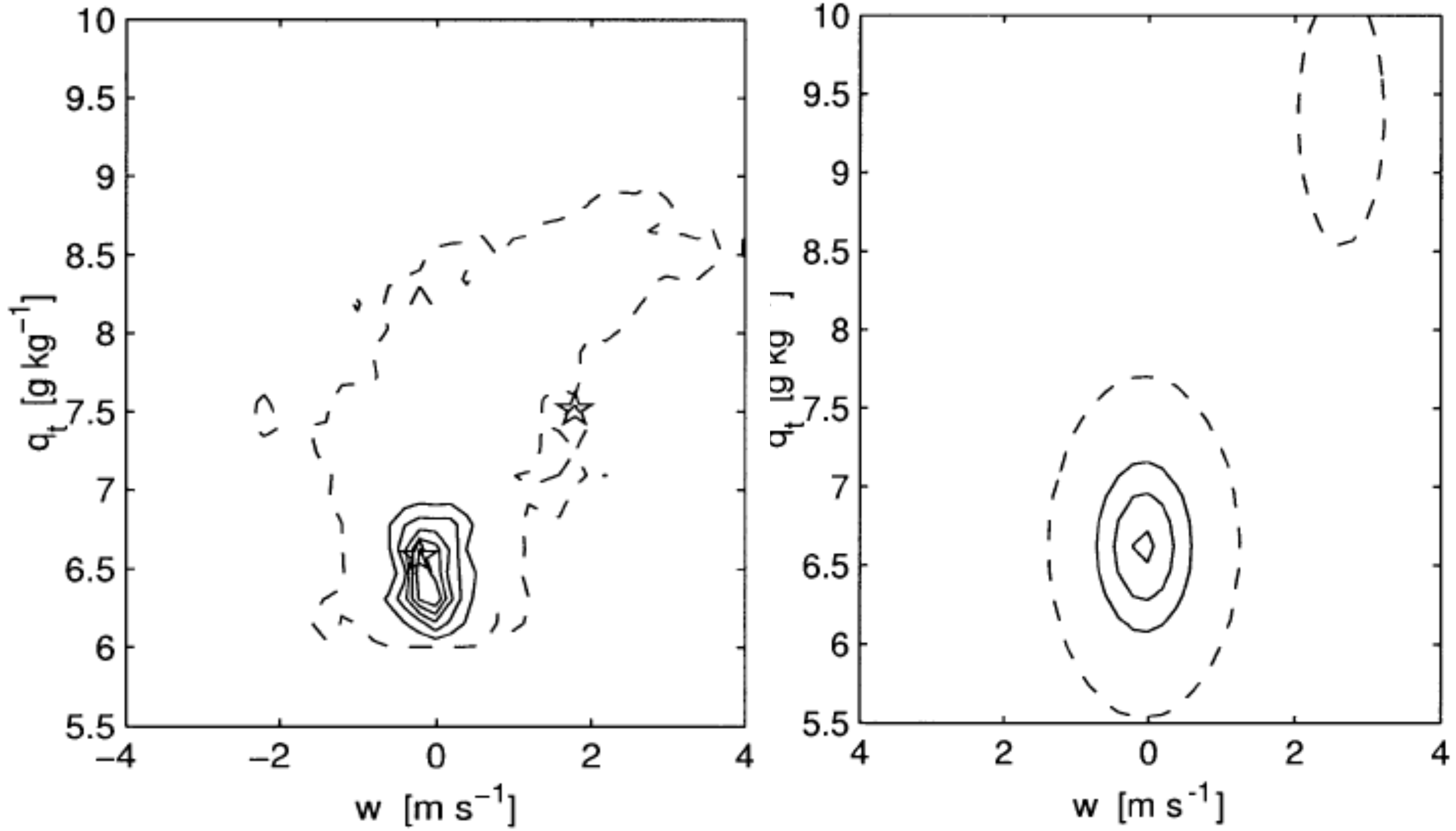
$$\overline{w'a'} = -K_a \frac{d\overline{a}}{dz}$$

Eddy diffusivity closure

Assumed PDF approach

If the PDFs of different variables are assumed to take a particular functional form, the number of parameters that are needed to fully describe the PDF is finite and closure becomes possible.

Double-Gaussian



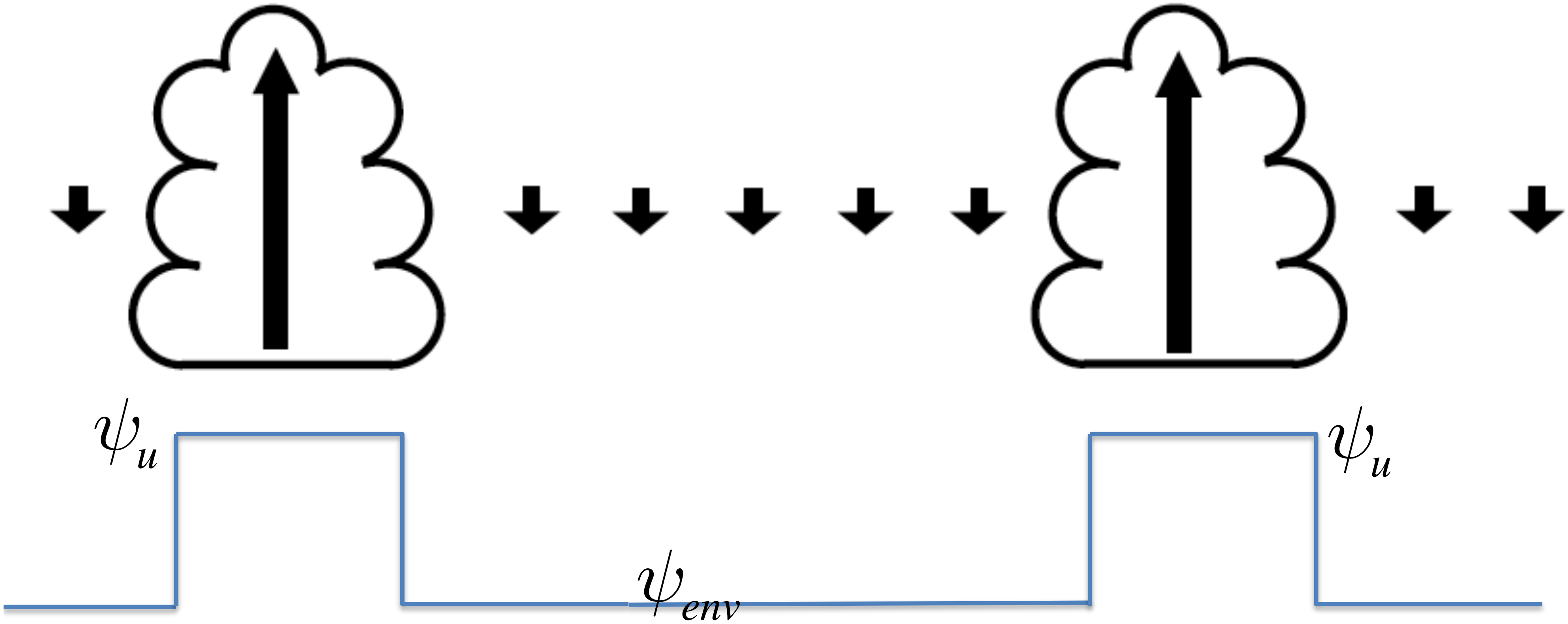
Larson et al., 2002

- Pros: make use of the underlying equations; appear to work well for stratocumulus and trade cumulus despite the approximations.
- Cons: need to track a quite large number of moments and the number of moments increases exponentially as chemical species are included; do not include information on the structures.

Deterministic cartoon

Bulk plume models

Assume clouds at a given height have uniform properties, and so does the environment



$$\rho \overline{w'\psi'} \approx M_u(\psi_u - \overline{\psi})$$ where M_u is the updraft mass flux

$$M_u = \rho_u \sigma_u w_u$$

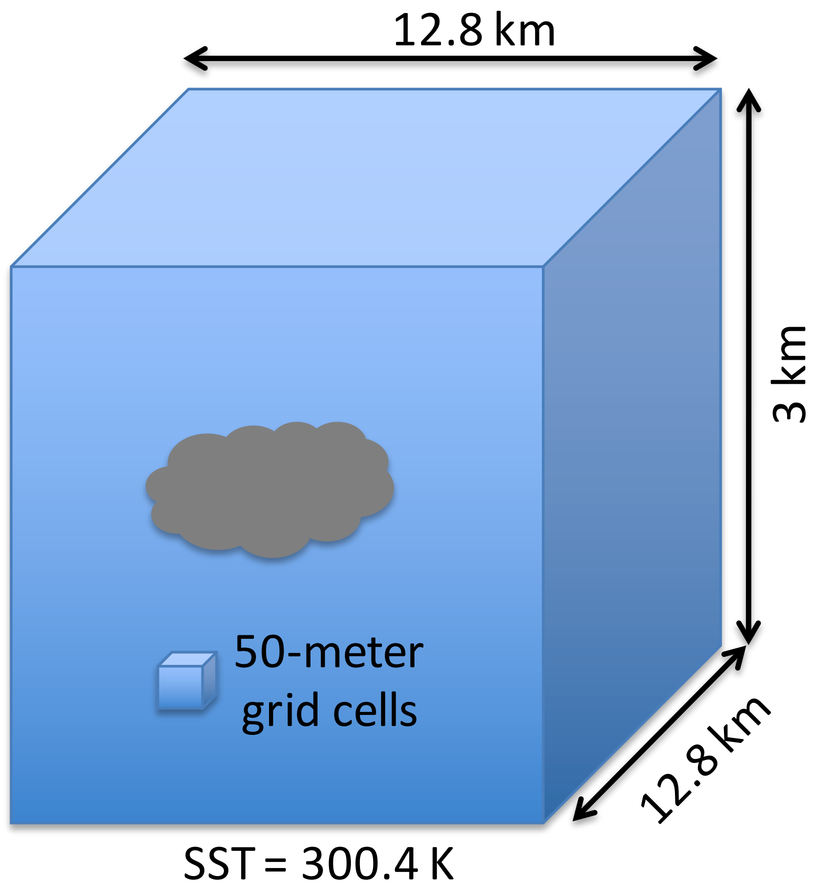
Bulk plume models

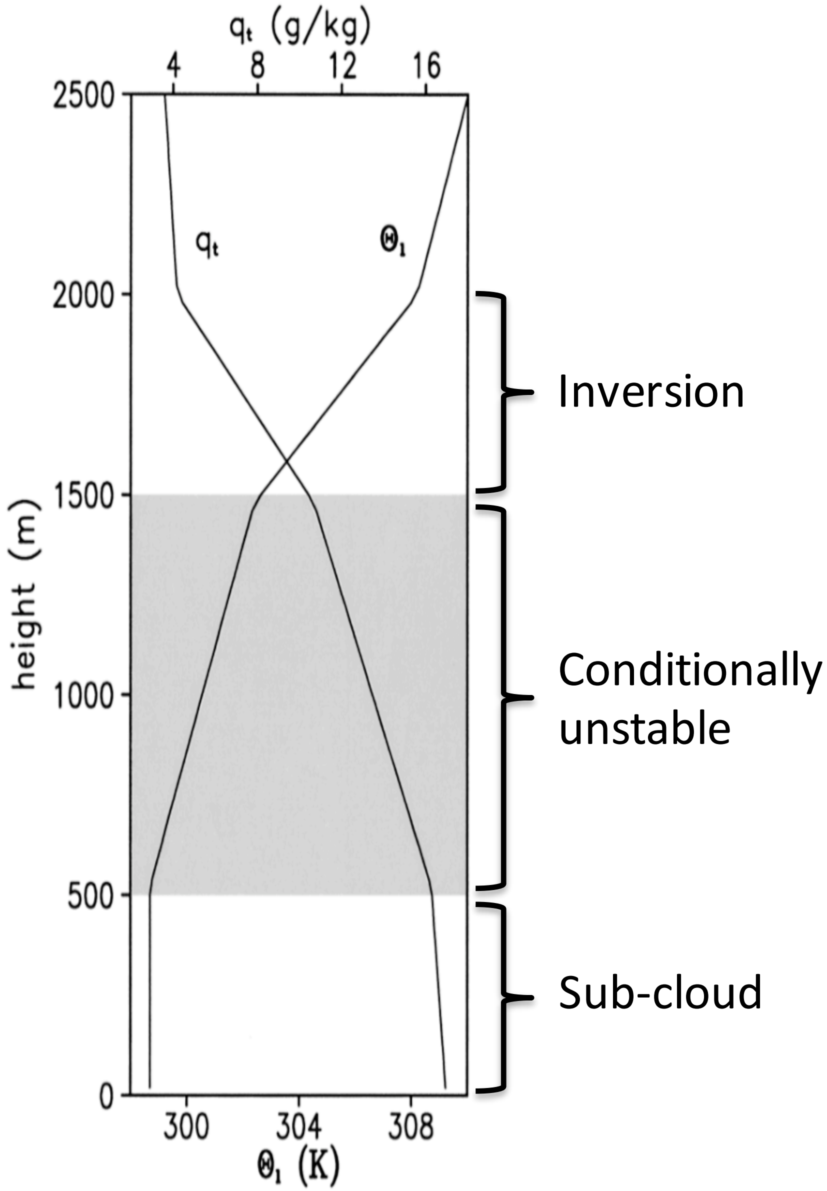
Cloud model

$$\frac{\partial M_u}{\partial z} = M_u(\varepsilon - \delta),$$

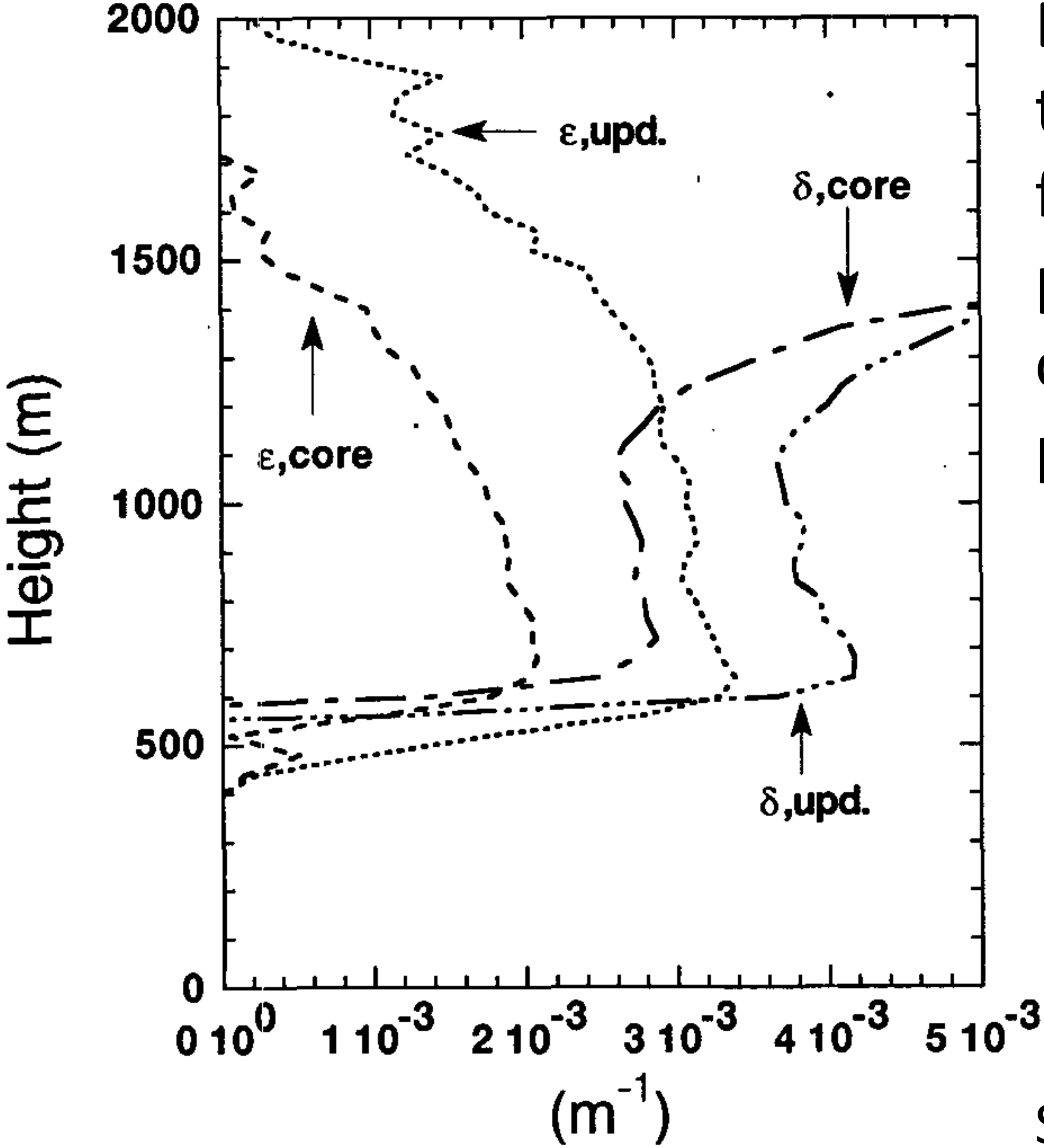
$$\frac{\partial \psi_u}{\partial z} = \varepsilon(\overline{\psi} - \psi_u) + S_\psi.$$

Large-Eddy Simulations of BOMEX





(Siebesma et al., JAS, 2003)

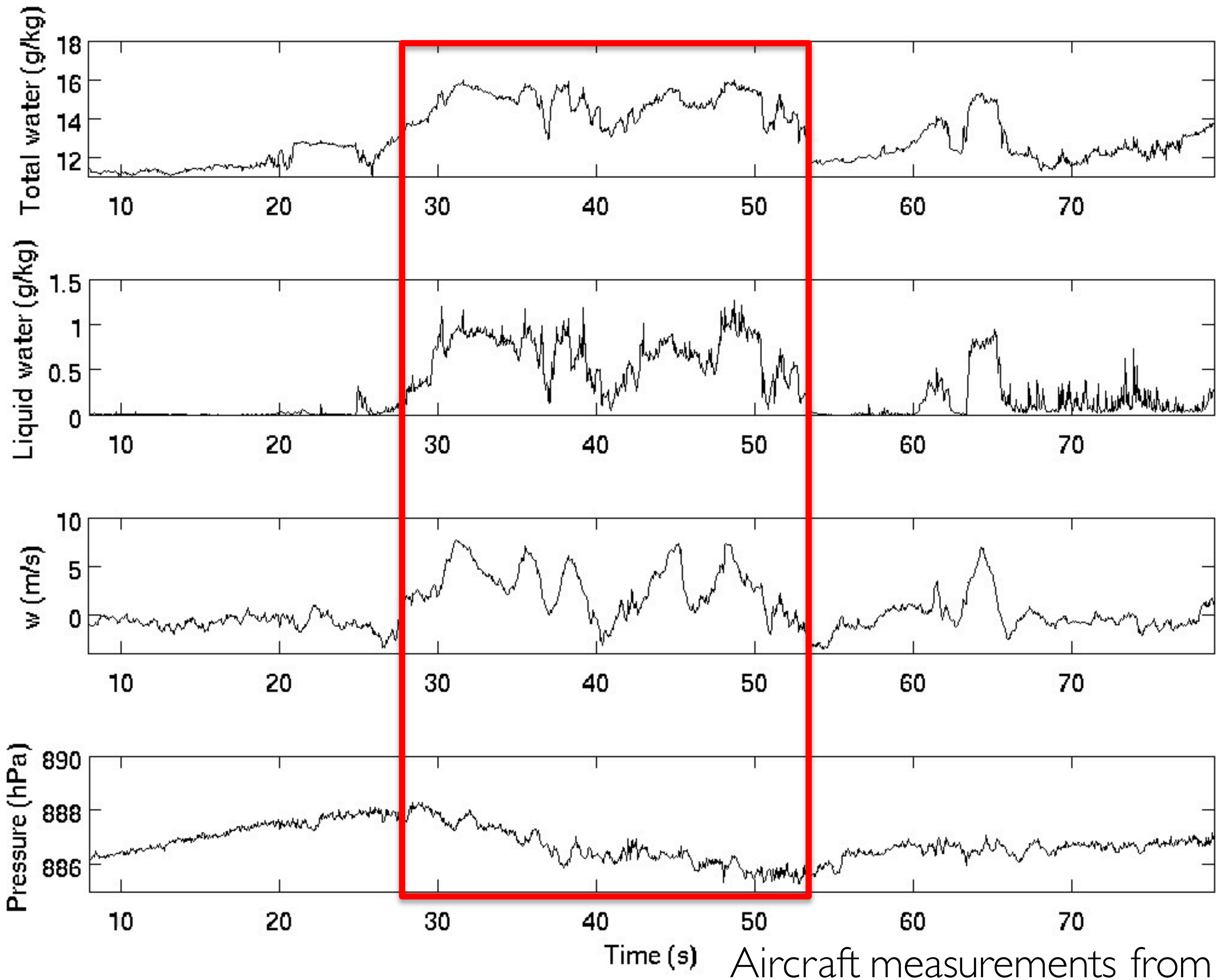


Detrainment/entrainment rates can be diagnosed from LES/CRM, and provide valuable constrains on parameterizations.

Siebesma and Cuijpers, 1995

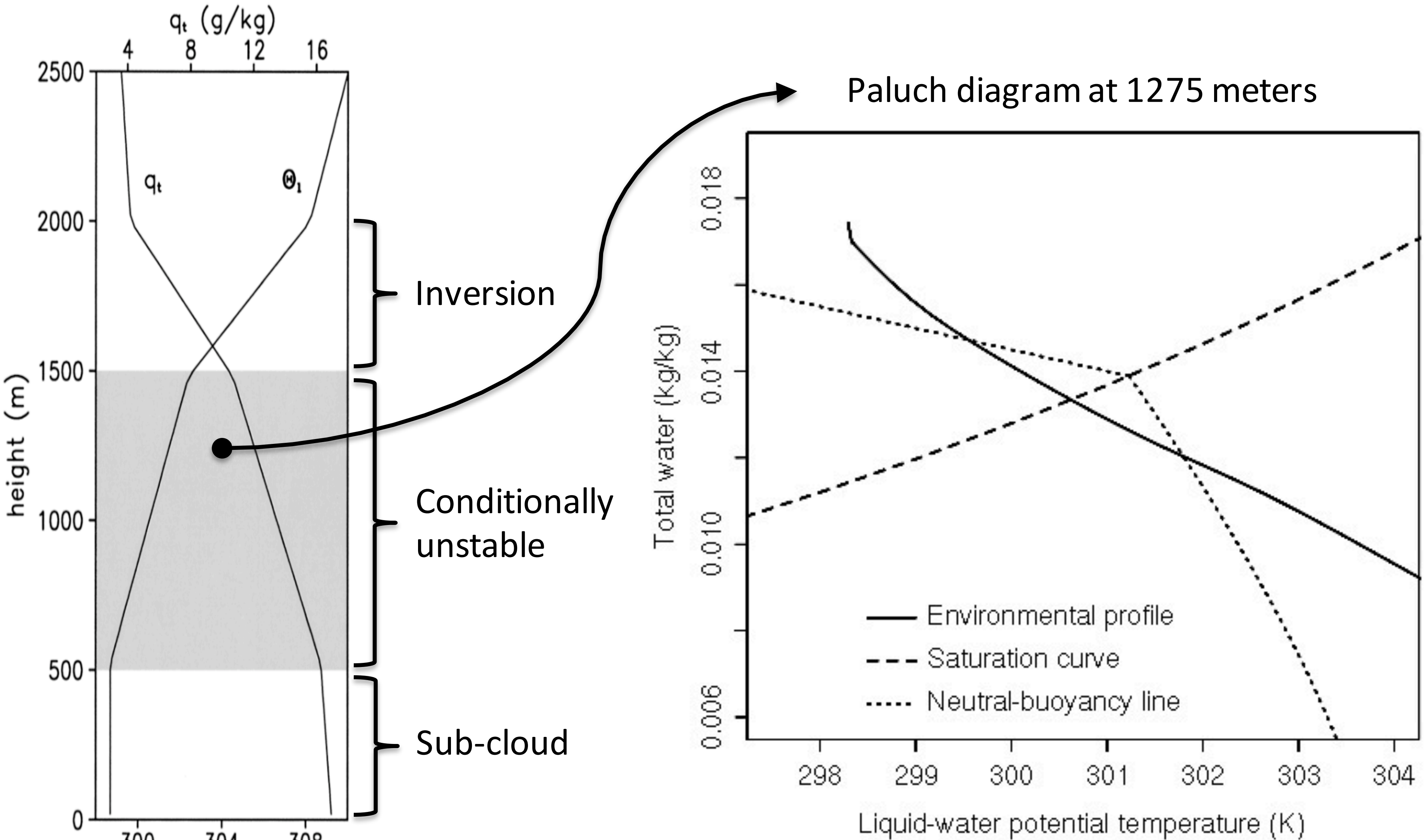
FIG. 11. Fractional entrainment ϵ and detrainment δ rate for both the core and the updraft decomposition averaged over the last 4 h.

Real clouds are certainly heterogeneous



Aircraft measurements from RICO campaign

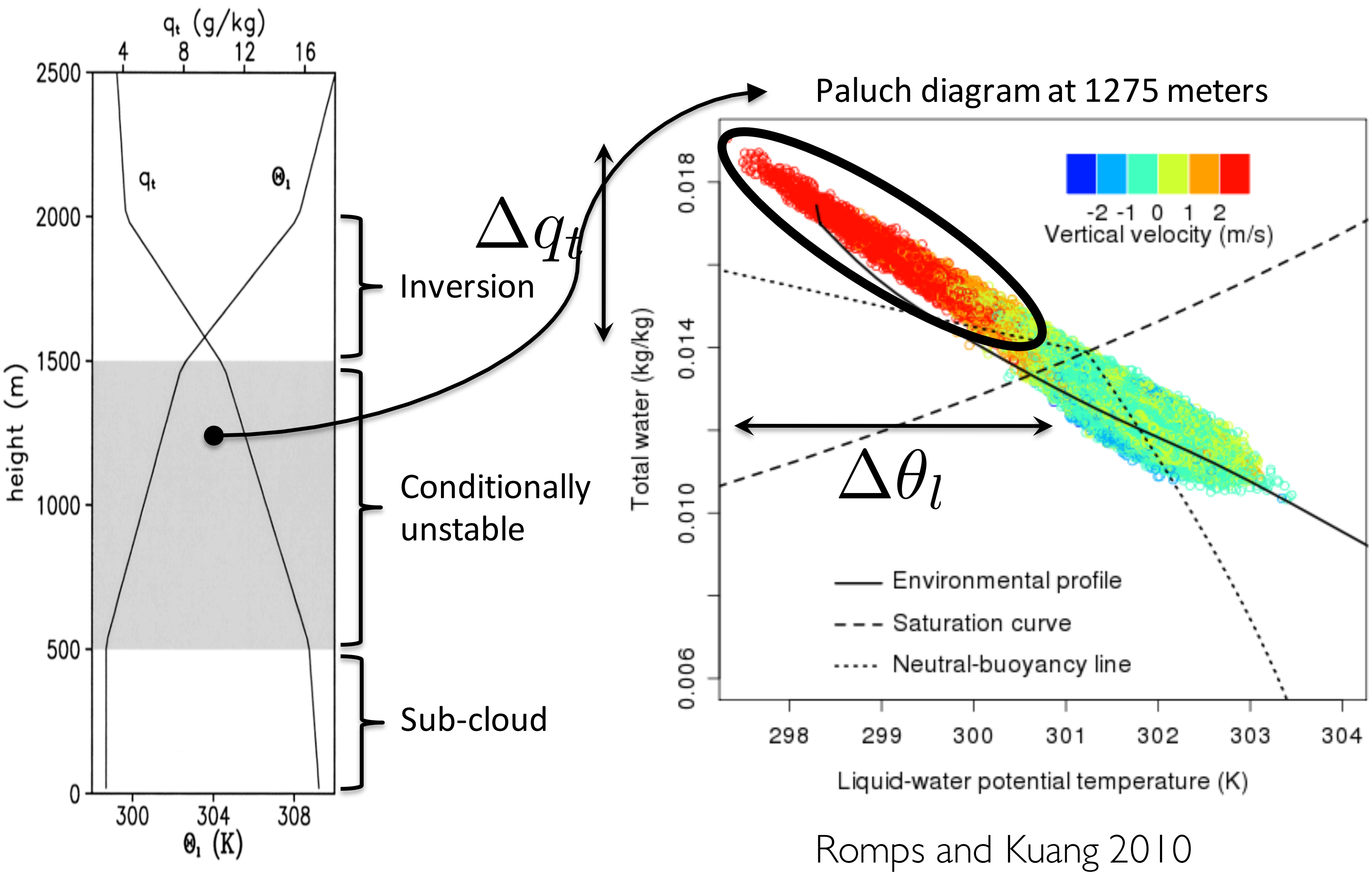
The "Paluch tail"



(Siebesma et al., JAS, 2003)

Romps and Kuang 2010
Following Paluch, 1979, JAS

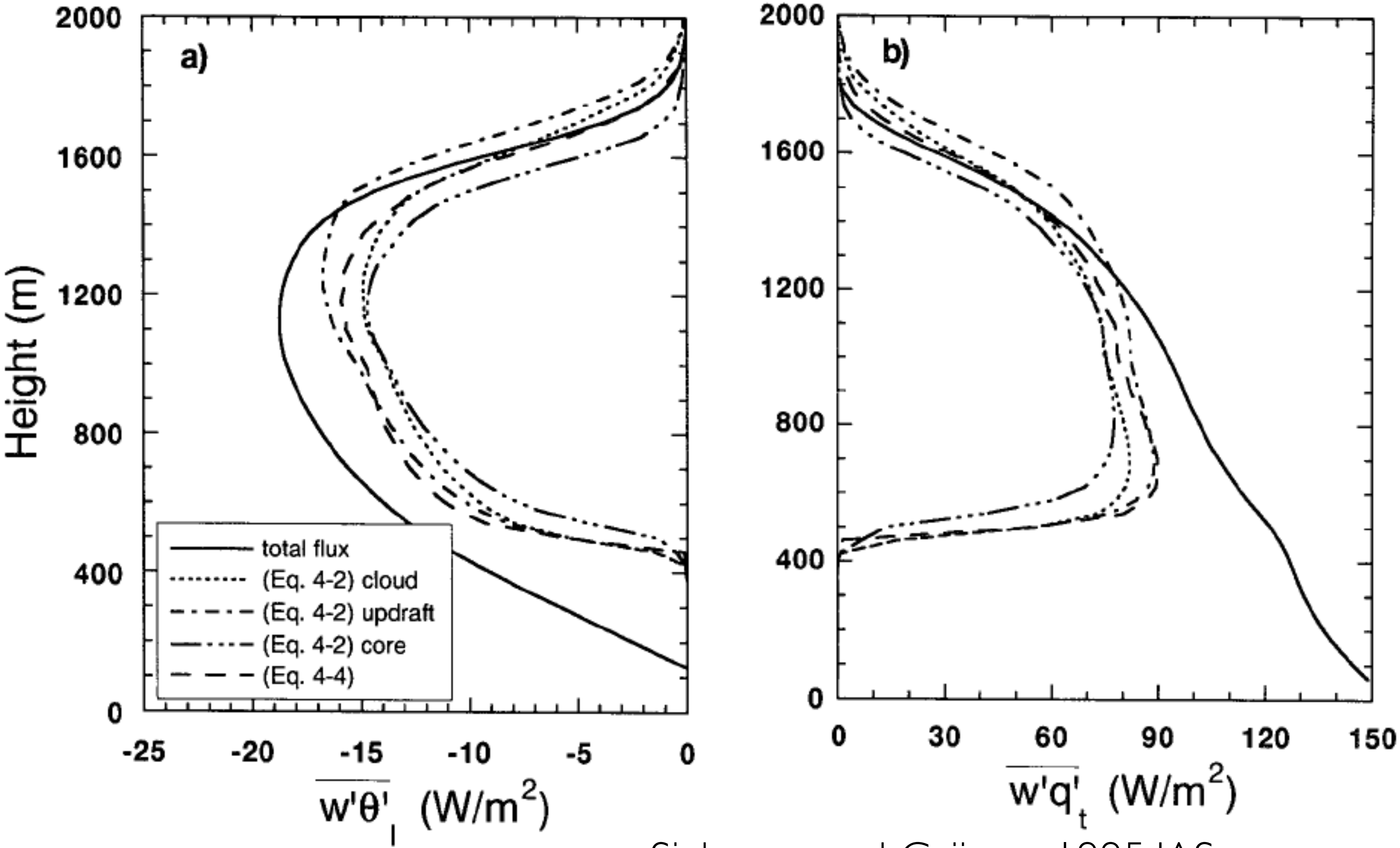
The "Paluch tail"



(Siebesma et al., JAS, 2003)

Romps and Kuang 2010
Following Paluch, 1979, JAS

- Despite the bold simplification, bulk plumes represent fluxes in the cloud layer reasonably well



Siebesma and Cuijpers 1995 JAS

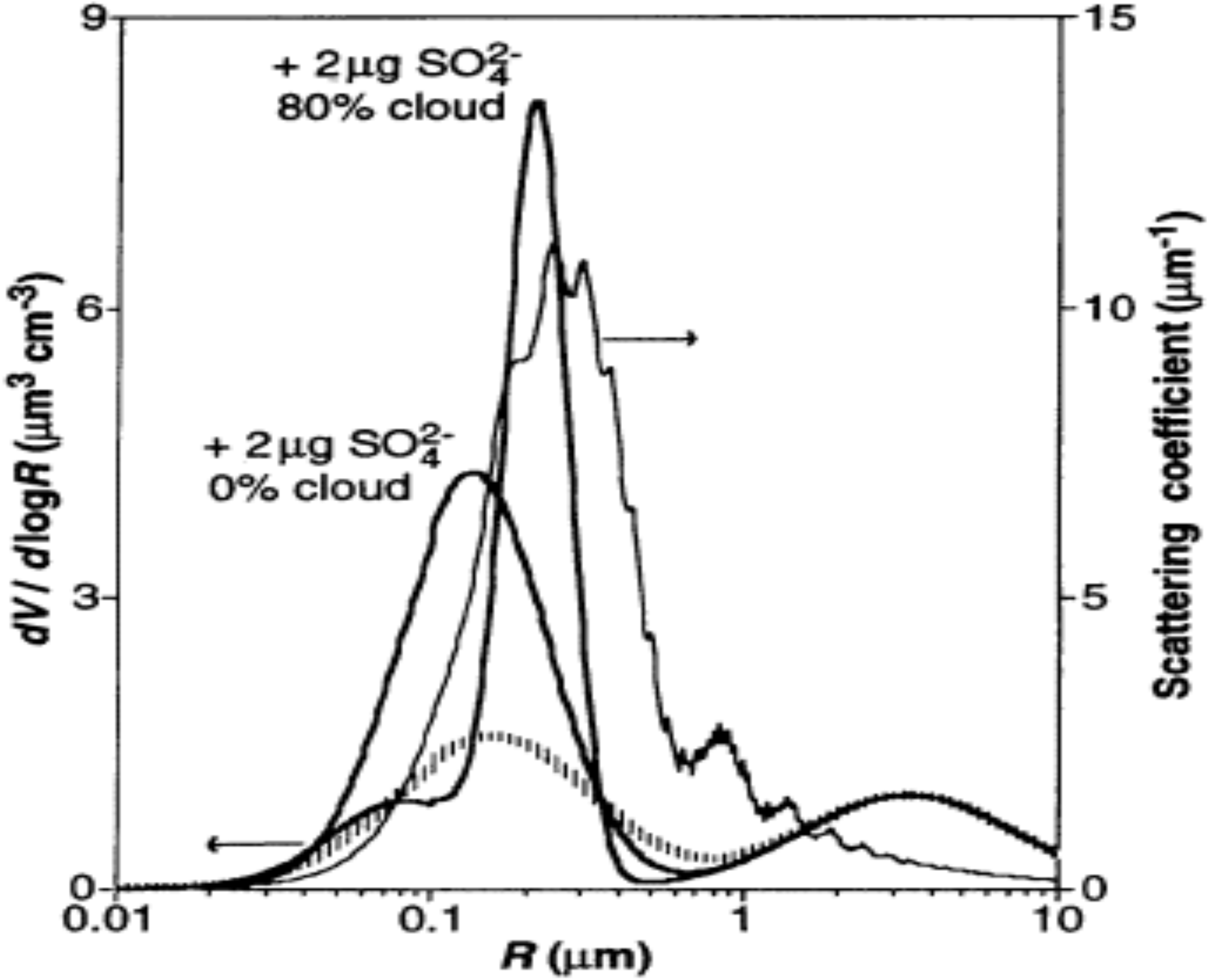
- Heterogeneity can be important in problems such as microphysics, tracer transport, and chemistry.

Aqueous phase oxidation of SO_2

Table 2. GEOS-CHEM Global Budgets for Sulfate Produced by Different Oxidation Pathways

	Source, Tg S yr^{-1}
Total sulfate	31.0
SO_2 + OH (gas phase)	8.2
S(IV) + H_2O_2 (in cloud)	15.7
S(IV) + O_3 (in cloud)	2.3
S(IV) + O_3 (fine sea salt)	0.4
S(IV) + O_3 (coarse sea salt)	2.3
Primary anthropogenic	2.0

Alexander et al., 2005, JGR



Aqueous phase oxidation of SO_2 accounts for 80% of sulfate production and increases its scattering efficiency

(Lelieveld and Heintzenberg, Science, 1992)

A LES simulation inspired by SO_2 oxidation by H_2O_2 (Nie et al., 2016, JGR)

- Large-scale meteorological forcing from BOMEX
- 6.4kmX6.4kmX3km with a resolution of 25mX25mX25m

"Chemistry":

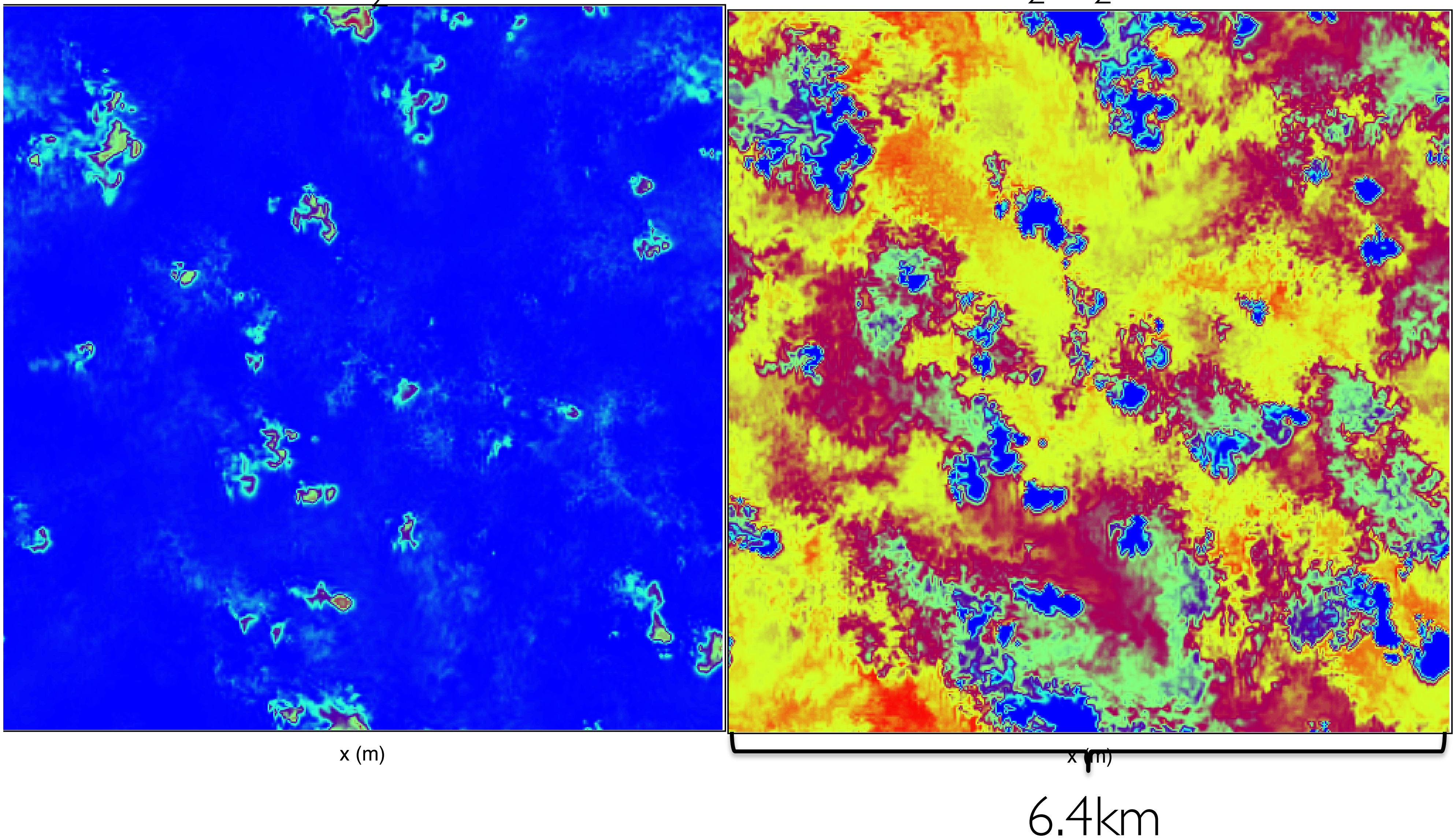
- Tracer1 (analogous to SO_2) is released from surface with a fixed flux,
- Tracer2 (analogous to H_2O_2) is relaxed to a constant reference profile
- In the presence of cloud liquid water, the two tracers react instantaneously to form tracer 3

$$\text{Tracer1} + \text{Tracer2} \rightarrow \text{Tracer3}, \qquad q_c > 0$$

$$\text{"}SO_2\text{"} + \text{"}H_2O_2\text{"} \rightarrow \text{"}H_2SO_4\text{"}, \qquad q_c > 0$$

Snapshots at 762.5 m

"SO_2" "H_2O_2"



Nie et al., JGR (2016) investigated the adequacy of a bulk plume model (eddy diffusivity and mass flux or EDMF) in representing aqueous reactions.

The "Paluch tail"

What explains this variability?

In other words, why is there this "Paluch tail"?

Is it

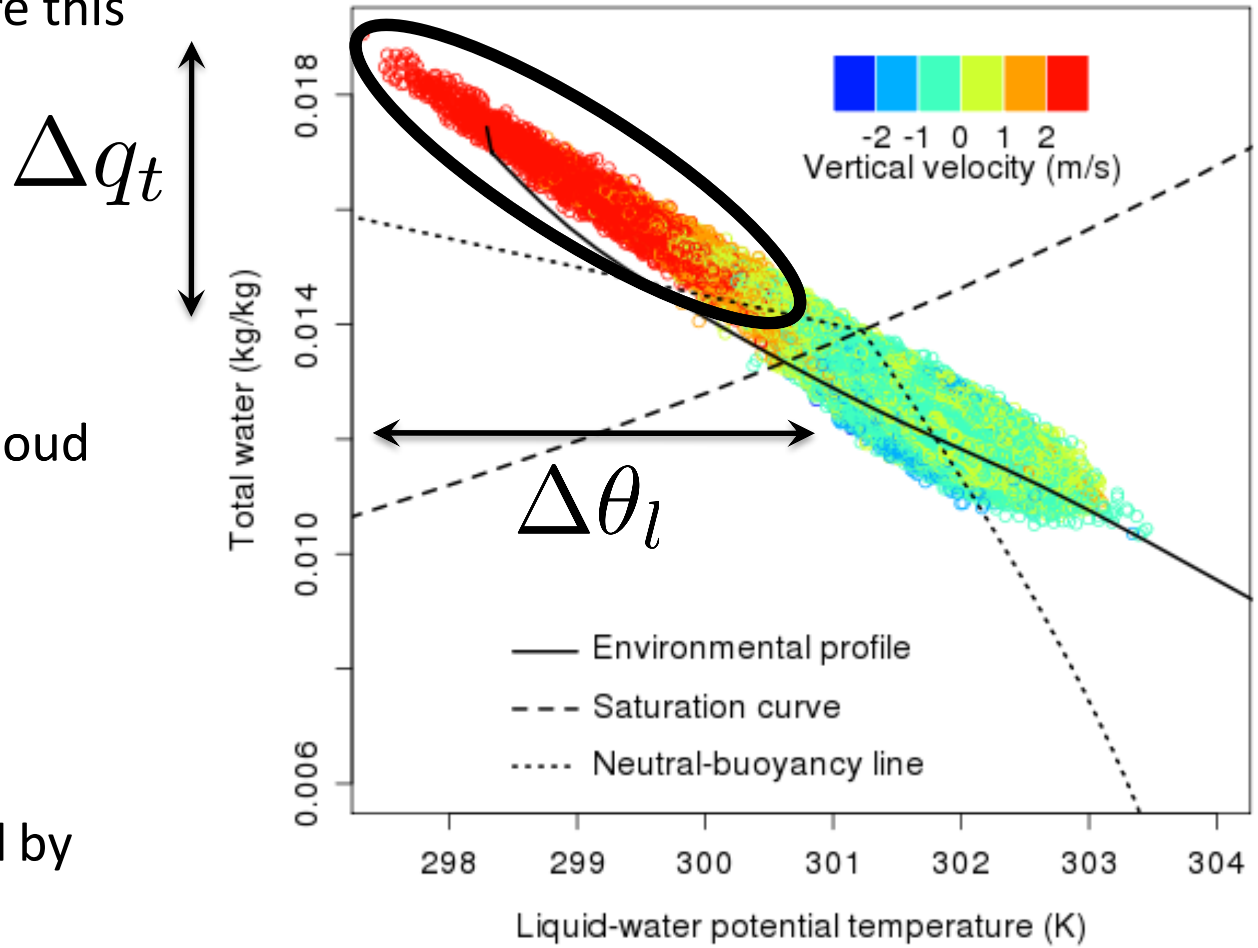
Nature
(variability built in at the cloud base, perhaps amplified)

Or

Nurture
(new variability introduced by stochastic entrainment)

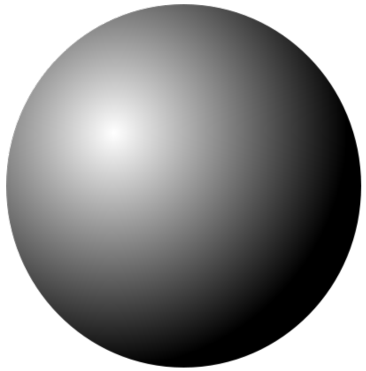
?

Paluch diagram at 1275 meters



Slide by David Romps

A Lagrangian parcel model



$z(t)$	Height
$w(t)$	Vertical velocity
$V(t)$	Volume
$T(t)$	Temperature
$\rho(t)$	Density
$q_v(t)$	Water vapor
$q_l(t)$	Liquid water
$p(t) = p_e(z(t))$	Pressure

Governing equations include:

Buoyancy perturbation pressure force

Turbulent drag (c_d = 0.2)

Simple microphysics

Mixing with the environment

Slide by David Romps

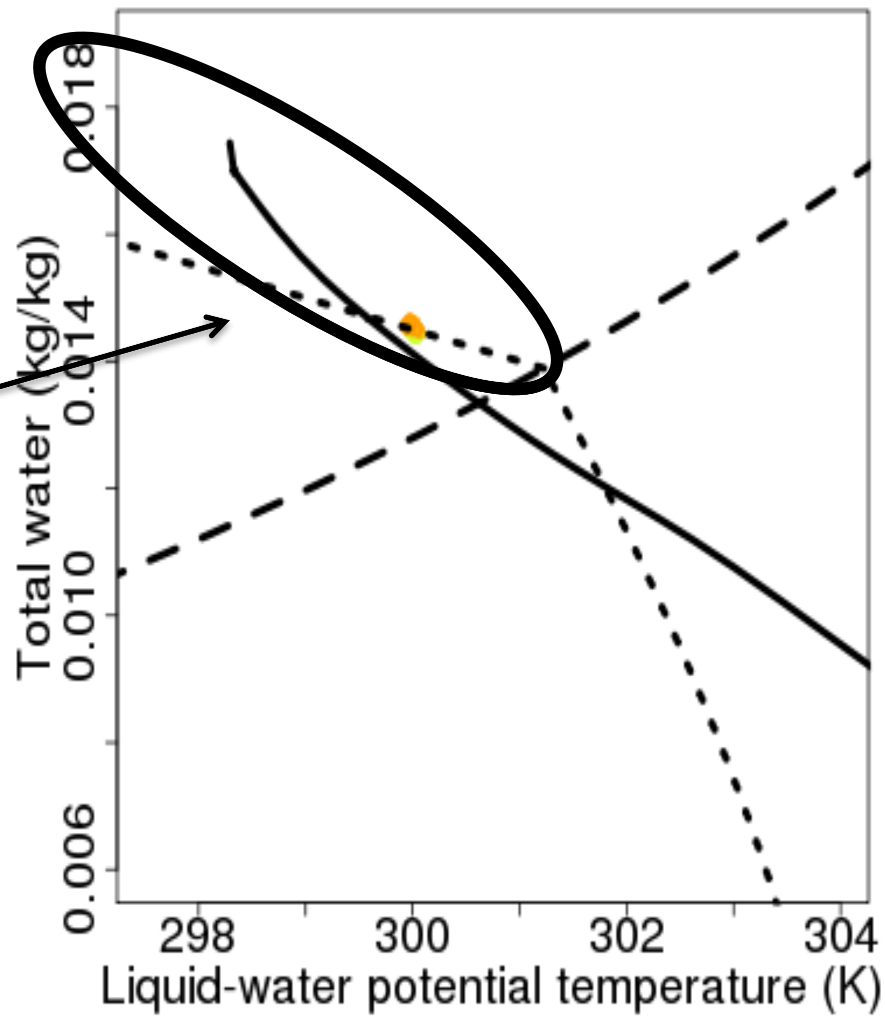
Could it be Nature?

Use LES cloud-base conditions to initialize Lagrangian parcel model

If we use a fixed fractional entrainment,

$$\epsilon = \text{constant}$$

No Paluch tail



Could it be Nature?

Use LES cloud-base conditions to Initialize Lagrangian parcel model

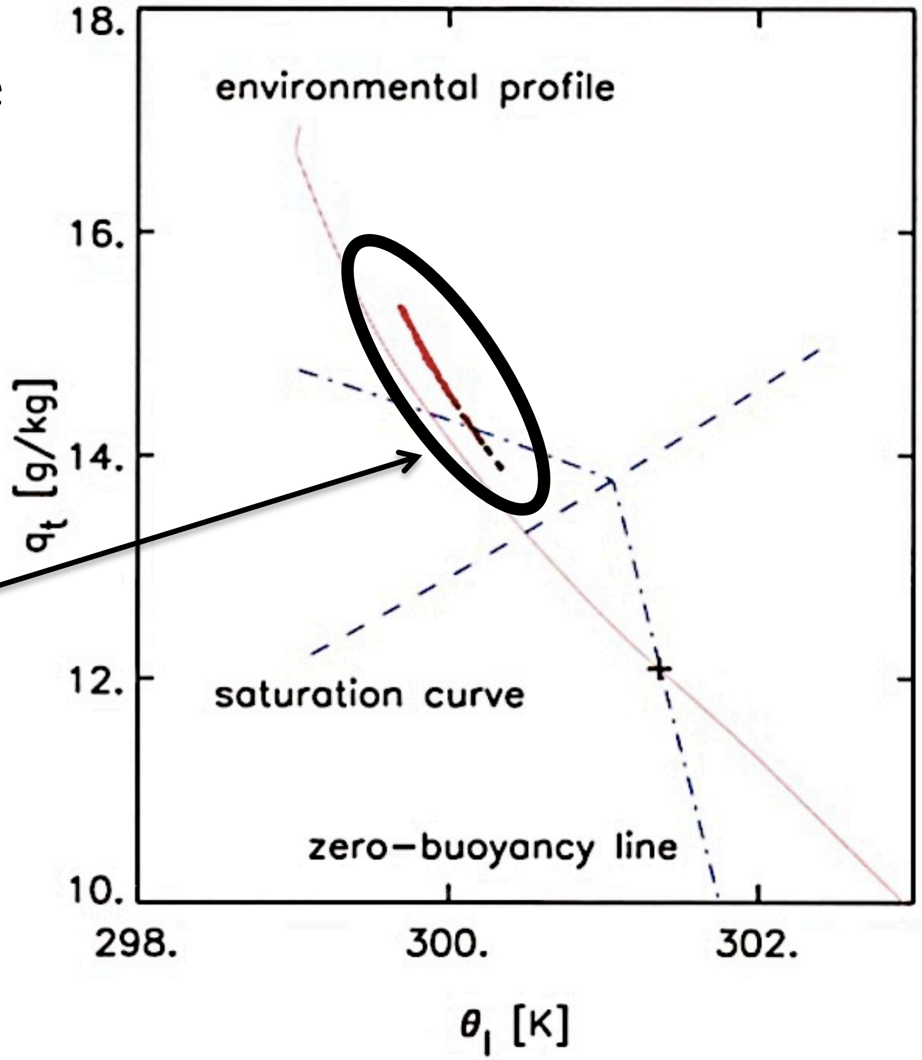
What if we amplify the cloud-base variability?

Try $\epsilon \sim 1/w$

(Neggers et al, JAS, 2002)

Yes, a Paluch tail

Implemented in ECMWF
(Neggers et al, JAS, 2008)



(Neggers et al, JAS, 2002)

Is it really nature? Test with tracers

Prognostic variables: $\vec{u}\,,\ \rho\,,\ T\,,\ q_v\,,\ \ldots\,,\ \phi$

Add "purity" tracer → ϕ

Is it really nature? Test with tracers

Prognostic variables: $\vec{u}\,,\ \rho\,,\ T\,,\ q_v\,,\ \ldots\,,\ \phi$

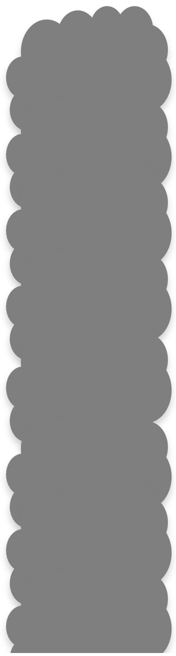
Add "purity" tracer → ϕ

$$\begin{aligned} \phi &= \text{Fraction of air from cloud base} \\ 1-\phi &= \text{Fraction of entrained air} \end{aligned}$$

Is it really nature? Test with tracers

Prognostic variables: $\vec{u}\,,\ \rho\,,\ T\,,\ q_v\,,\ \ldots\,,\ \phi\,,\ \zeta$

Now, add a second tracer to record cloud-base θ_e



$$\zeta/\phi \;=\; \text{cloud-base } \theta_e$$

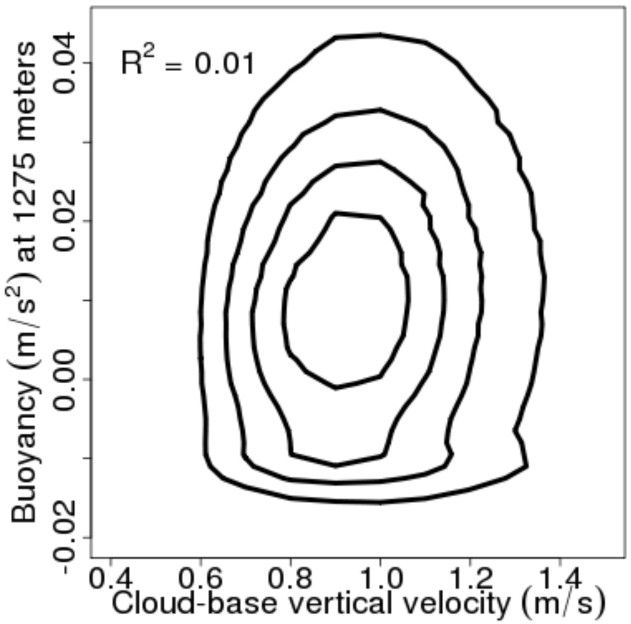
Entrainment reduces ϕ and ζ by same fraction

$$\phi = 1\,,\ \zeta = \theta_e$$

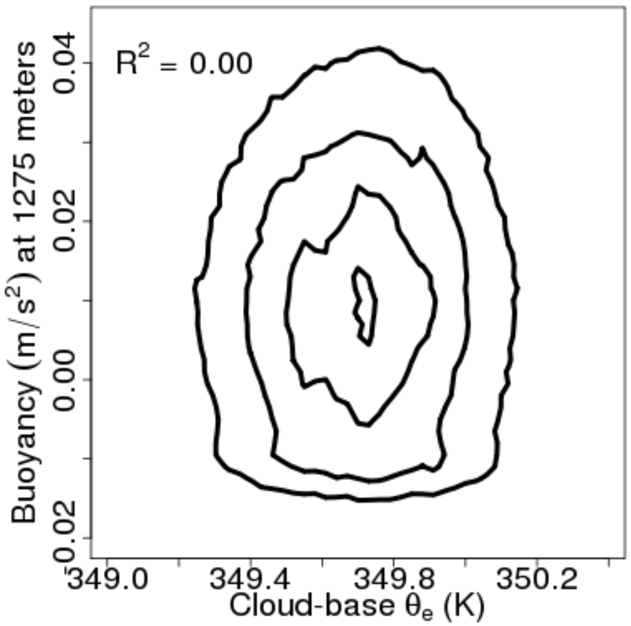
The answer is… Nurture

Correlations at 1275 meters

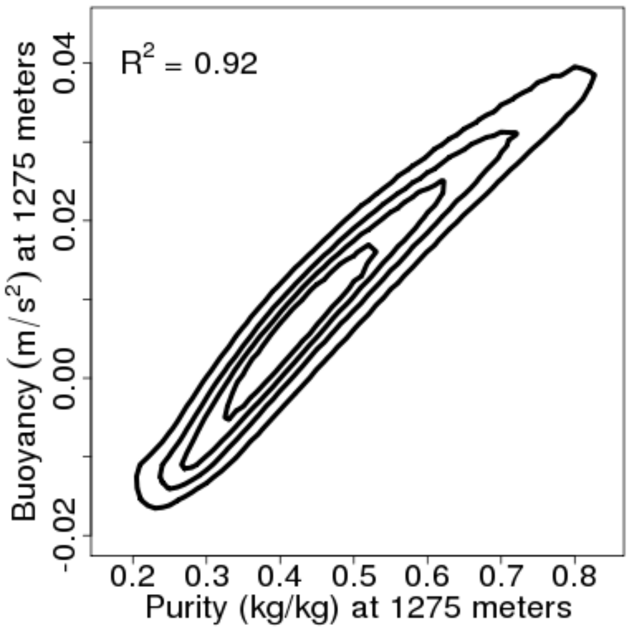
Buoyancy vs. cloud-base w



Buoyancy vs. cloud-base θ_e



Buoyancy vs. purity, ϕ



~~$\epsilon \sim 1/w$~~

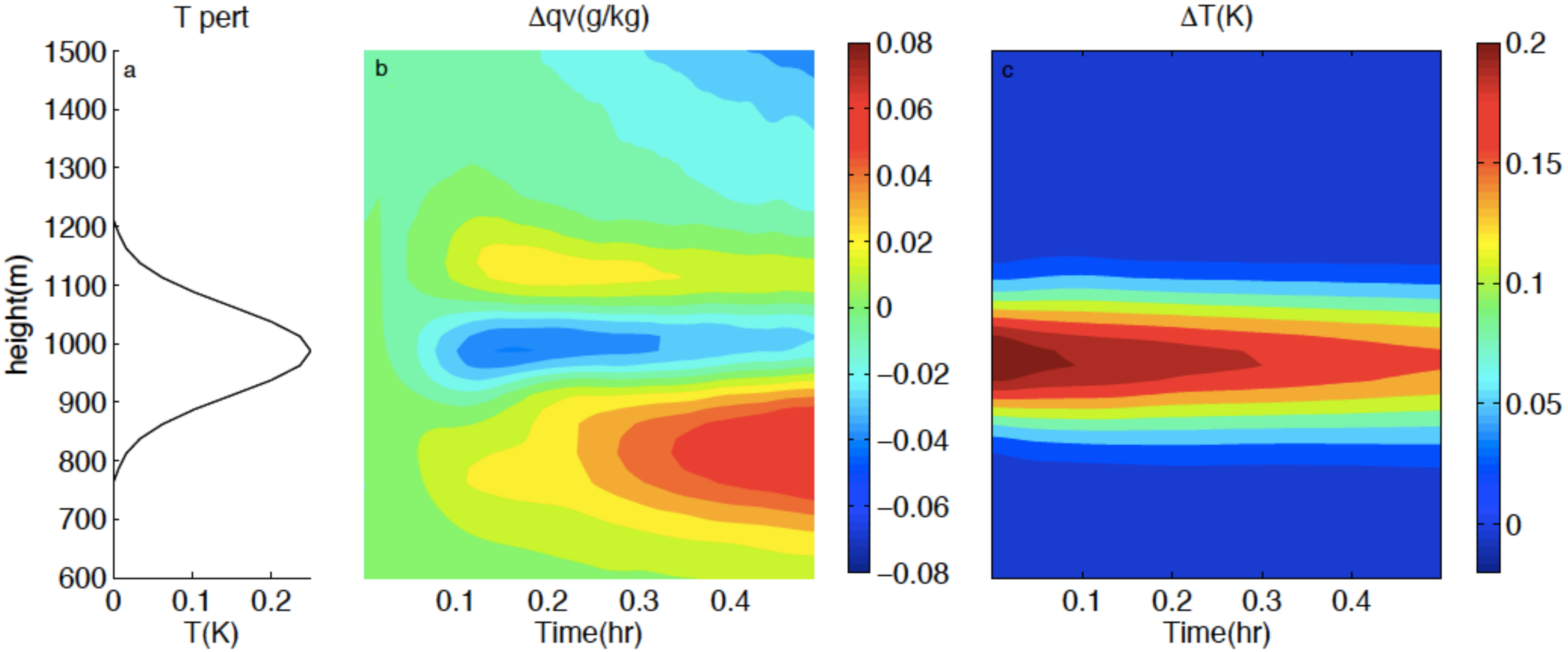
~~Nature~~

Nurture

Combining linear response functions and Lagrangian particle tracking

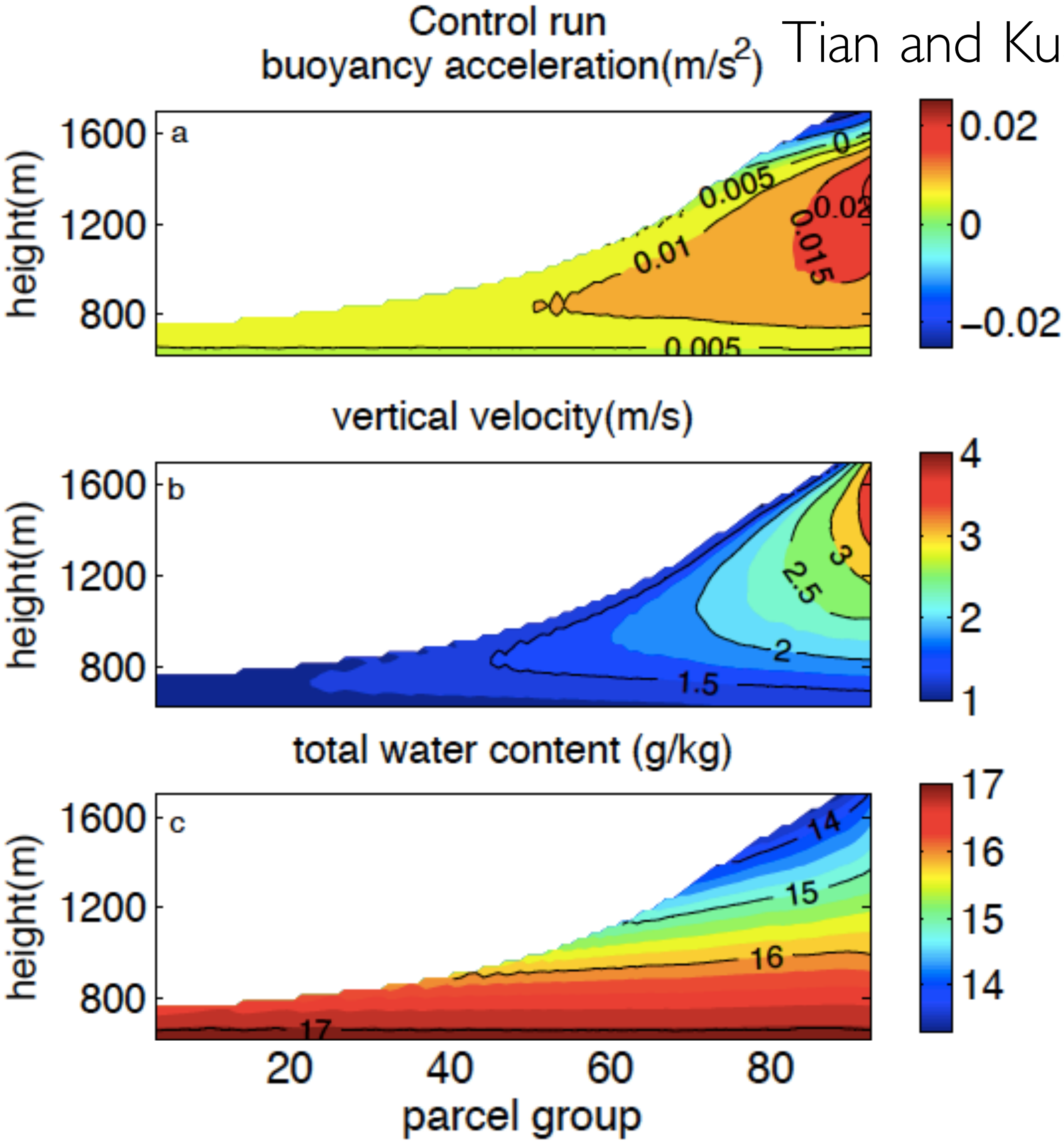
- Linear response functions can reduce the extent of confounding
- Lagrangian particle tracking provides the full history of parcels as they evolve, a connection that is lost in the Eulerian framework.
  - It is more direct and powerful than the purity tracer (and generates much bigger datasets), and does not need the assumptions made in the stochastic parcel model

Linear response of shallow convection to a compact perturbation

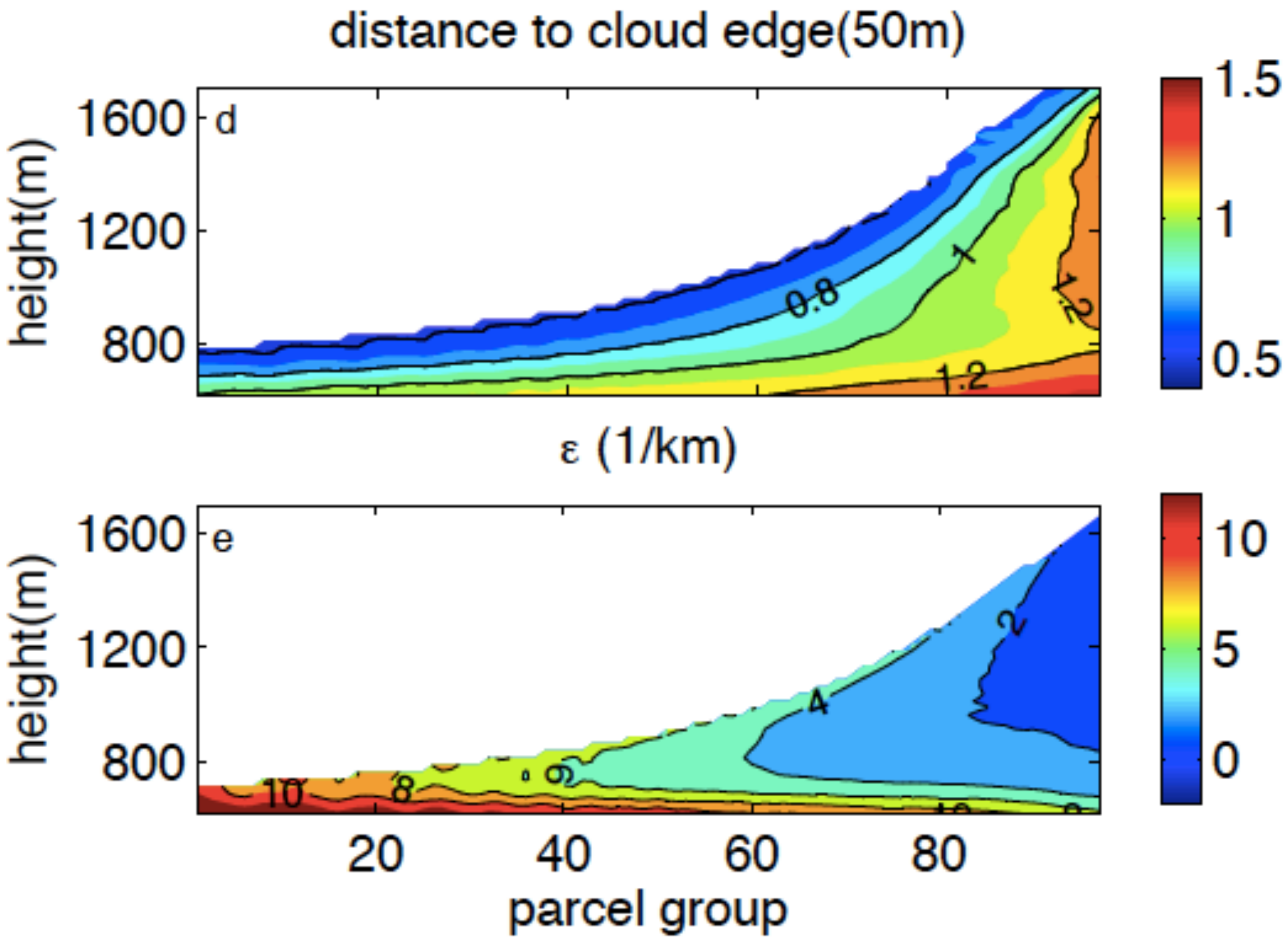


Tian and Kuang, 2016

Tian and Kuang, 2016



Tian and Kuang, 2016

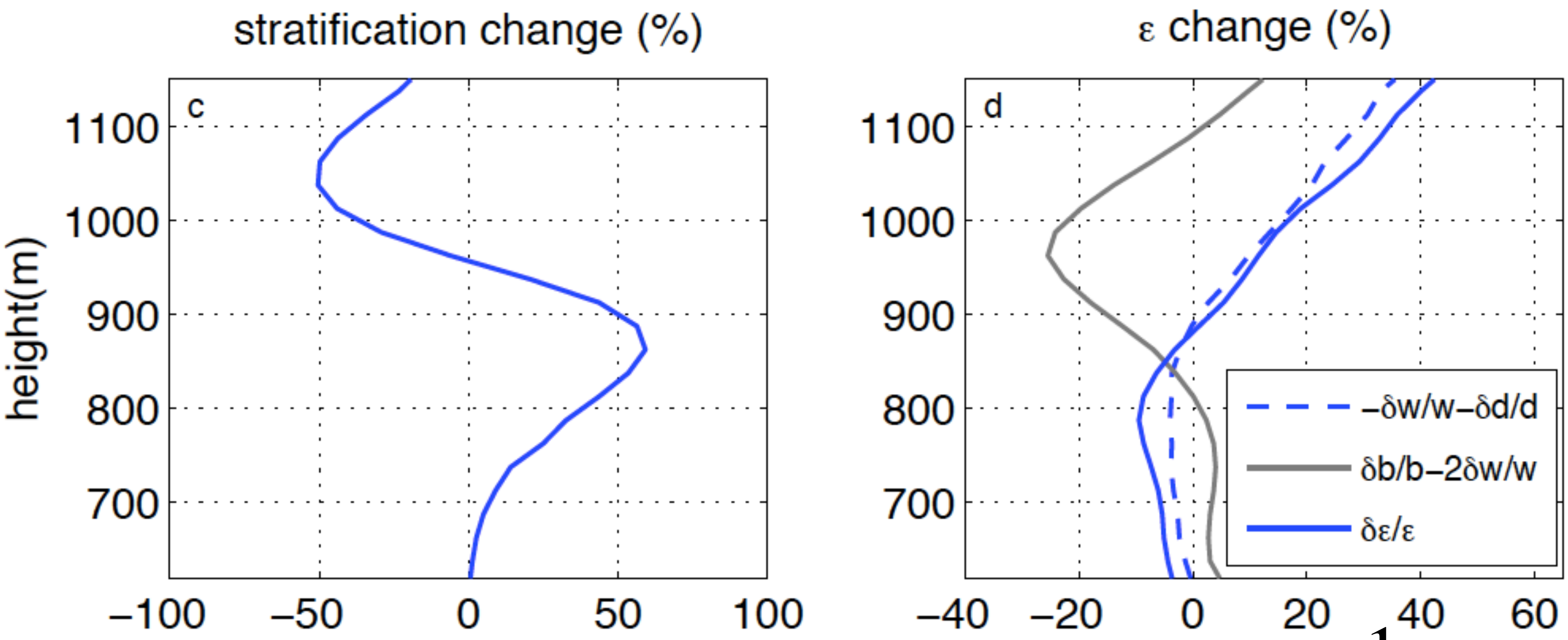


How to parameterize entrainment?

- $\varepsilon \propto R^{-1}$ (e.g. Simpson and Wiggert , 1969; Tiedtke, 1989; Siebesma, 1998; Bretherton et al., 2004)
- $\varepsilon \propto z^{-1}$ (Siebesma, 1998)
- $\varepsilon \propto \frac{db}{dz}$ Emanuel and Zivkovic-Rothman [1999]
- $\varepsilon \uparrow b \downarrow$ Lin [1999]
- $\varepsilon \uparrow RH \downarrow$ Bechtold et al. [2008]
- $\varepsilon \propto \frac{b}{w^2}$ Gregory [2001]
- $\varepsilon \propto w^{-1}$ Neggers et al. (2008)

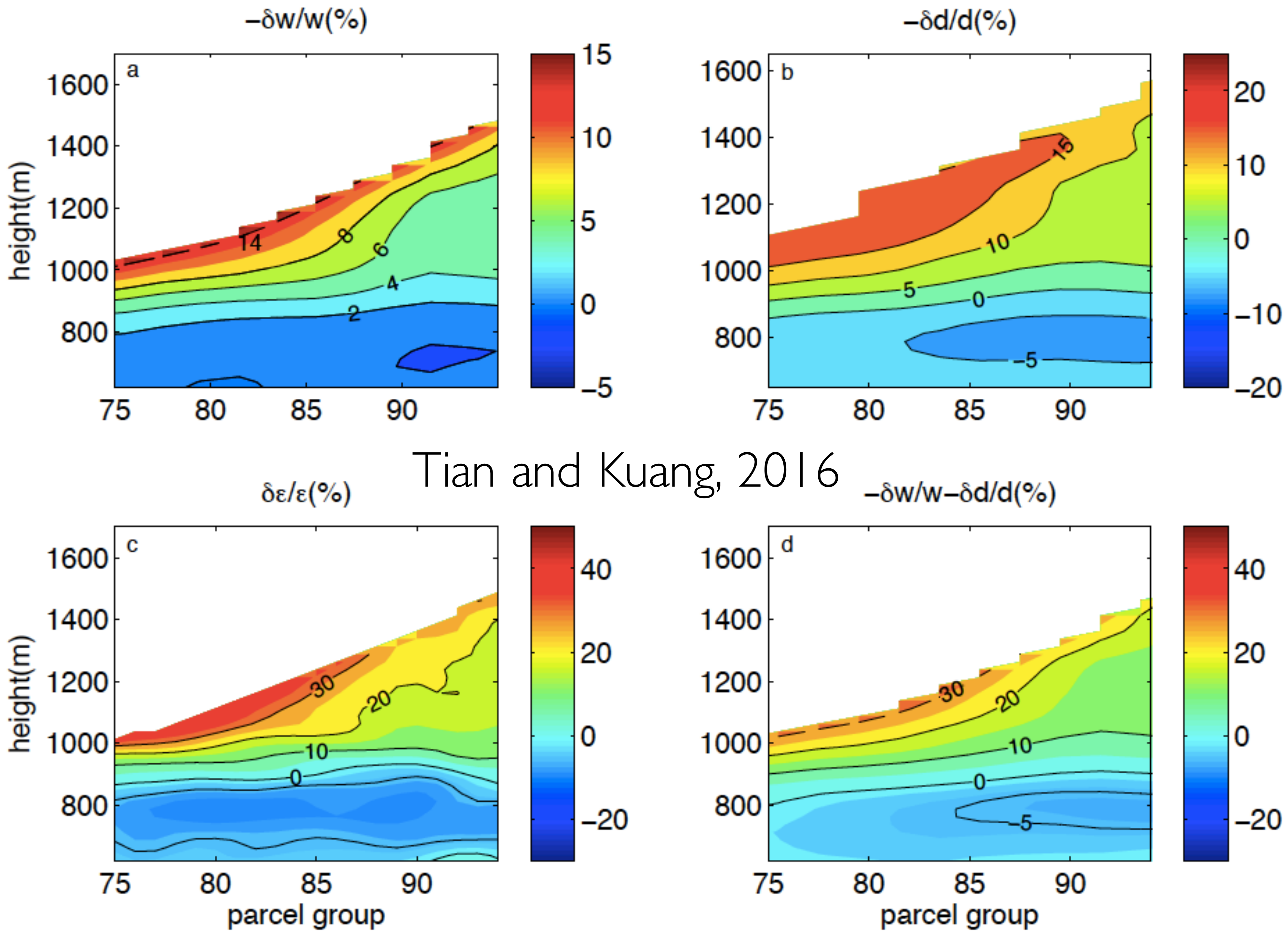
We can now test these formulations

Tian and Kuang, 2016



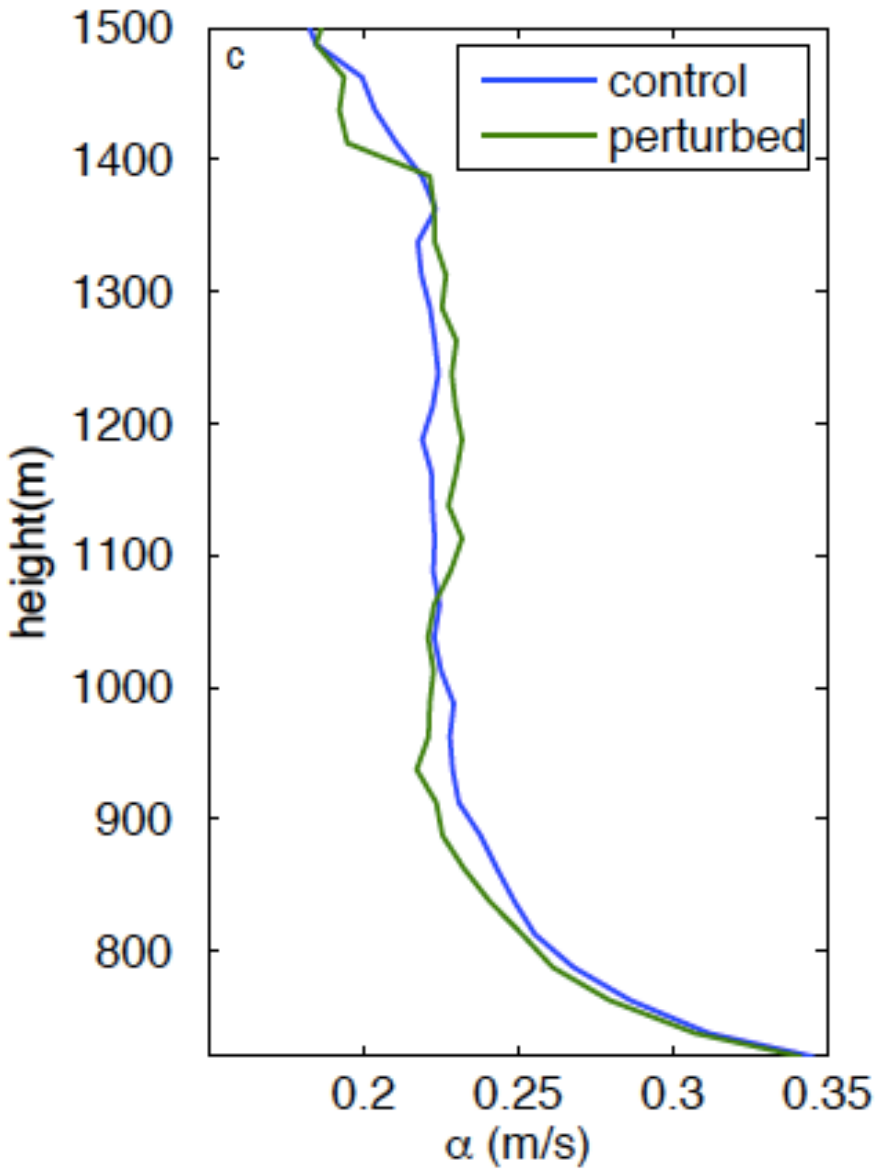
Suggests fractional entrainment rate $\varepsilon \propto \frac{1}{wd}$

w is updraft vertical velocity, d is updraft size



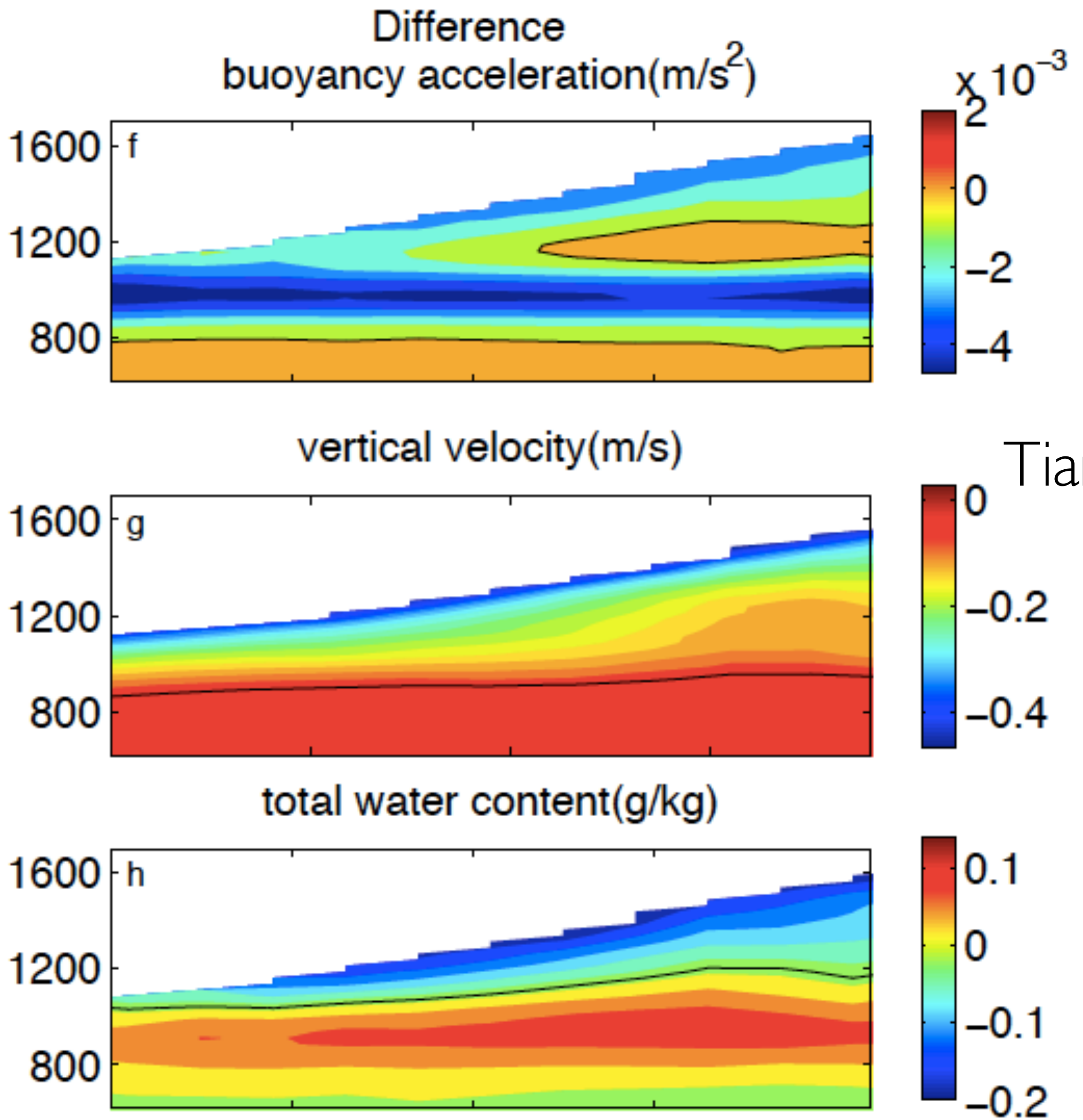
Tian and Kuang, 2016

$$\epsilon_i = \frac{\alpha_i}{w_i d_i}$$



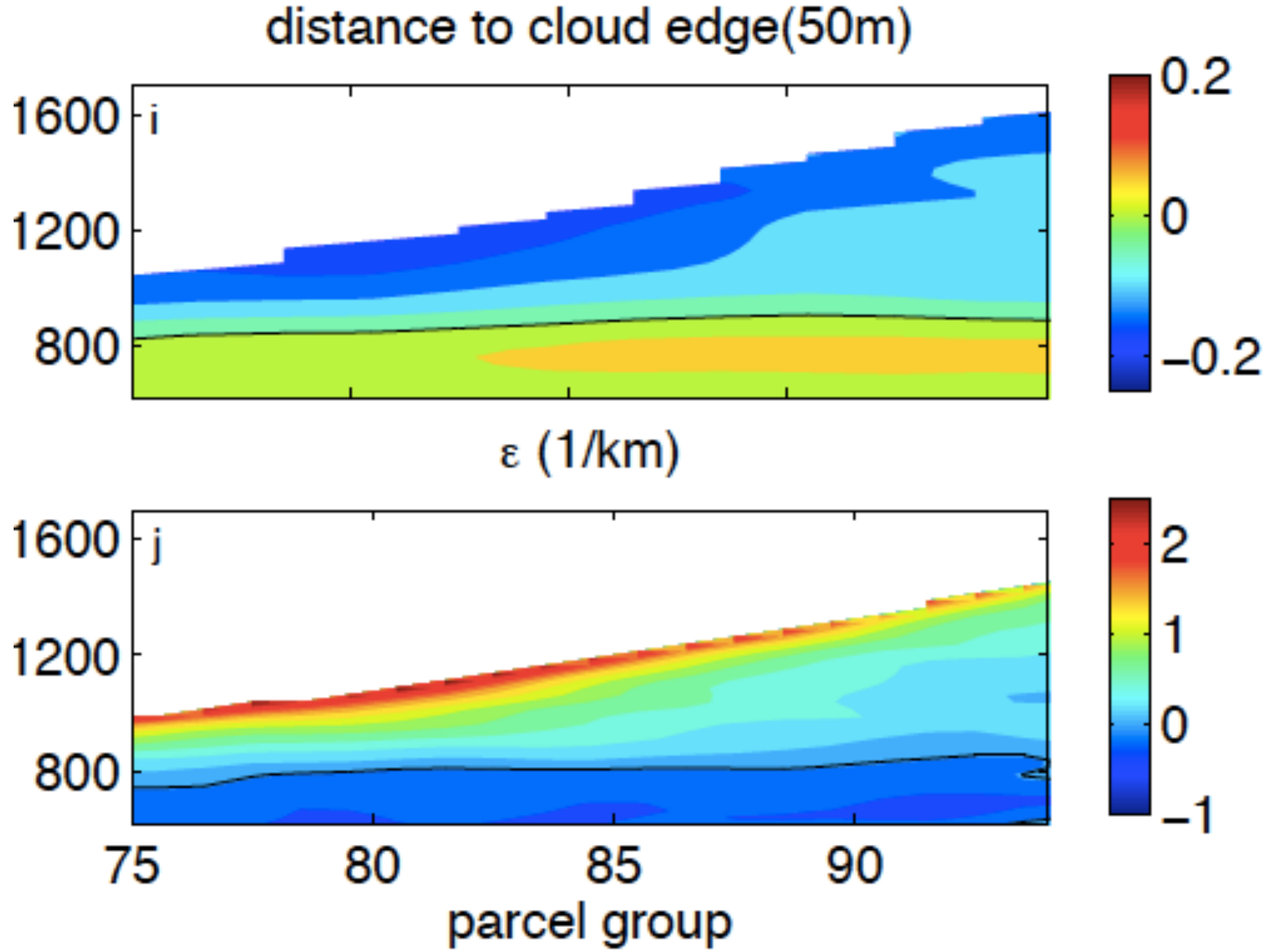
Concluding remark

- Much is to be learned about cumulus dynamics through clever diagnostics of CRM/LES outputs.



Tian and Kuang, 2016

Tian and Kuang, 2016



Is it really nature? Test with tracers

Recap so far

- We ask the following question:

  Is the variability within and between clouds (Paluch tail)

  caused by Nature (cloud-base variability)

  or by Nurture (stochastic entrainment) ?

- Neggers says the answer is Nature amplified through $\epsilon \sim 1/w$

- We now have tracers to diagnose cloud-base properties

Is it really nature?   Test with tracers

If $\epsilon \sim 1/w$, then

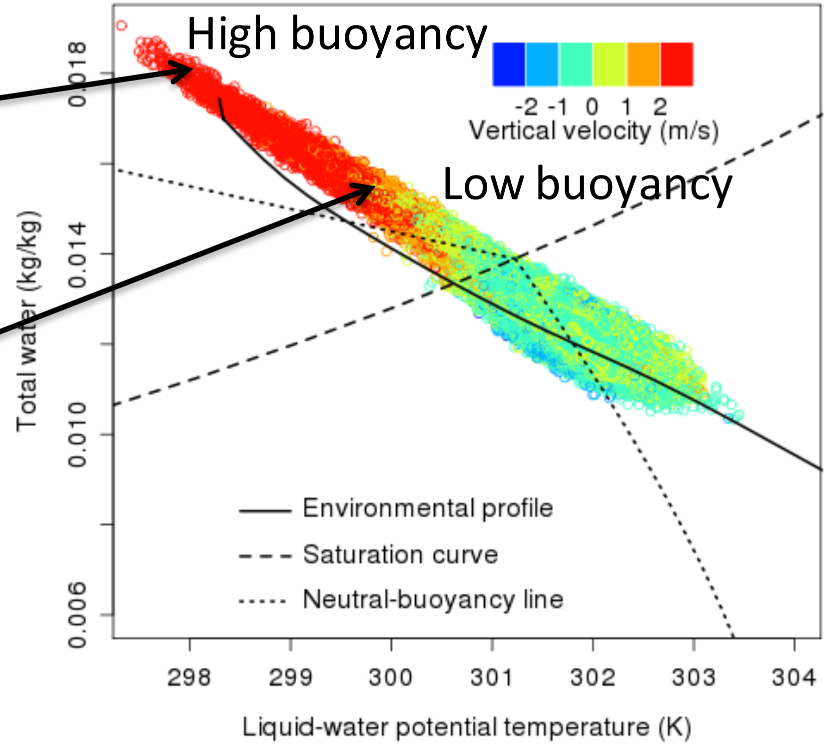
buoyancy, q_t, and θ_l in clouds

will be highly correlated with

the clouds' values of θ_e and w at the cloud base.

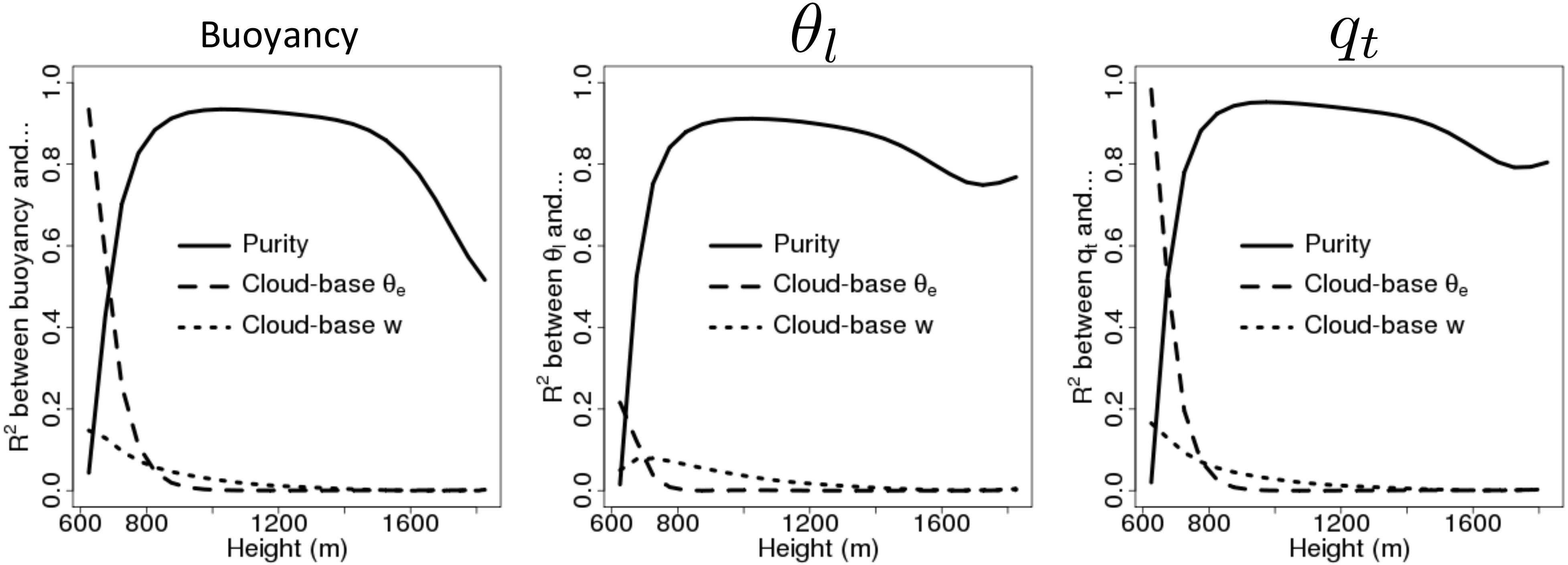
High θ_e → High w → Low ϵ

Low θ_e → Low w → High ϵ

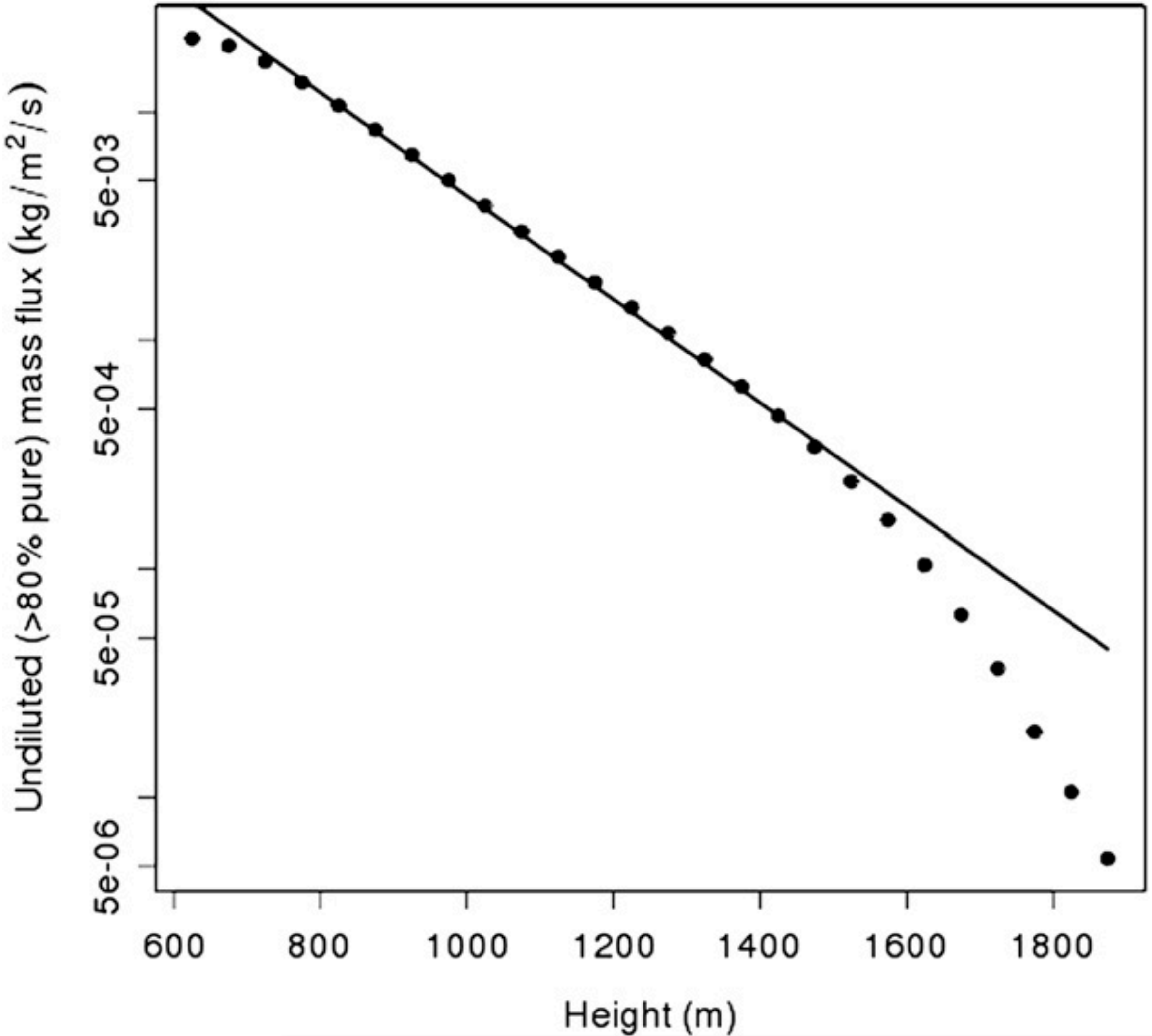


The answer is… Nurture

Correlations as a function of height



Parcels are uncorrelated with their cloud-base properties 200 meters above the cloud base



Undiluted mass flux decays exponentially with height

In time step δt, the probability of an entrainment event is:

$$P(\text{an entrainment event}) = |w|\delta t/\lambda$$

Stochastic parcel model

Cloud modeled as a collection of entraining parcels.

(The LNB's of parcels define the cloud's detrainment profile.)

Entrainment occurs only in discrete events, modeled using Monte Carlo

Two parameters, λ and σ , define entrainment

In time step δt, the probability of an entrainment event is:

$$P(\text{an entrainment event}) = |w|\delta t/\lambda$$

If there is a mixing event, entrain a fractional amount f :

$$P(\text{entrain fraction } f) = \frac{1}{\sigma} e^{-f/\sigma}$$

Stochastic parcel model

In time step δt, the probability of a entrainment event is:

$$P(\text{an entrainment event}) = |w|\delta t/\lambda$$

If there is a mixing event, entrain a fractional amount f:

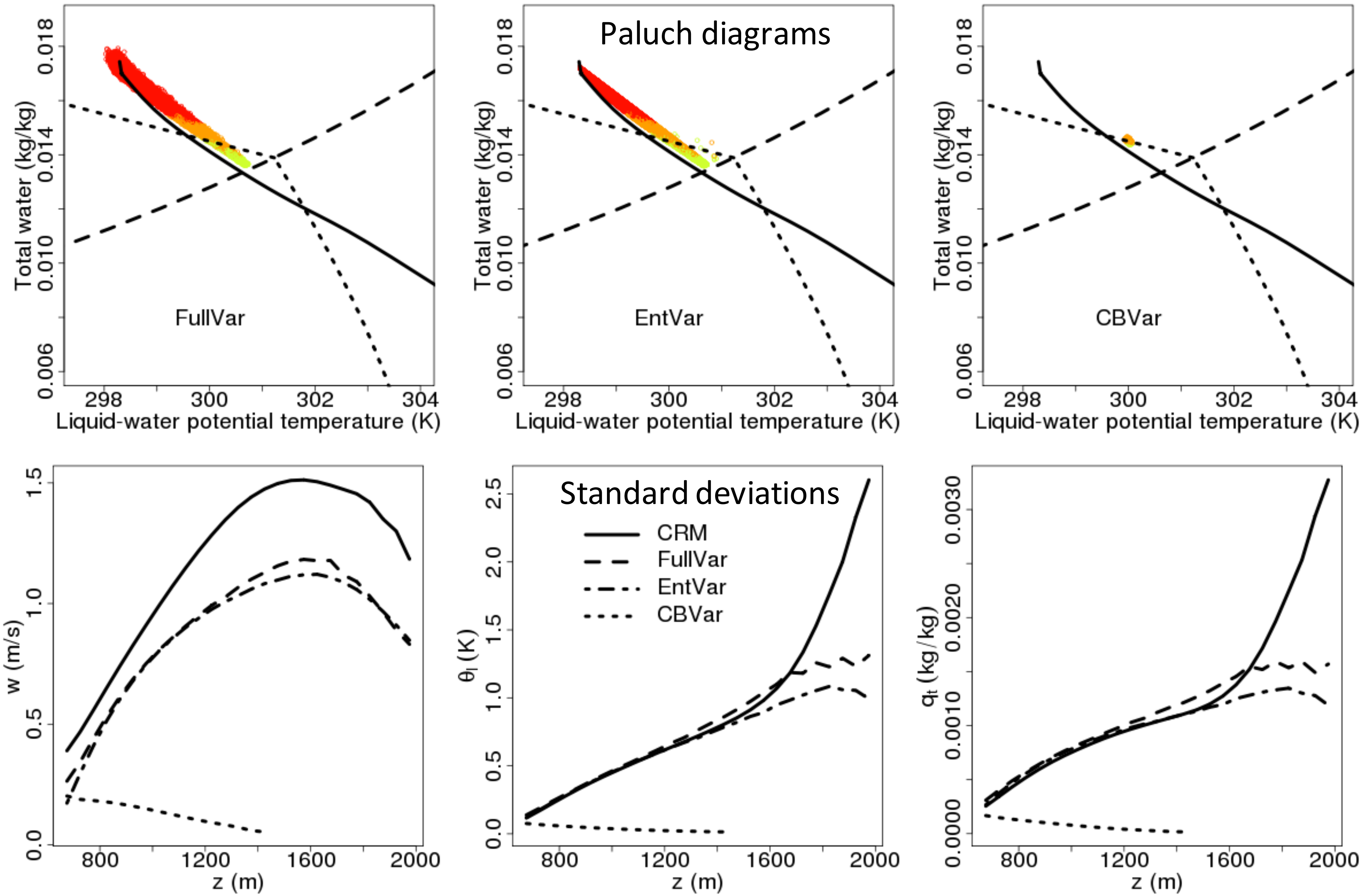
$$P(\text{entrain fraction } f) = \frac{1}{\sigma} e^{-f/\sigma}$$

In the limit of small λ, the model approaches a constant fractional entrainment rate of σ/λ

Stochasticity becomes substantial for large λ

Stochastic parcel model

Lagrangian parcel model with stochastic entrainment

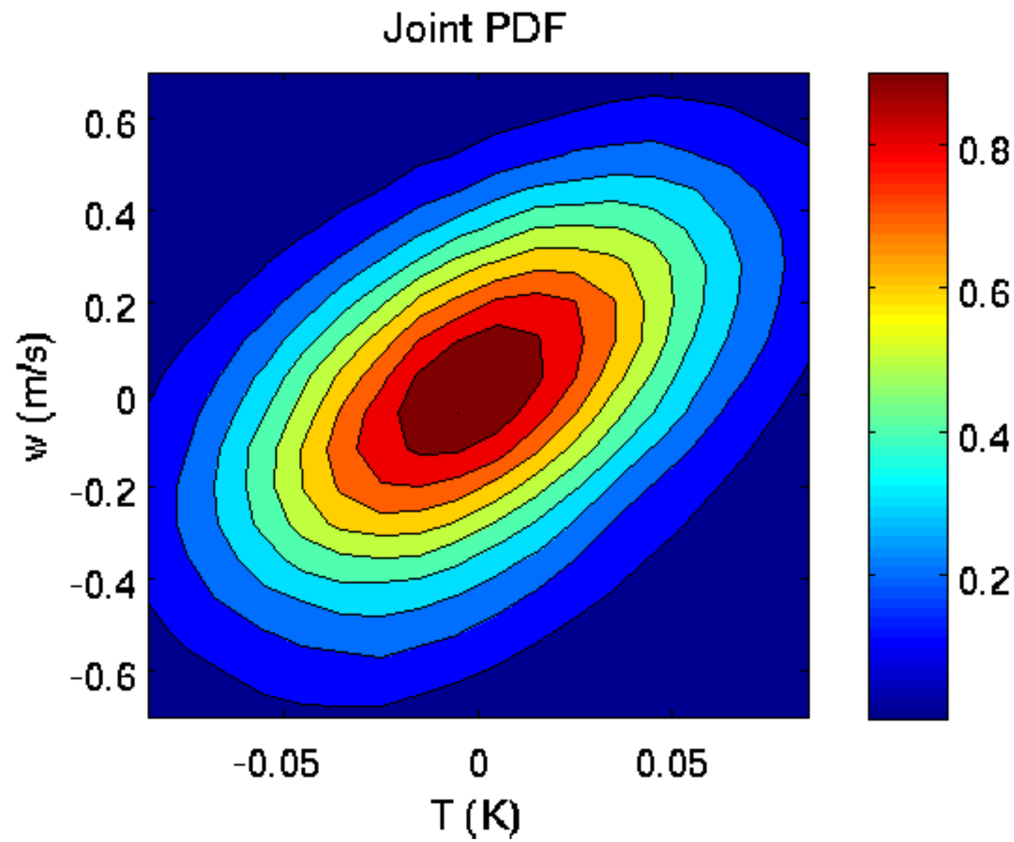


1. Stochastic entrainment is the source of the variability among cloudy updrafts in shallow convection (Nurture, not Nature).

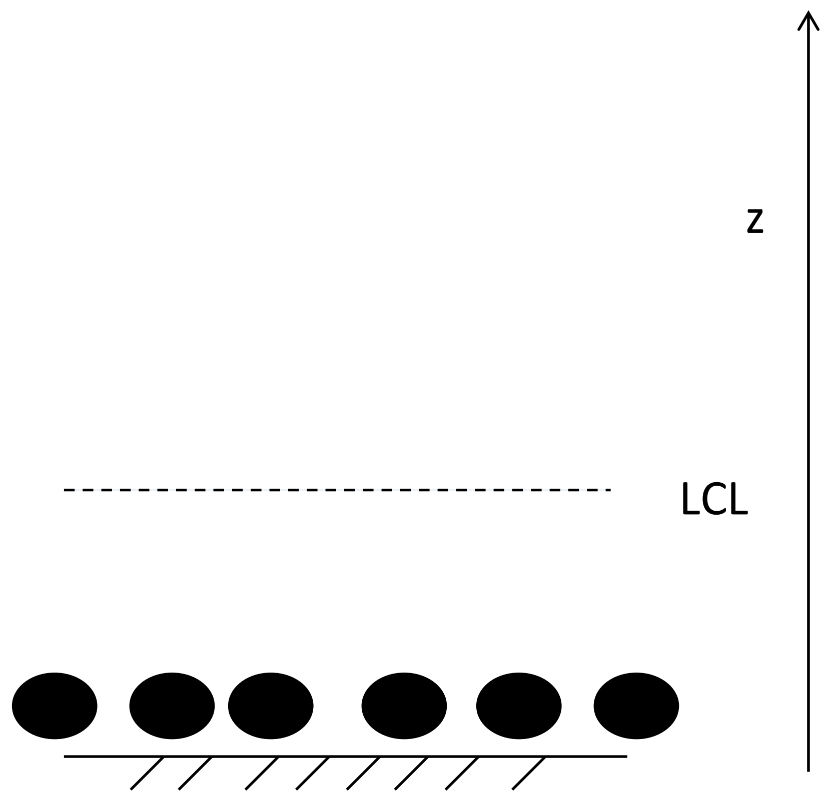
2. Next, we develop a shallow cumulus parameterization based on stochastically entraining parcels to capture in-cloud heterogeneity (Nie and Kuang, 2012, JAS).

Starting from the surface:

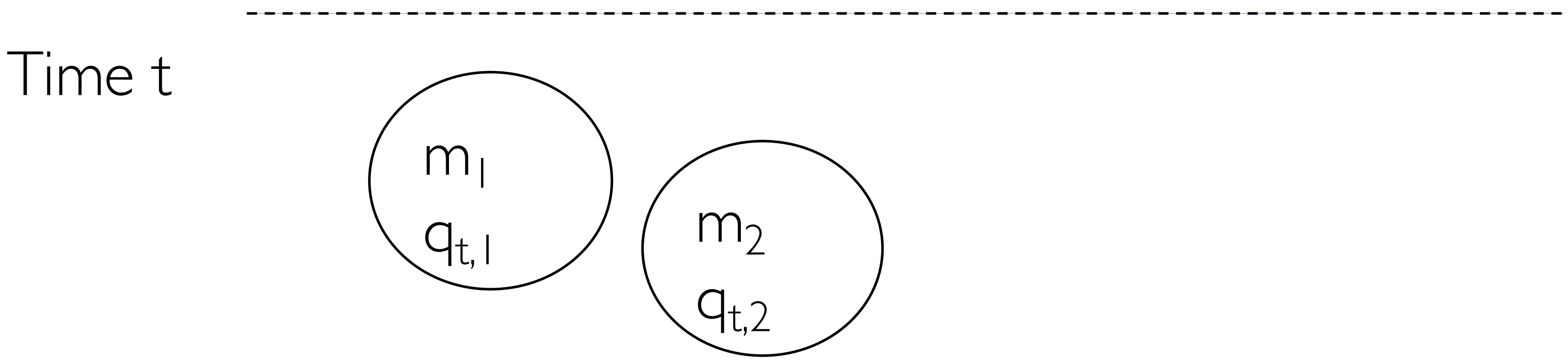
From surface fluxes, we determine the Gaussian joint PDF of parcel properties near the surface. We then release parcels near the surface with properties drawn randomly from this PDF (similar to Cheinet, 2004).



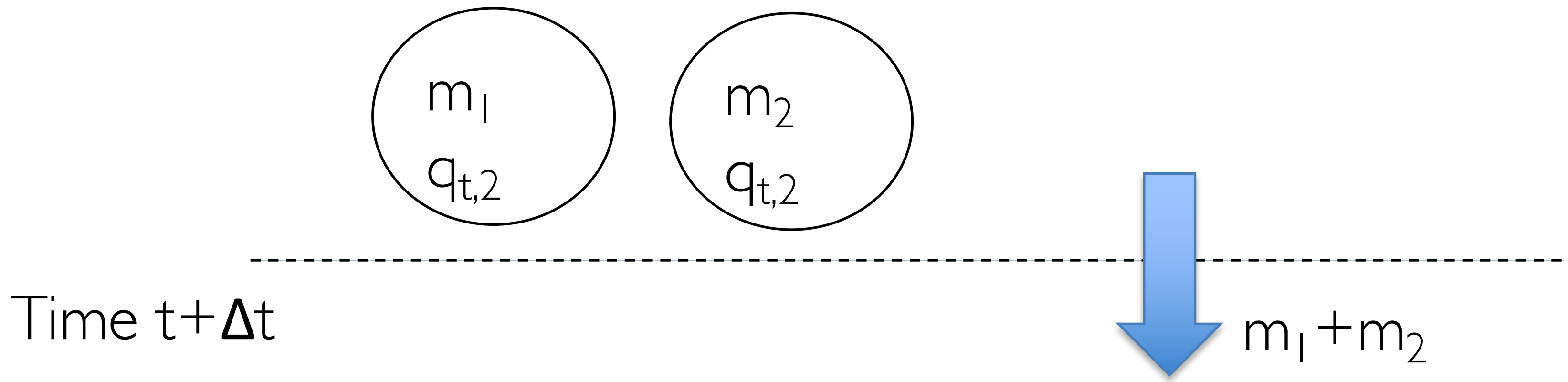
The parcels then follow their Lagrangian trajectories with stochastic entrainment until they come to rest



"Counting Beans"

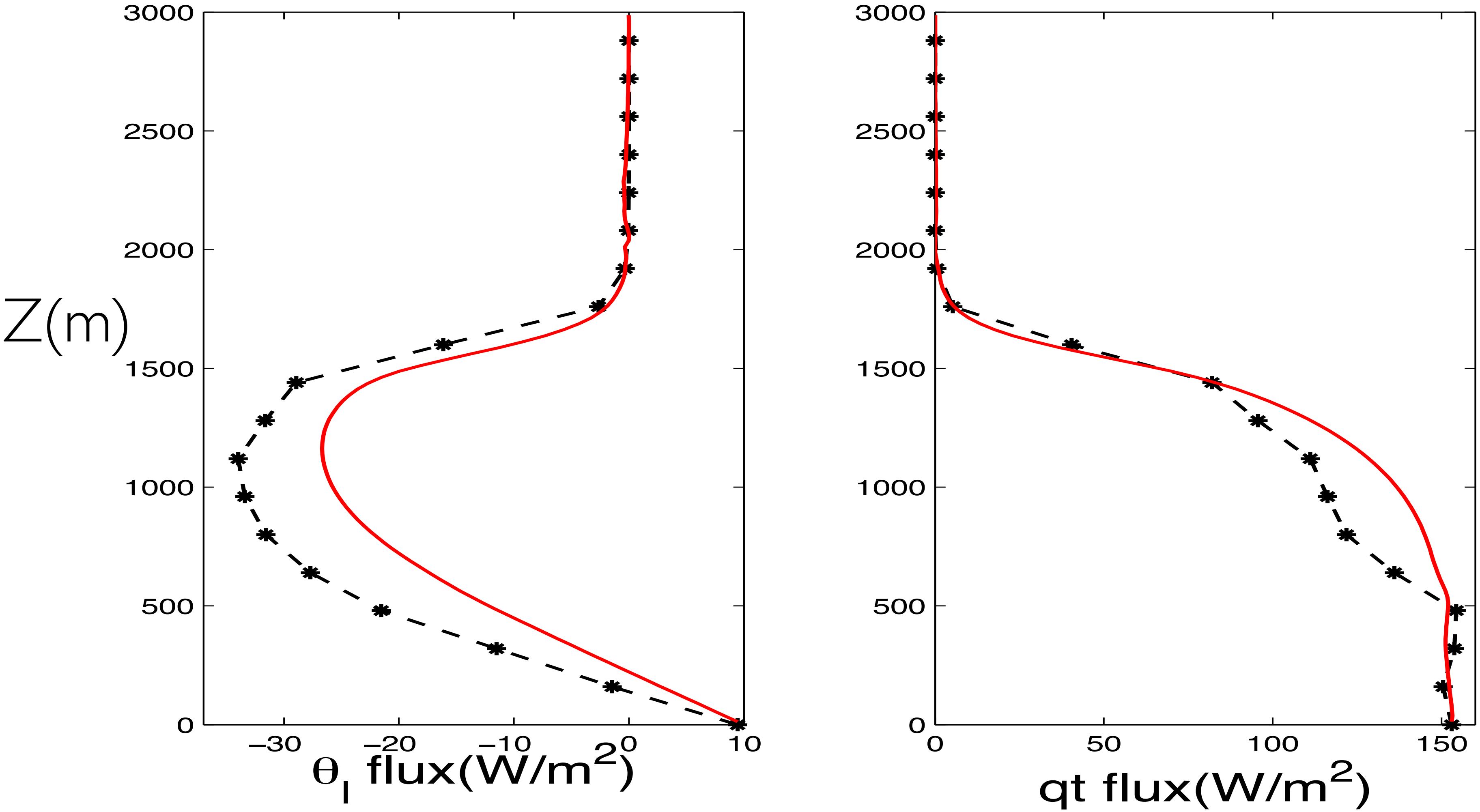


We count all parcels that cross an interface over an unit time and represent convective transport as the total transport by all these parcels and the associated compensating motions.

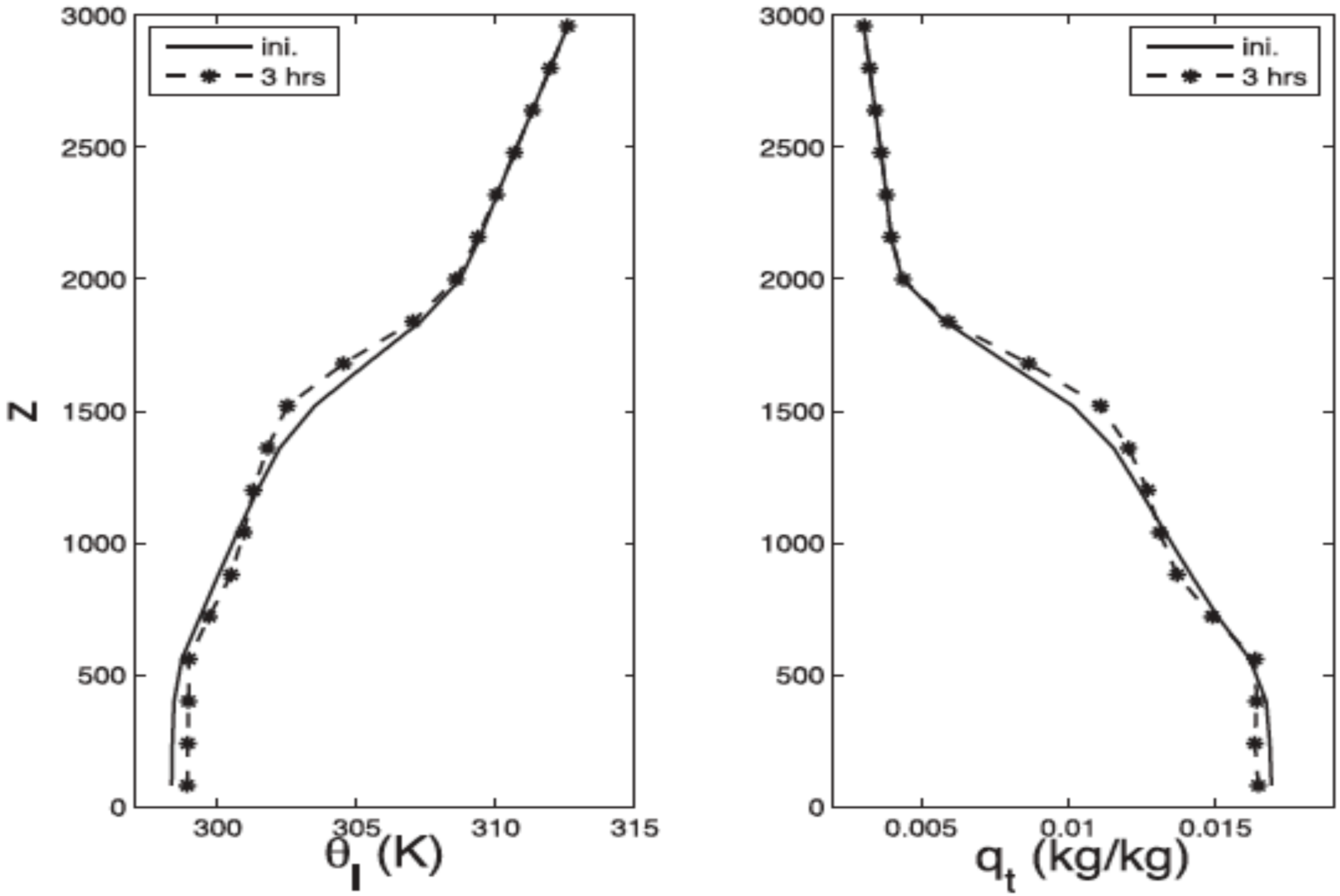


Total water flux across the interface: $$\frac{\sum(m_k q_{t,k}) - \sum m_k q_{t,\mathrm{dn}}}{A\Delta t}$$

Fluxes (red: LES, black: parcel model)



Temperature and moisture profiles



Some attractive aspects of Nie and Kuang (2012)

- Conceptually simple
- Naturally combines the sub-cloud layer and the cloud layer
- Includes forced clouds, which can be important to radiation
- Can represent increased stochasticity when the domain size (or GCM grid size) decreases
- Represents in-cloud heterogeneity

Similar points were made in Suselj, Teixeira, Chung, JAS, 2013

Future work on the stochastic parcel model

- In-cloud/inter-parcel mixing

Explicit mixing parcel model

(Krueger et al., 1997, JAS)

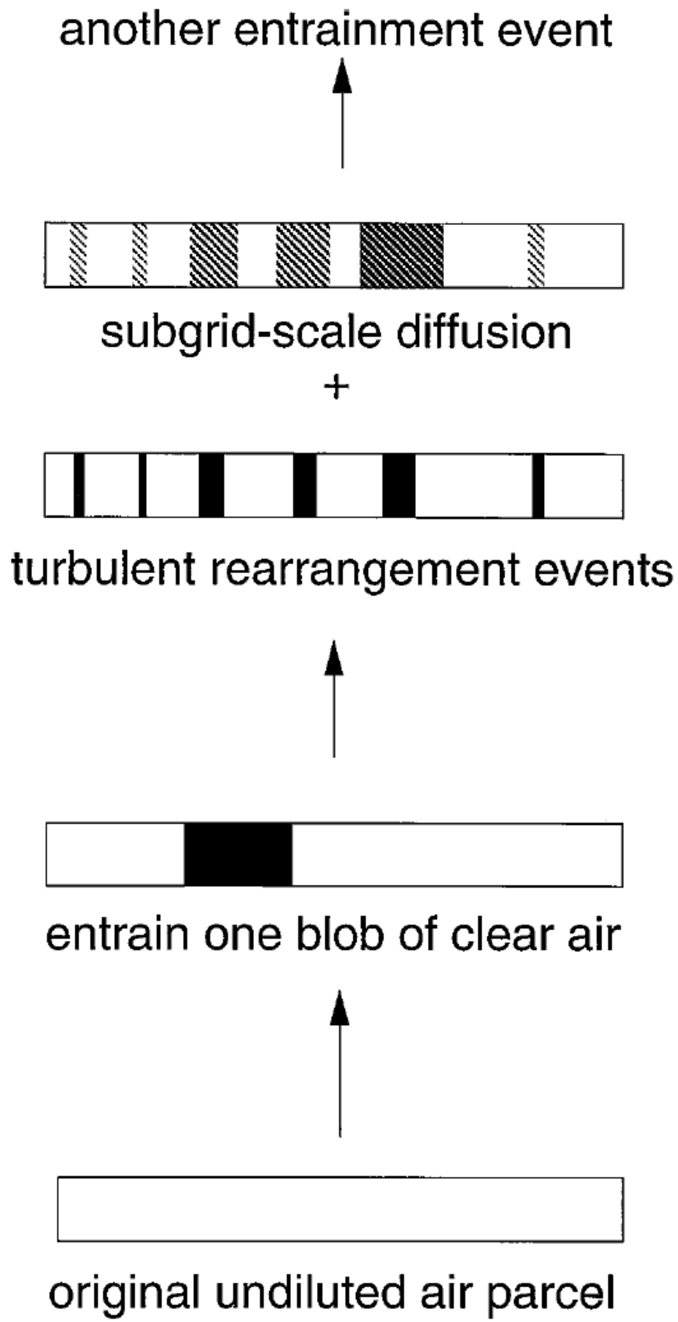


FIG. 3. A parcel is represented by a 1D domain in the EMPM. The parcel's internal structure evolves due to discrete entrainment events and turbulent mixing (rearrangement events and subgrid-scale diffusion).

Future work on the stochastic parcel model

- In-cloud/inter-parcel mixing
- More realistic treatment of momentum drag (such as gravity wave drag)
- Processes associated with precipitation

Bulk plume models

Cloud model

$$\frac{\partial M_u}{\partial z} = M_u(\varepsilon - \delta),$$

$$\frac{\partial \psi_u}{\partial z} = \varepsilon(\overline{\psi} - \psi_u) + S_\psi.$$

Detrainment/entrainment rates can be diagnosed from LES/CRM

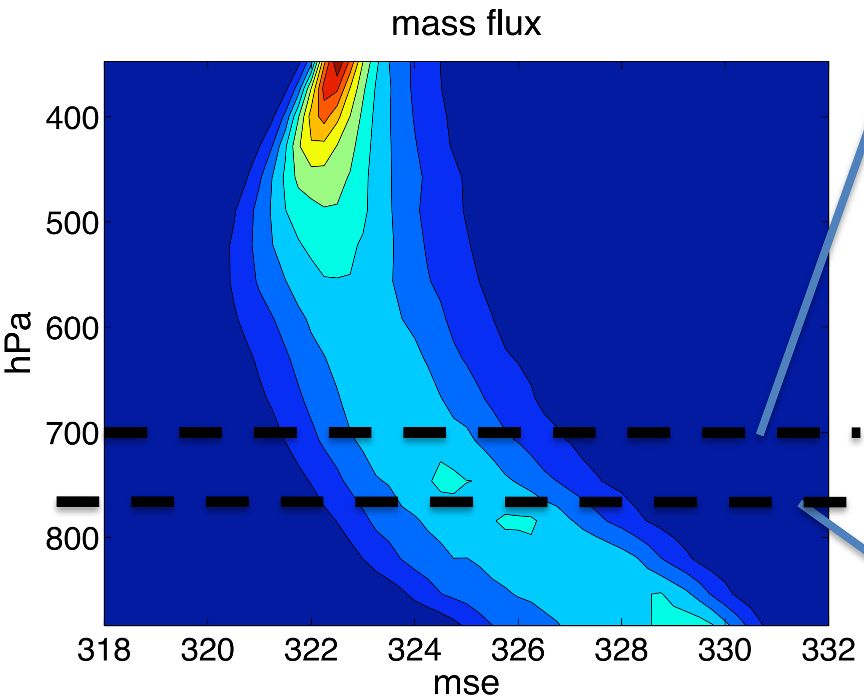
Extension to account for in-cloud variations

Flux of a conserved variable (ϕ) is determined by the mass flux distribution in terms of ϕ, assuming the environment is uniform.

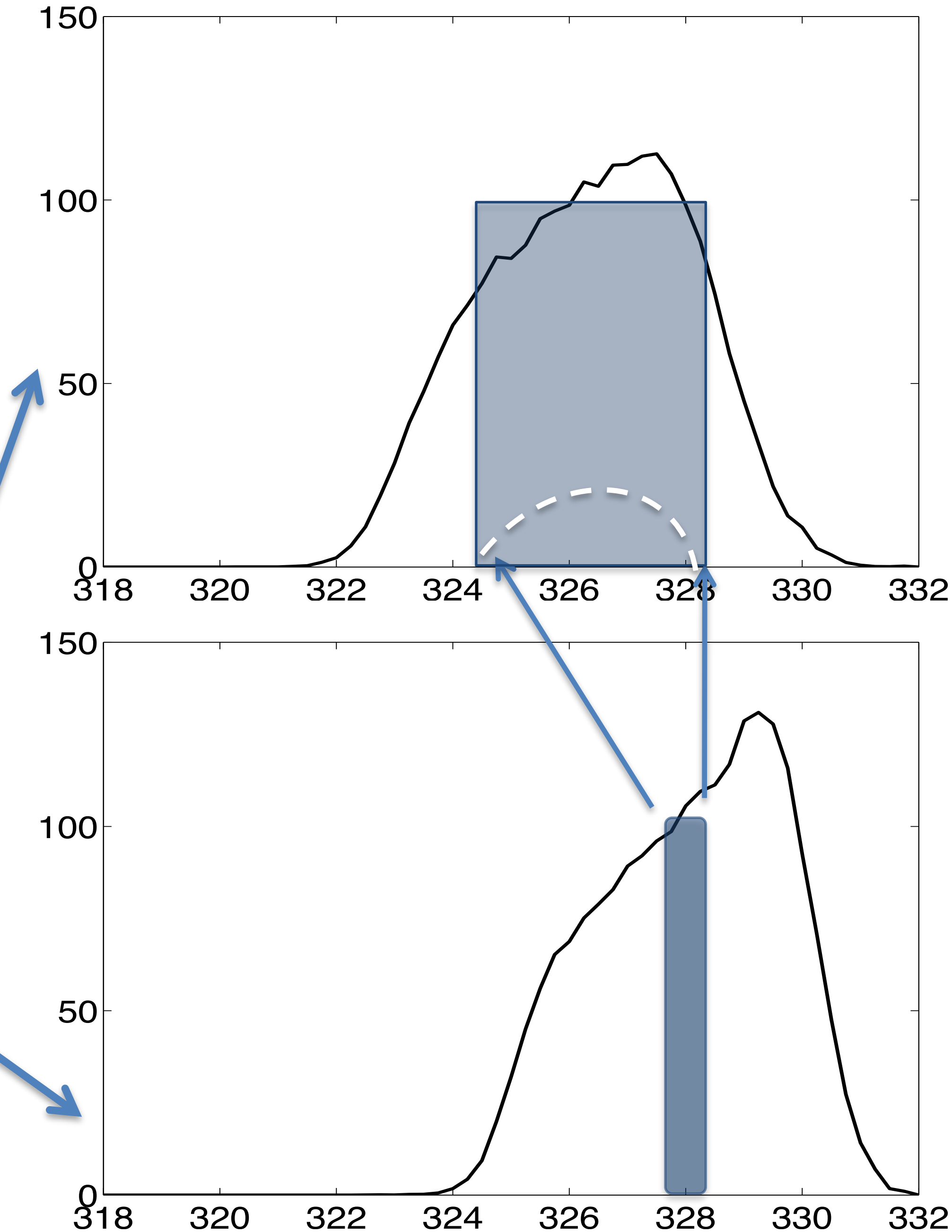
$$F(\phi) = \int m(\phi)(\phi - \phi_{env})d\phi,$$

We would like to know how m(ϕ) evolves with height.

We shall view this as a mapping process



Ctl: Mass flux distribution on mse



Construction with a Lagrangian Particle Dispersion model

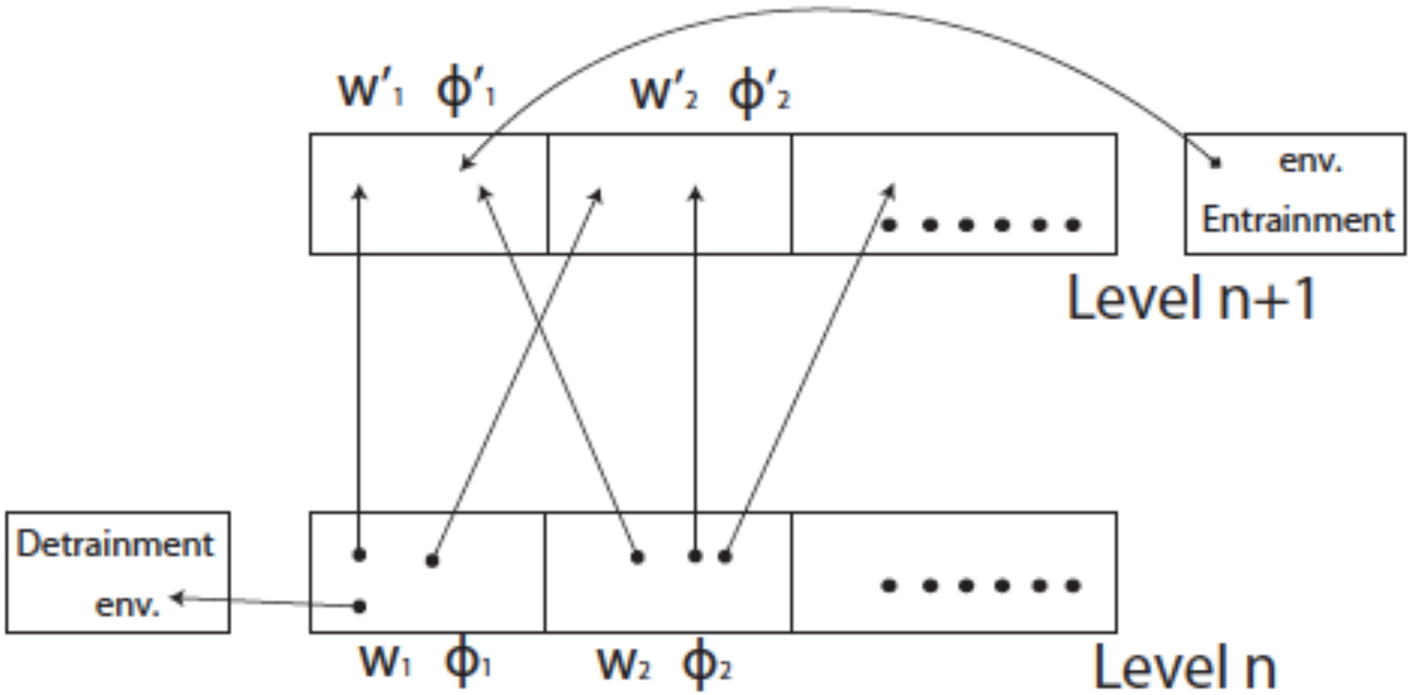
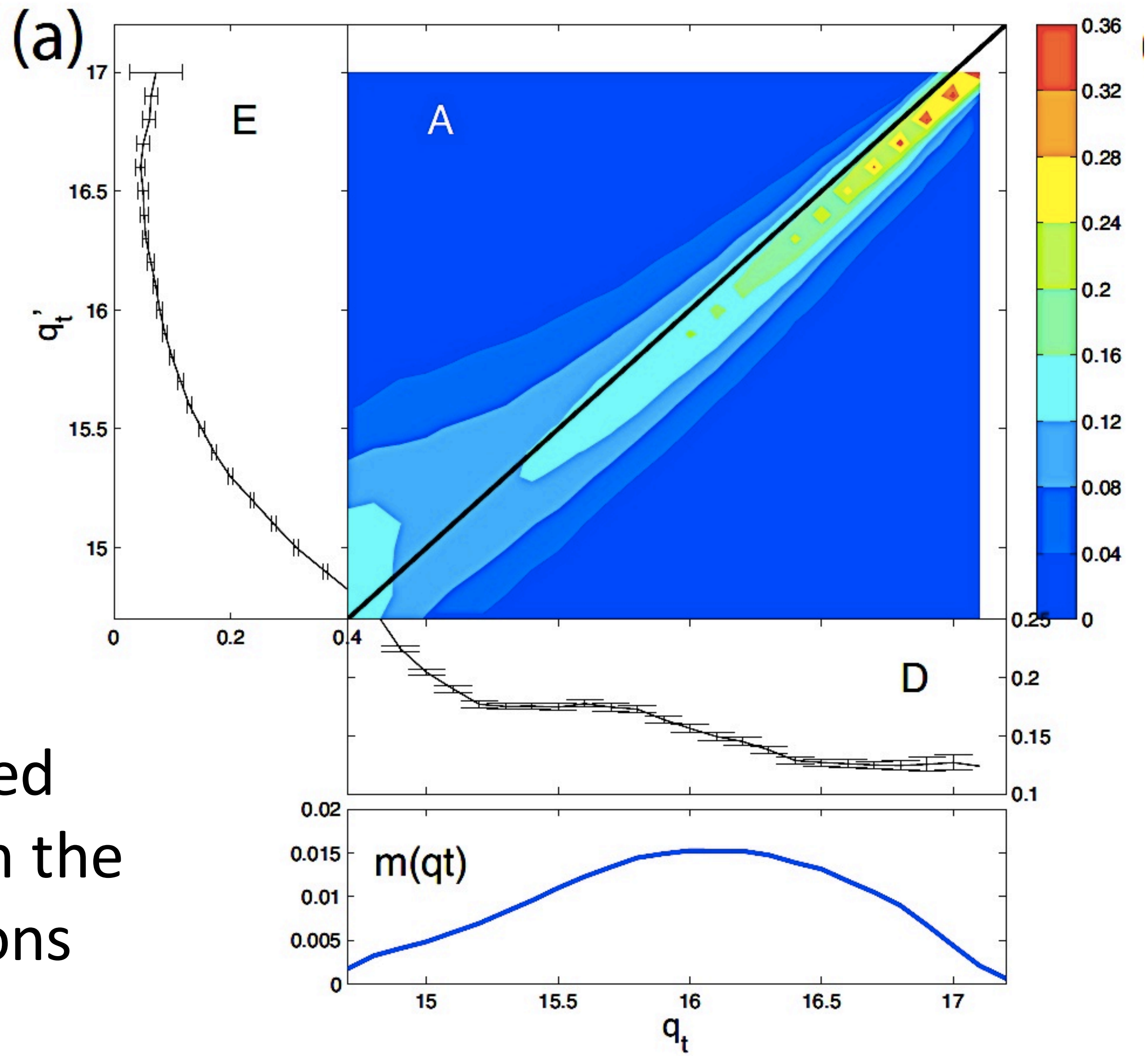


Figure 1. The diagram of the mapping process.

The mapping process

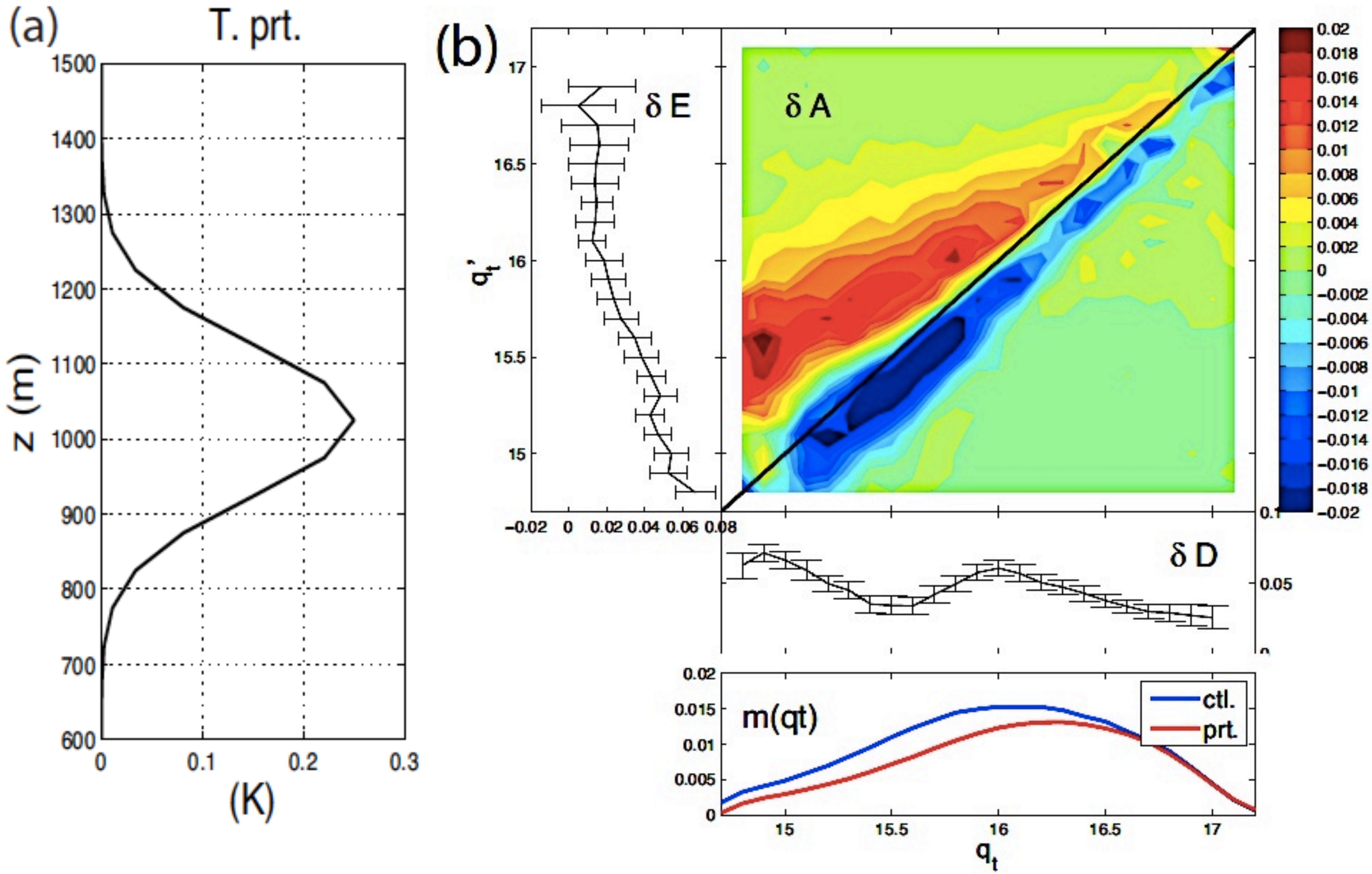
$$m_{n+1}(\phi') = (I + E(\phi', \phi'))A(\phi', \phi)(I - D(\phi, \phi))m_n(\phi),$$

The mapping matrices



Can be compared with those from the parameterizations

Response to small perturbations



- The Lagrangian particles carry with them their complete history and are powerful tools to study mixing within clouds and between clouds and their environment.

Convective available potential energy (CAPE)

$$\frac{1}{2}w_{\max}^2 = \int_{LFC}^{LNB} \frac{\rho_e - \rho}{\rho} g dz = R \int_{LNB}^{LFC} (T - T_e) d \ln p$$

- A similar quantity can be defined for convective inhibition
- Complications:
  - What are initial properties of the lifted parcel?
  - Nonhydrostatic pressure gradient
  - Entrainment

Compute the linear response functions

$$\frac{d\vec{x}}{dt} = M\vec{x}$$

- Define the state vector to include profiles of T and q anomalies (vertical shear could be included in the future)
- Assuming that T, q completely describe the column, i.e. the cumulus ensemble is in equilibrium with the T, q profiles. Reasonable for waves with periods of days or more.
- It's approximately linear for perturbations of relevant size

Method 1: introduce initial perturbations

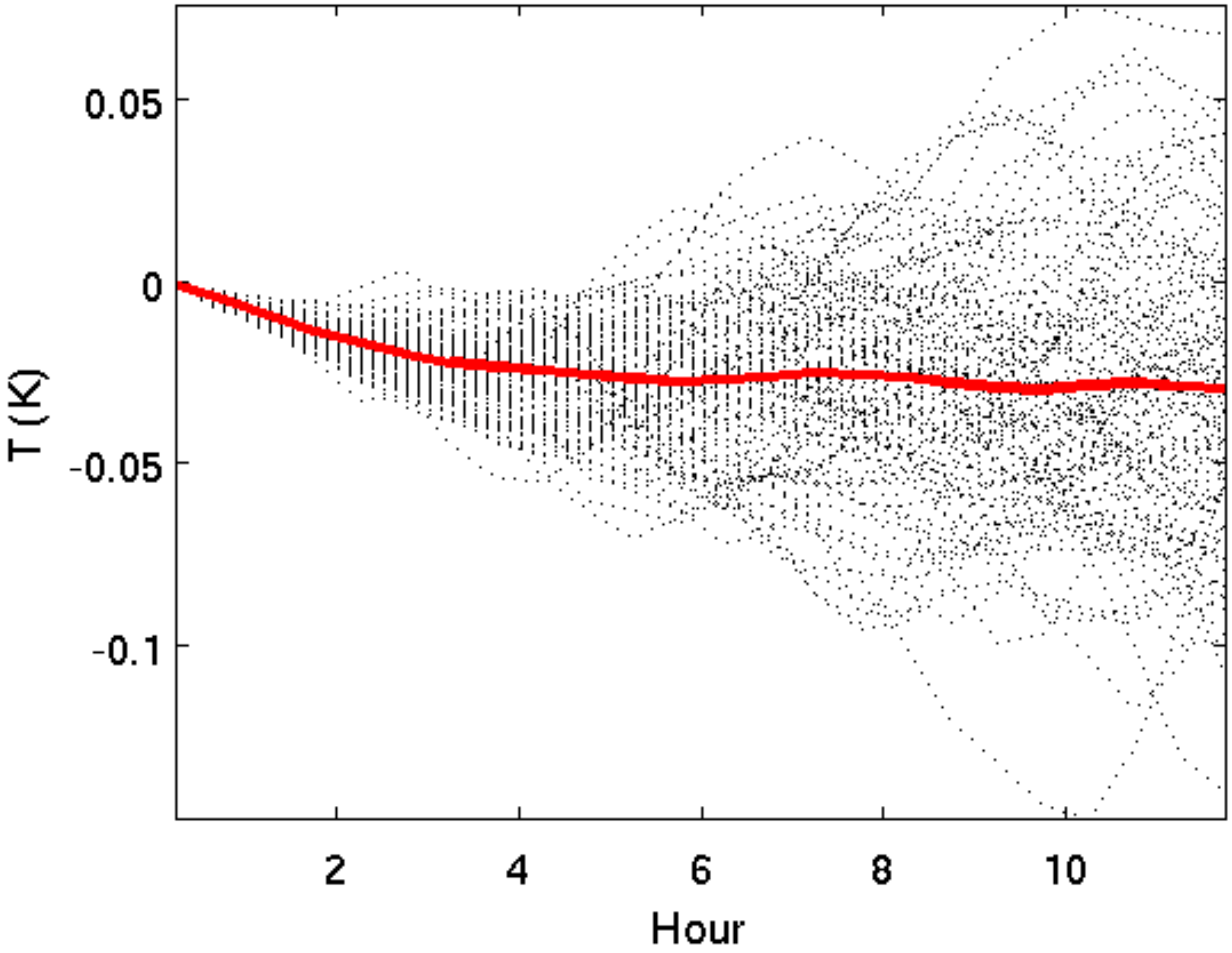
$$\left[\left(\frac{d\vec{x}}{dt} \right)_1 \quad \left(\frac{d\vec{x}}{dt} \right)_2 \quad \cdots \quad \left(\frac{d\vec{x}}{dt} \right)_n \right] = M \left[\vec{x}_1 \quad \vec{x}_2 \quad \ldots \quad \vec{x}_n \right]$$

•Intuitive, but…

•When the anomalies are first introduced, convection is not in equilibrium with the perturbed T, q profiles

•Large ensembles are needed to reduce the stochastic noise (as the anomalies constantly evolve (decay) with time, extensive time averaging is not an option)

The need for a sizable ensemble



Method 2: apply anomalous forcing

$$\left[\left(\frac{d\vec{x}}{dt}\right)_1 \quad \left(\frac{d\vec{x}}{dt}\right)_2 \quad \cdots \quad \left(\frac{d\vec{x}}{dt}\right)_n\right] = M\left[\vec{x}_1 \quad \vec{x}_2 \quad \cdots \quad \vec{x}_n\right]$$

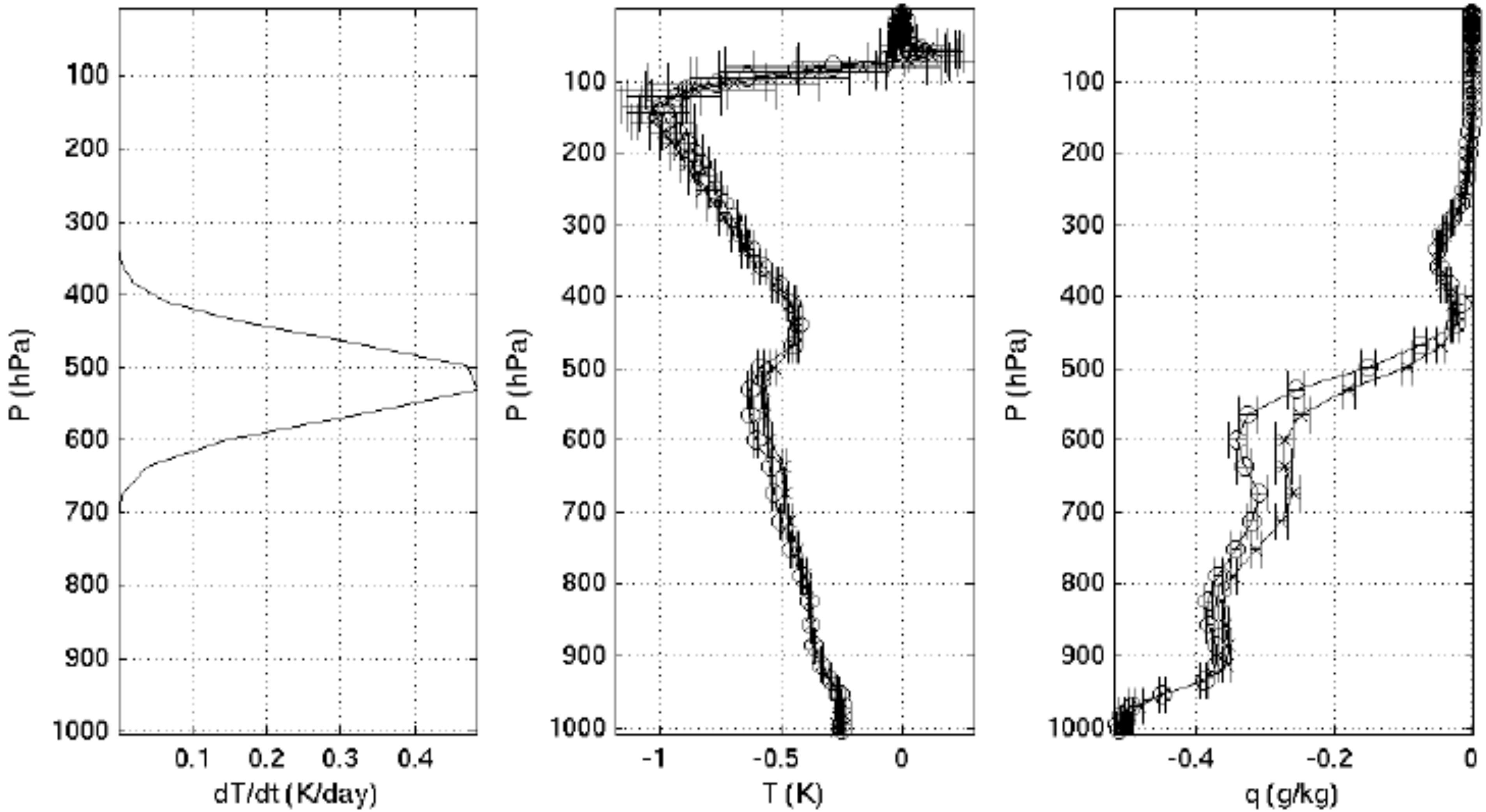
Prescribed forcing (precisely known)

Equilibrium response X
(has uncertainties)

$$|\delta\lambda| \propto |\lambda^2| \|\delta X\|$$

- The fastest decaying modes of M (i.e. with largest (in modulus) eigenvalues) have the largest errors
- The slowest decaying modes of M (i.e. smallest eigenvalues) are the most accurate.
- The latter are of the most interest for coupling with large-scale waves of relatively long periods

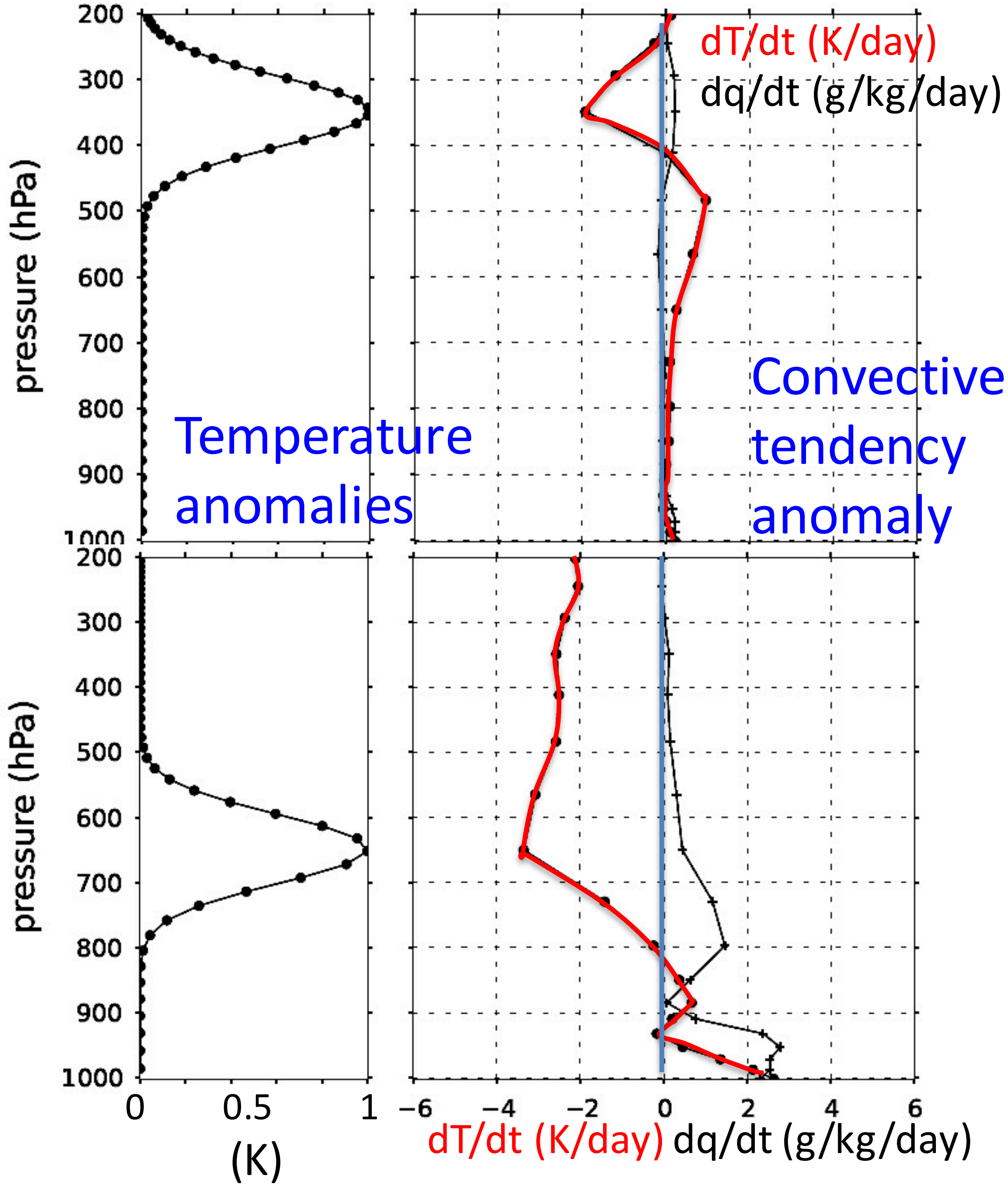
An example



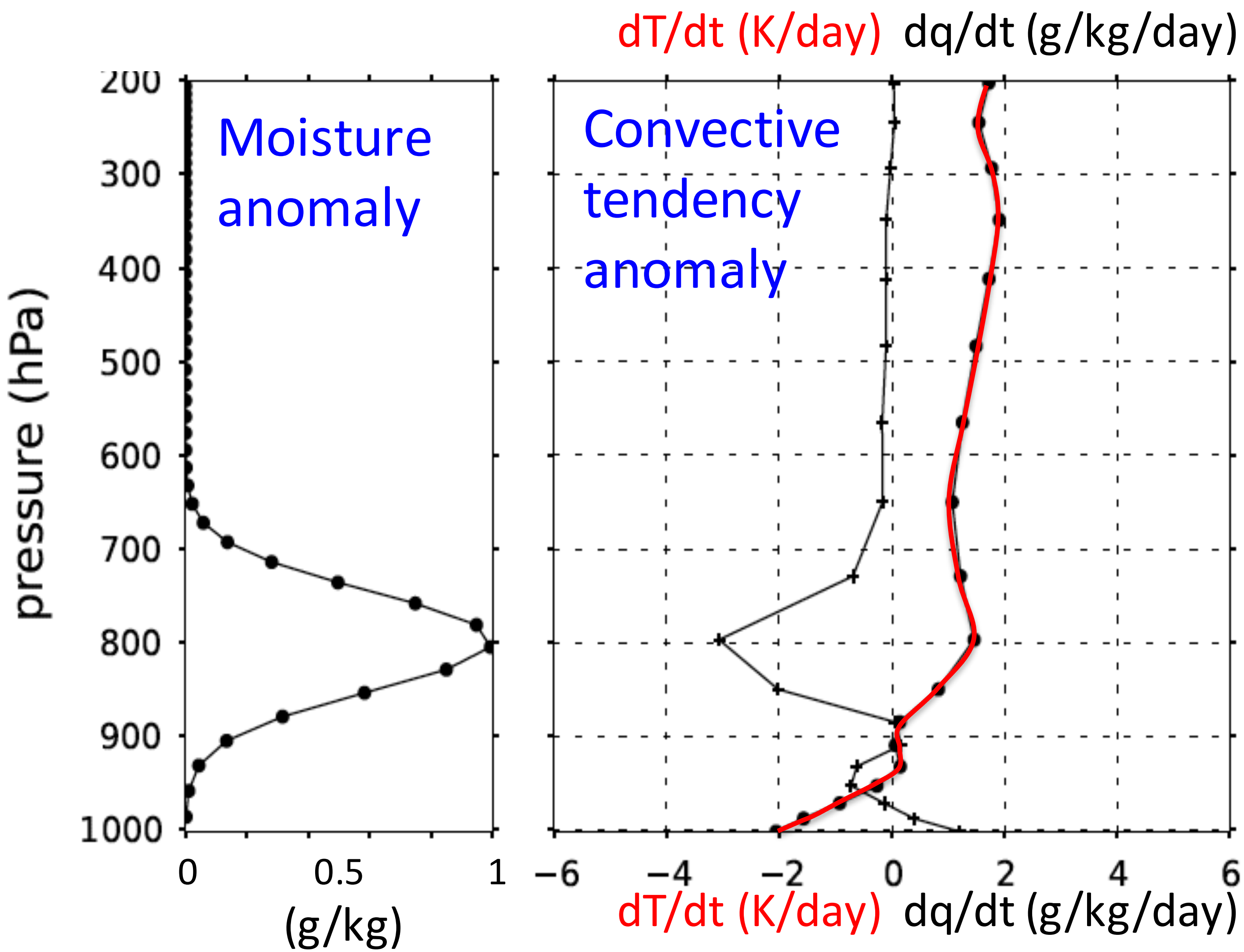
Approximately linear. Combining the two to increase the accuracy

Responses to temperature anomalies

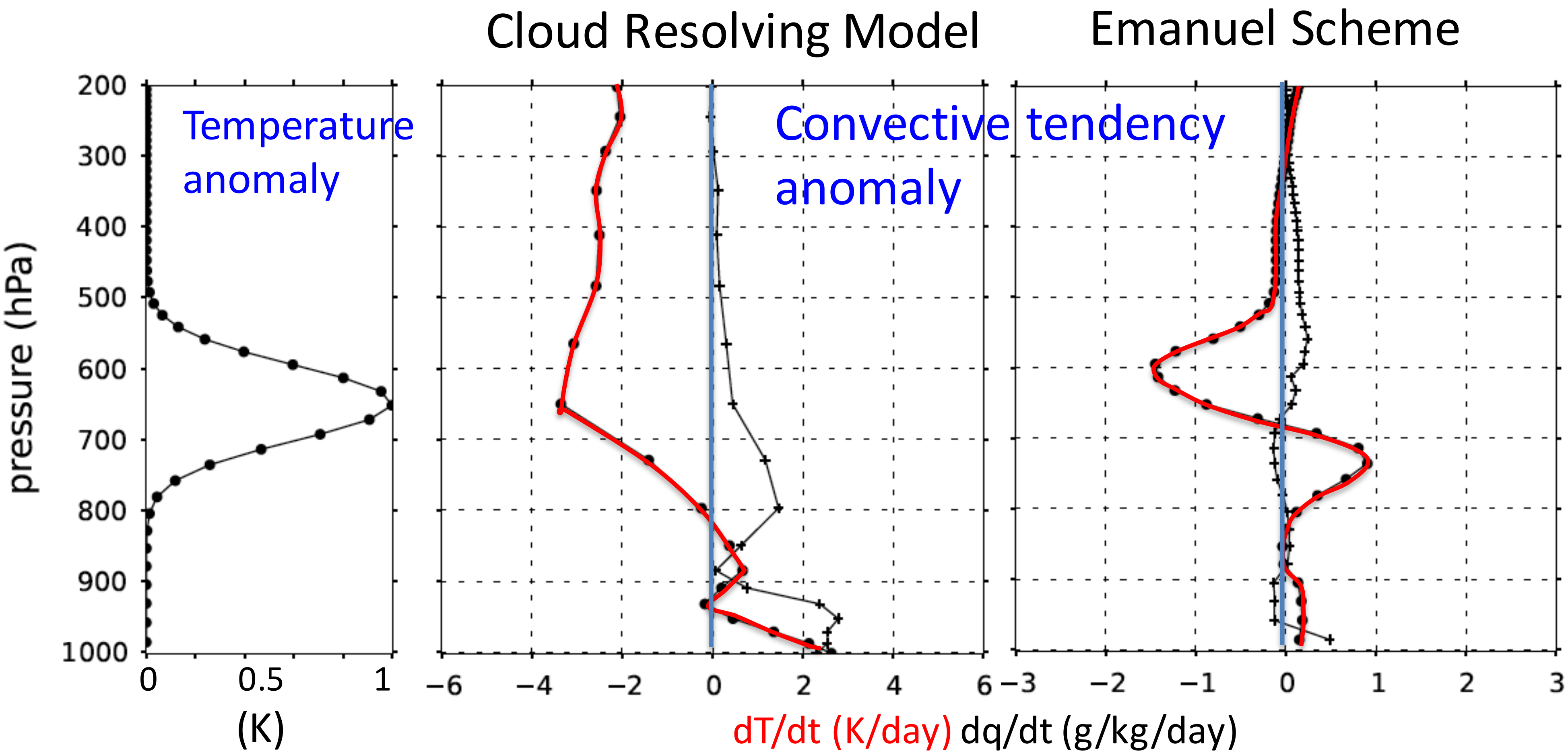
Convective responses to temperature anomalies in the lower troposphere are stronger and extend to the upper troposphere



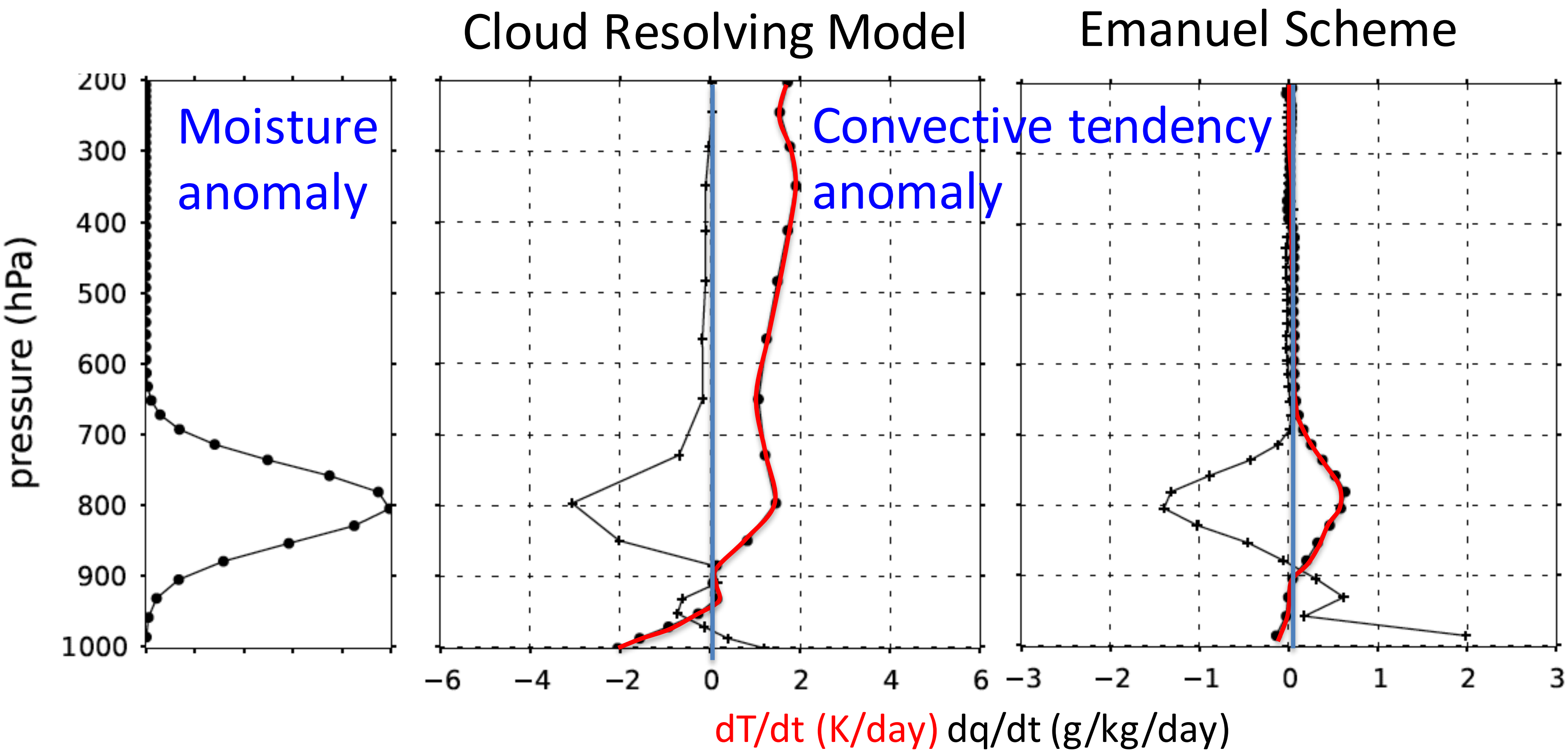
Effects of free troposphere humidity



Direct evaluations of the macroscopic behaviors of convective schemes



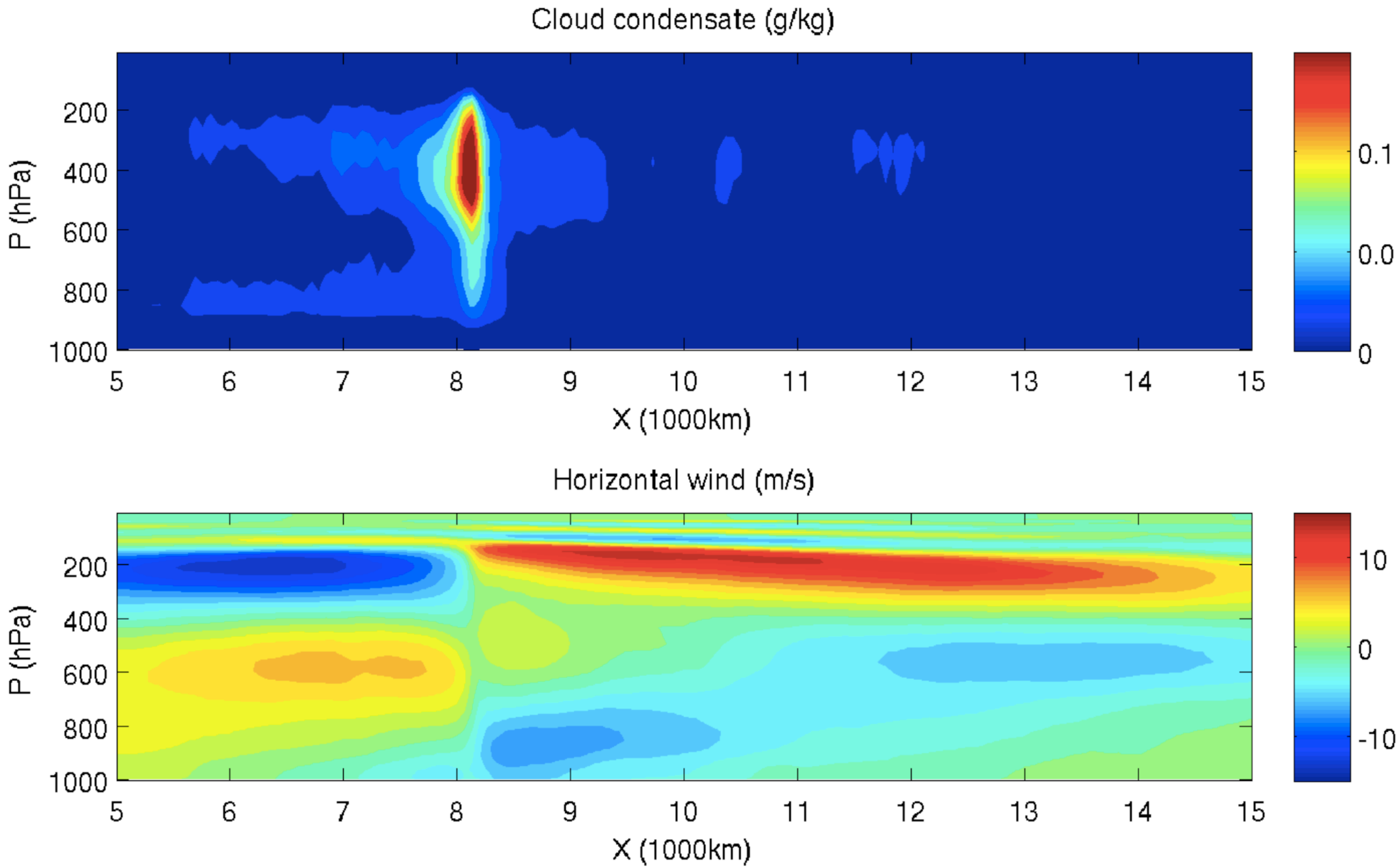
Herman and Kuang, in prep.



These comparisons offer clarity on why schemes don't produce convectively coupled tropical waves.

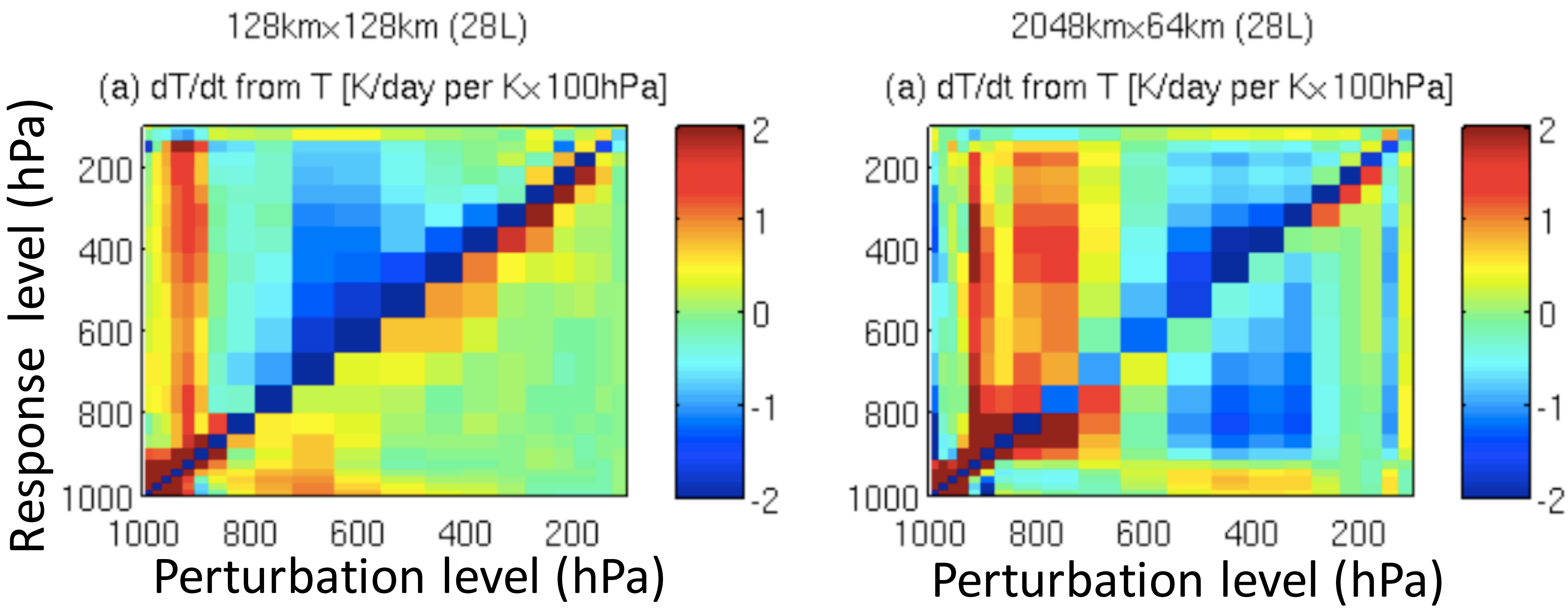
Herman and Kuang, in prep.

In the Walker experiments, convection is highly organized with deep low level inflows



Unorganized convection (parcel mode)

Organized convection (layer mode)



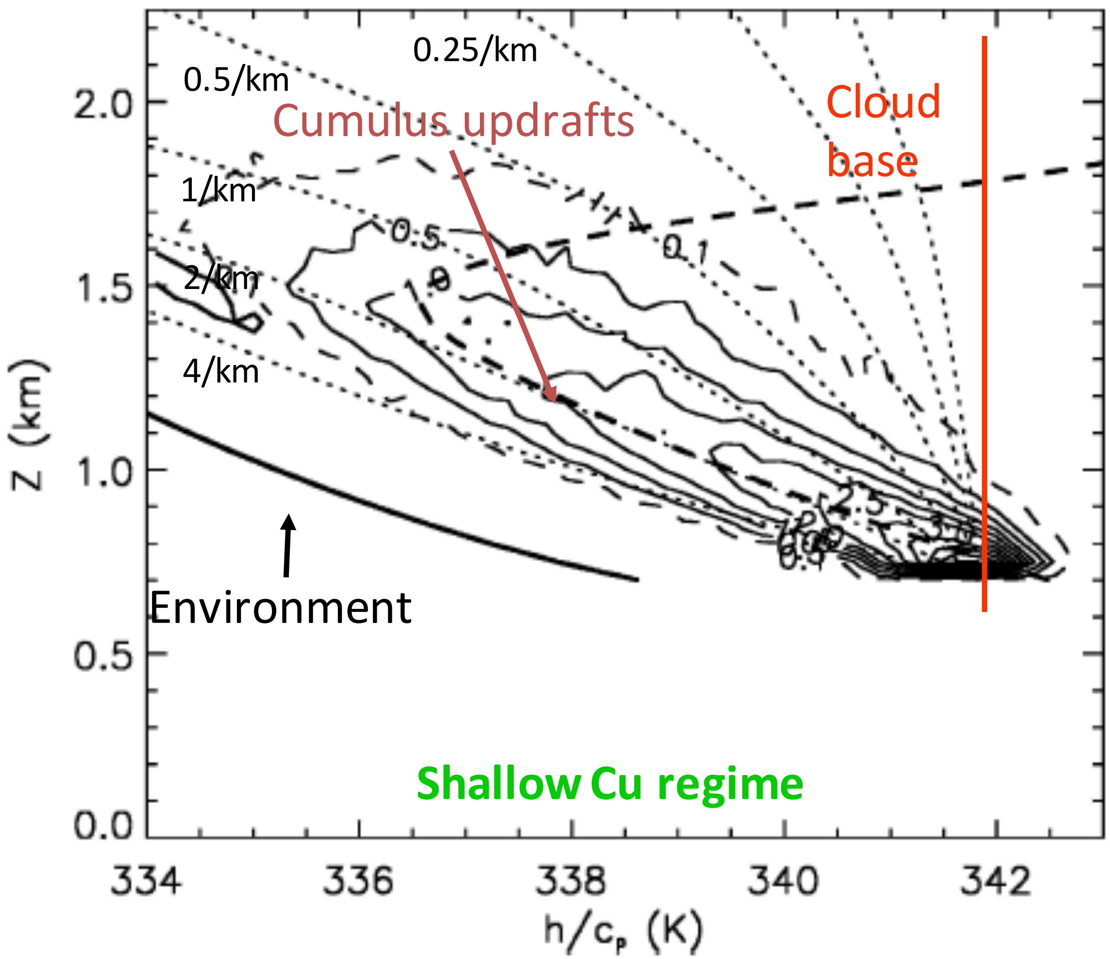
Responses to temperature and moisture perturbations depend on the degree of convective organization

MSE as an entrainment diagnostic

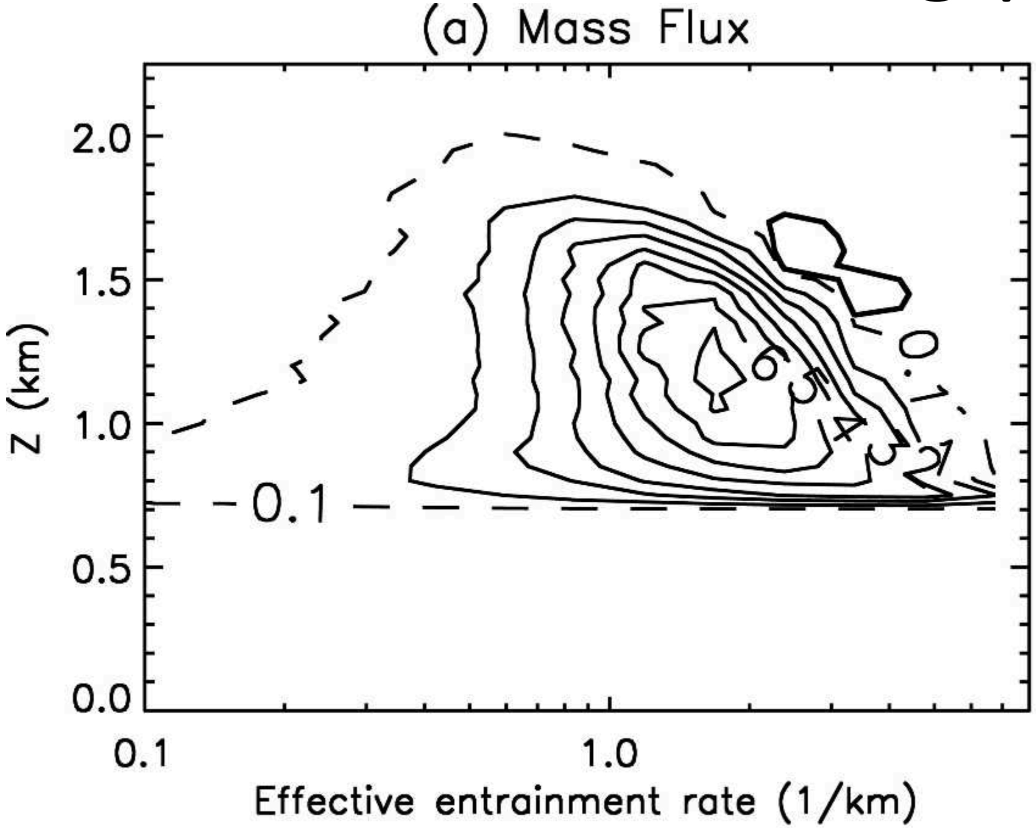
Invoke the entraining plume metaphor:

$$dh_{cu}/dz = \varepsilon(h_{env} - h_{cu})$$

Kuang and Bretherton, JAS, 2006



Viewed in terms of an ensemble of entraining plumes



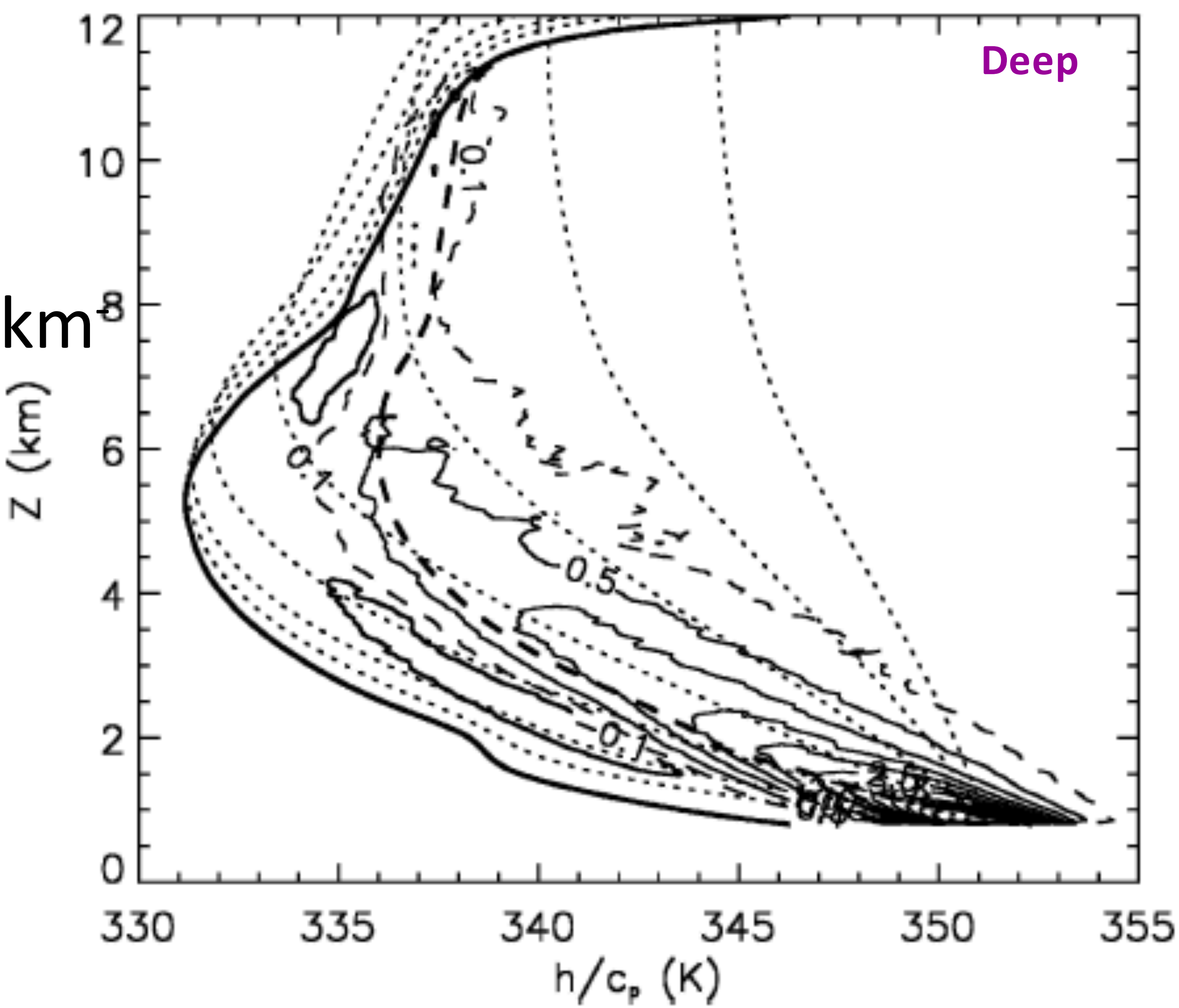
$dh_{cu}/dz = \varepsilon(h_{env} - h_{cu})$

- Mass flux concentrated at ε = 1-3 km^{-1} near cloud base.
- Strongly diluted parcels less buoyant, don't reach as high.

Is deep Cu regime very different?

No.

- Updrafts diluted
- ε = 0.5-1 km^{-1}
- bases uniform.



A refinement: Use of purity tracer

Romps and Kuang, JAS, 2009

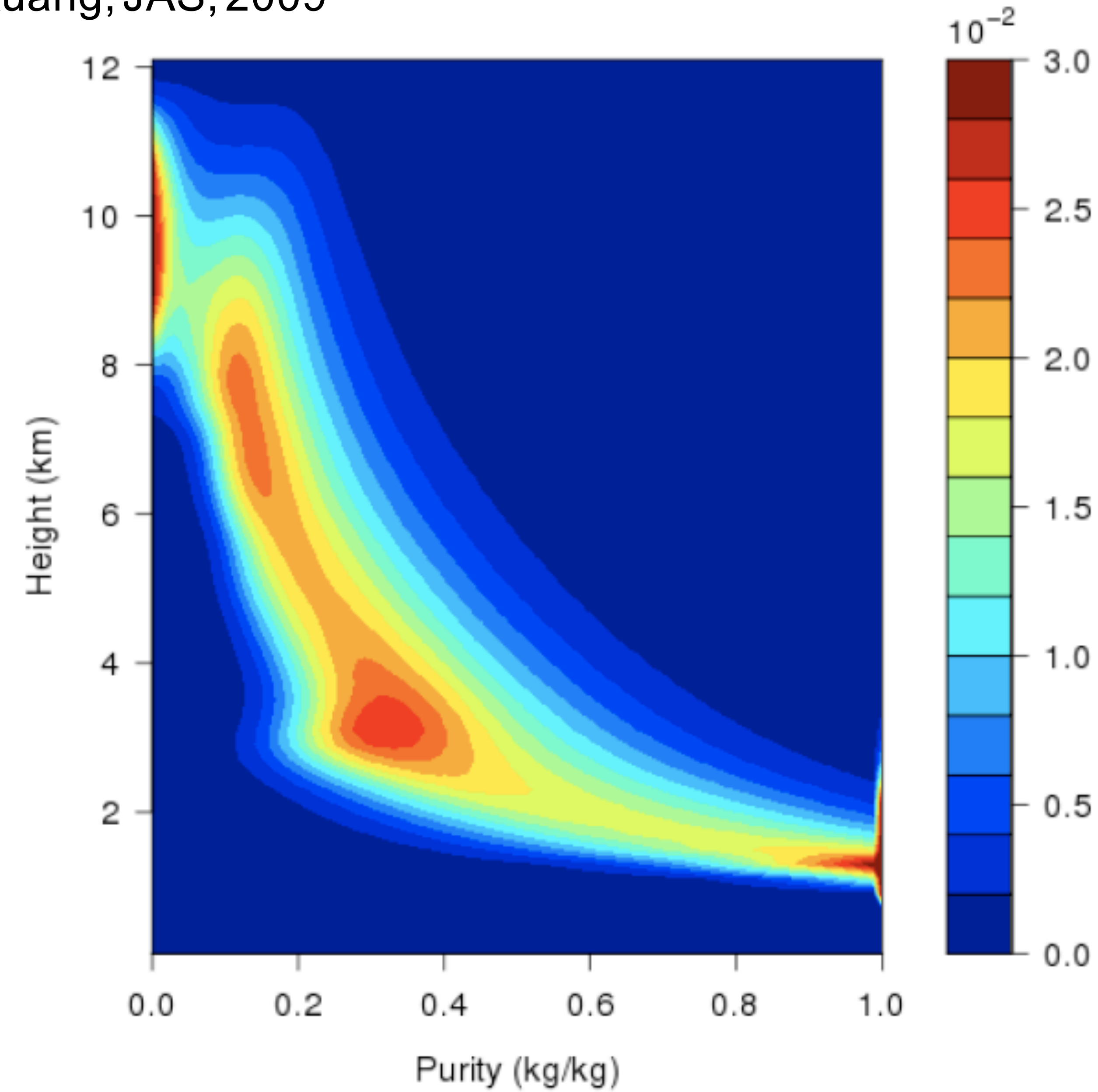
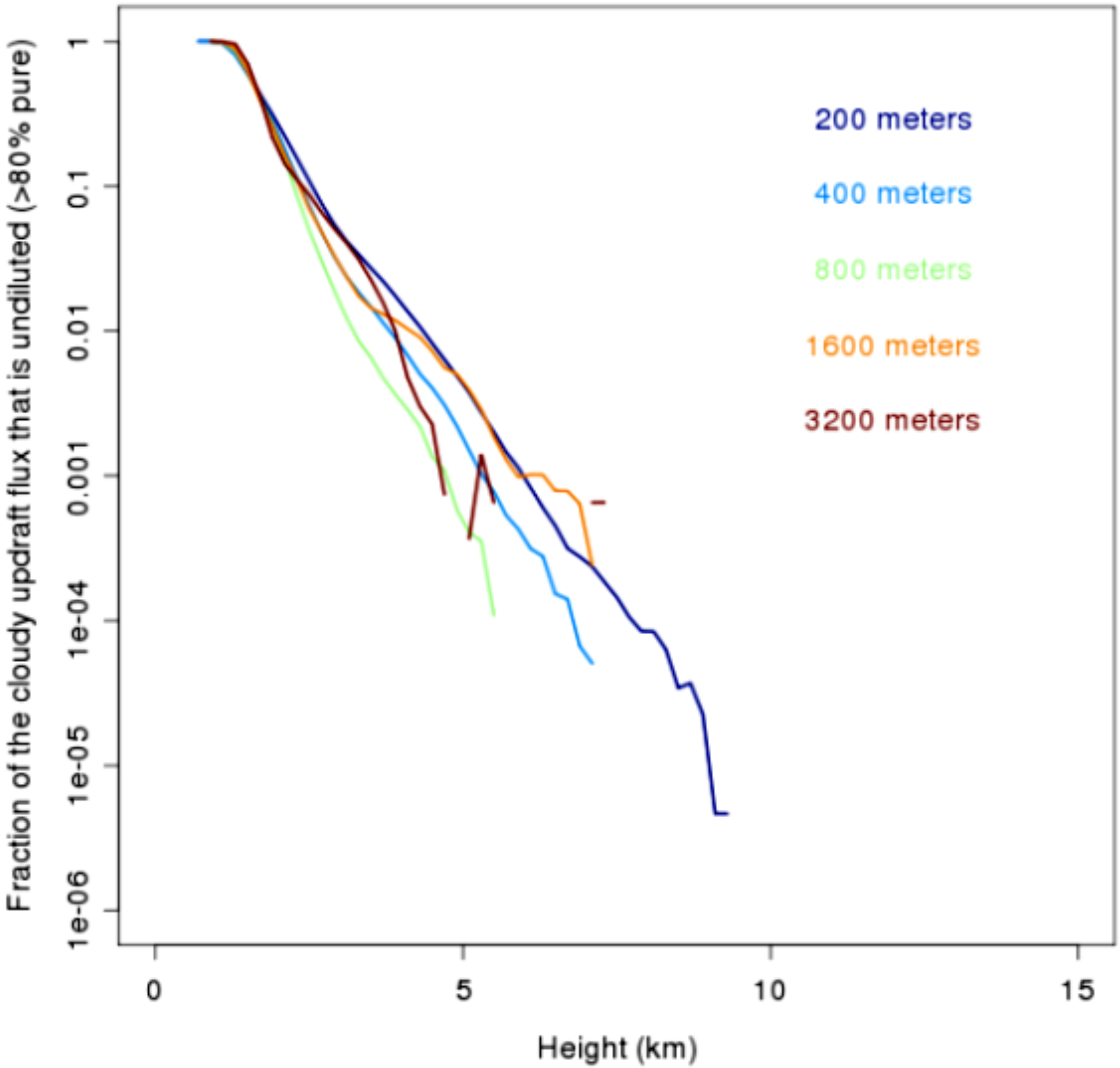
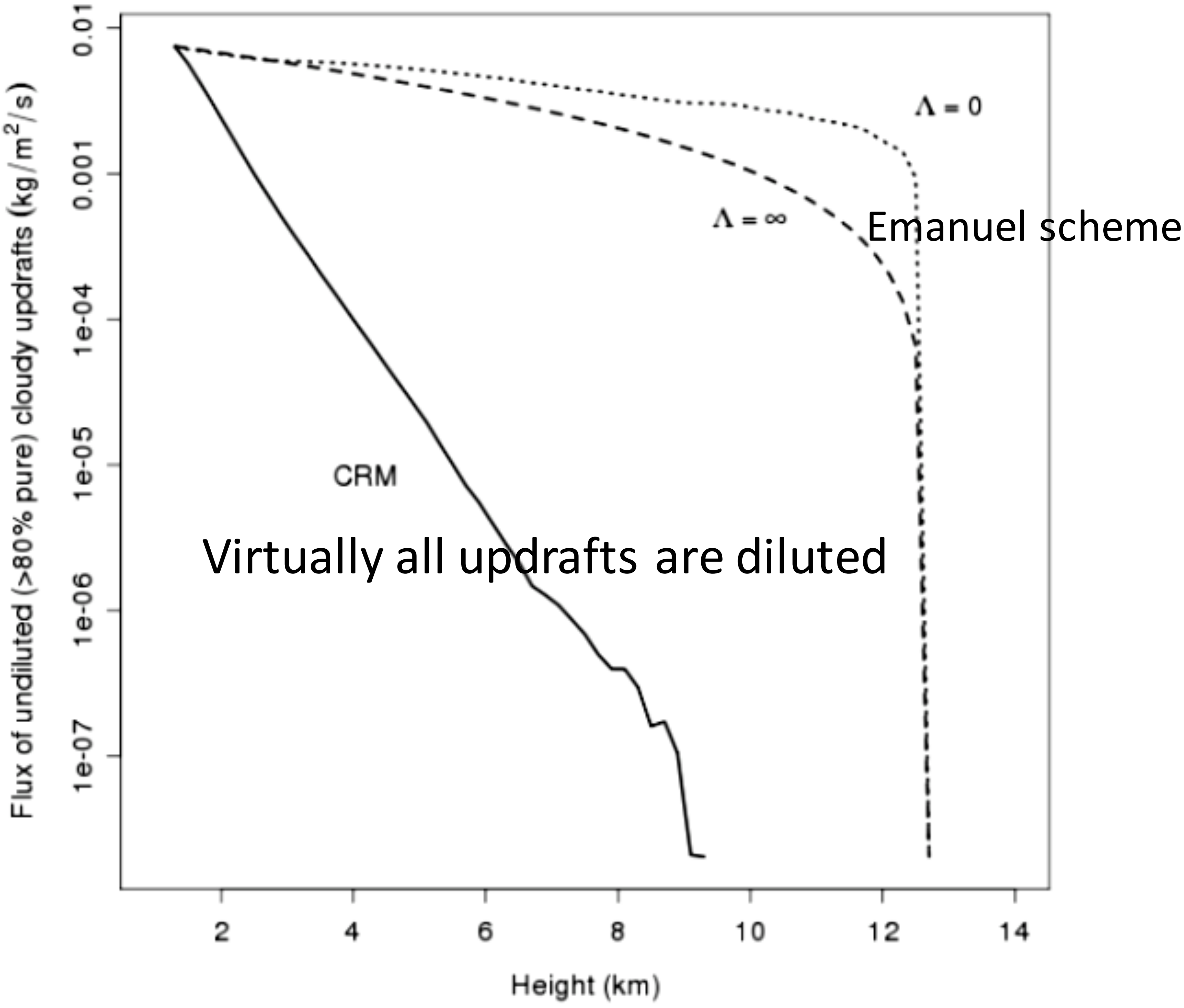


FIG. 3. Cloudy-updraft mass-flux density (kg/m^2/s per kg/kg of purity interval) for the 200-meter run binned according to height and purity.



Fraction of the cloudy updraft flux that is undiluted (>80% pure)
1
0.1
0.01
0.001
1e-04
1e-05
1e-06
0
5
10
15
Height (km)
200 meters
400 meters
800 meters
1600 meters
3200 meters


Flux of undiluted (>80% pure) cloudy updrafts (kg/m^2/s)
0.01
0.001
1e-04
1e-05
1e-06
1e-07
Λ = 0
Λ = ∞
Emanuel scheme
CRM
Virtually all updrafts are diluted
2
4
6
8
10
12
14
Height (km)

Probing the response of convection to large-scale temperature anomalies with a Lagrangian Particle Dispersion Model

Ji Nie and Zhiming Kuang

Harvard University

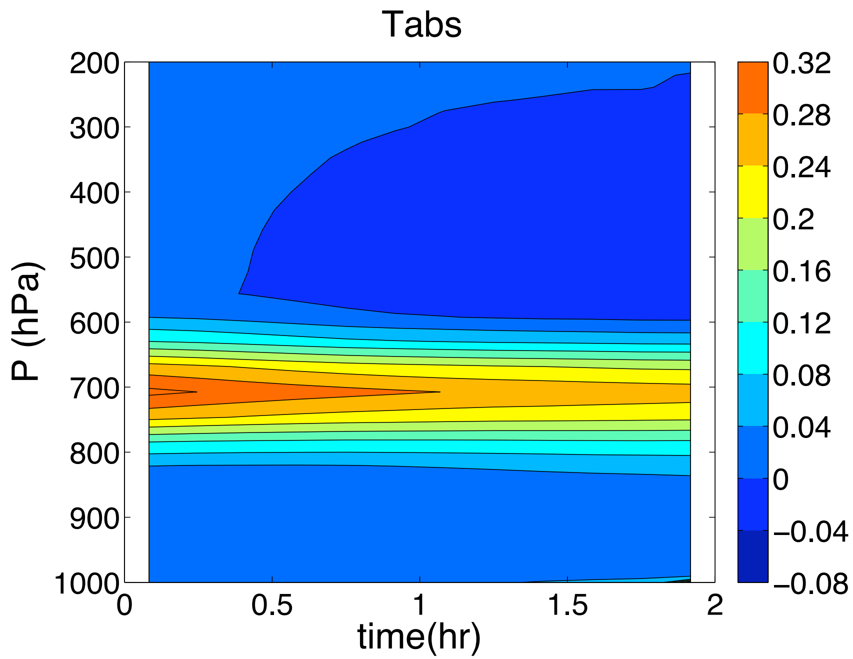
April, 2012

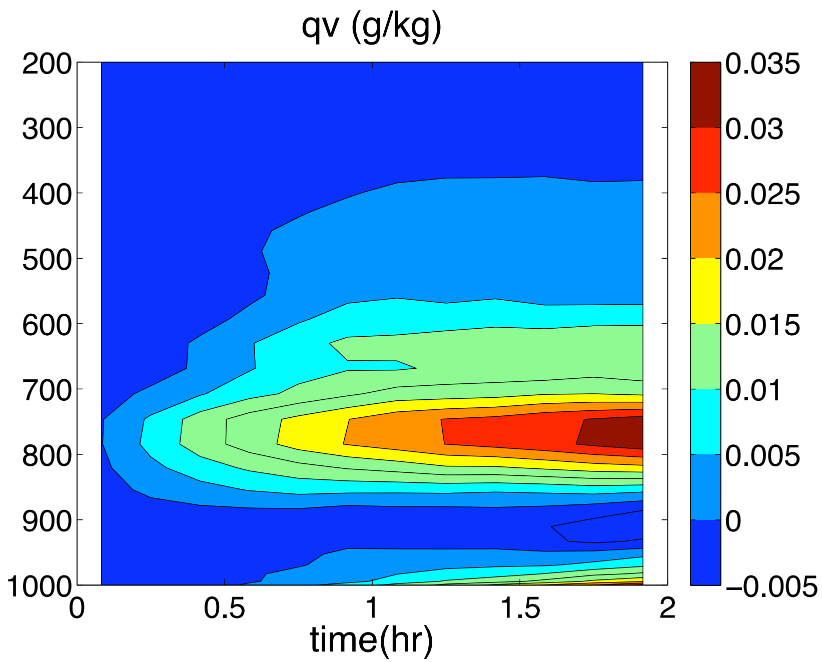
Motivation:

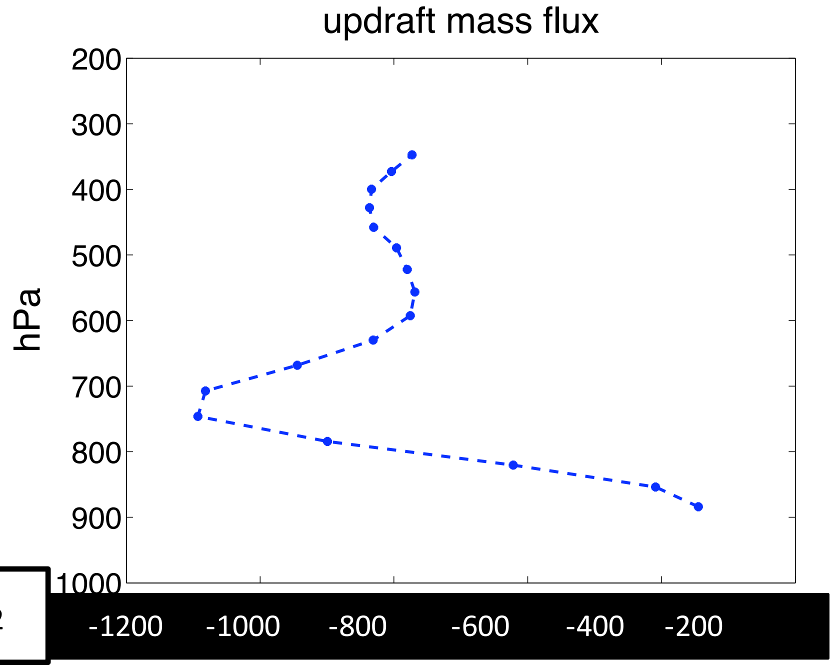
The responses of convection to small large-scale temperature and moisture perturbations summarize its macroscopic behaviors around a reference state (Kuang 2010; Tulich and Mapes, 2010).

These responses can be used to probe dynamics of convection. It was done for shallow convection in Nie and Kuang (in press). In this talk, we will look at deep convection.

A warm anomaly that peaks at 700 hPa:



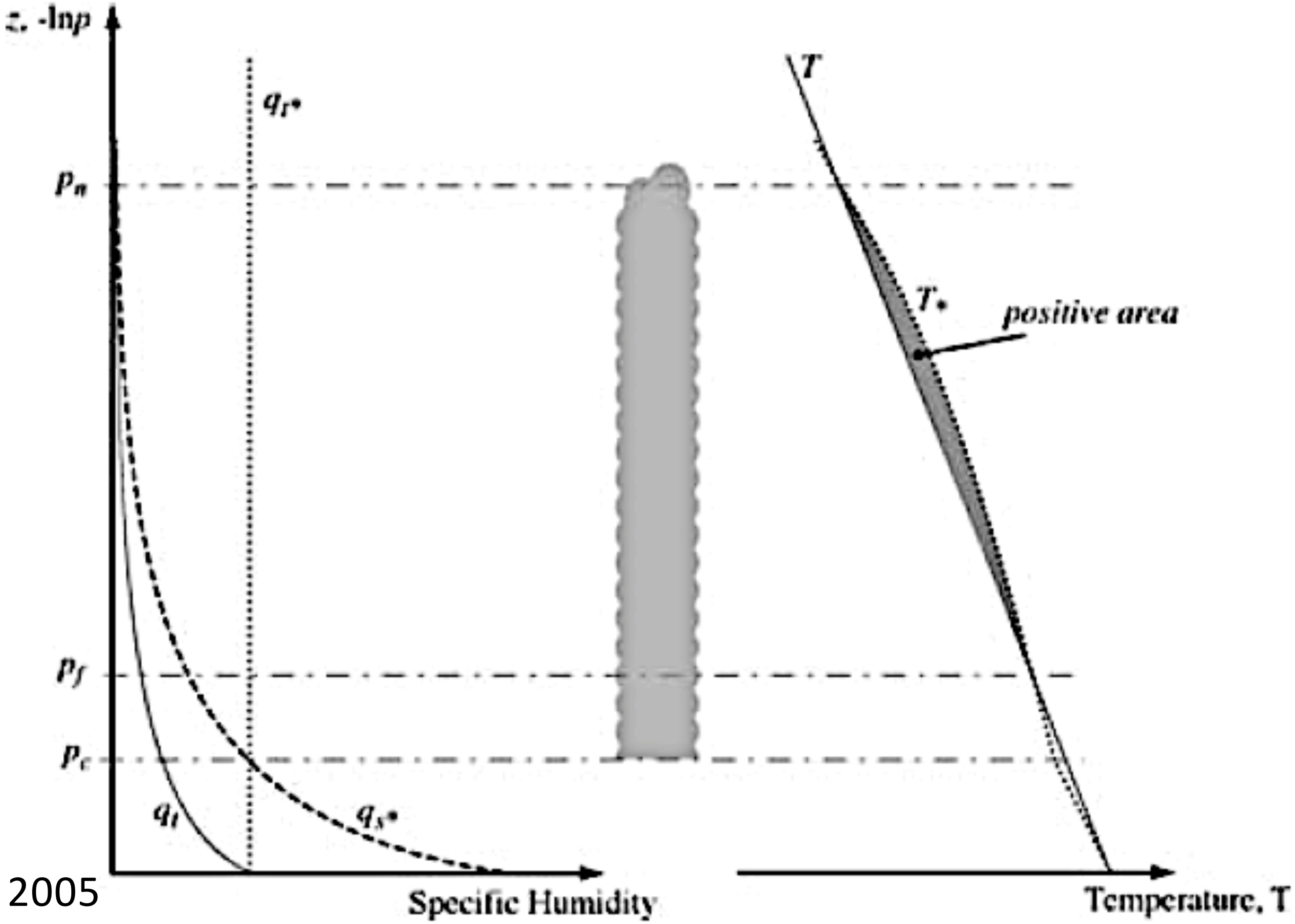




Unit: 1e-5 kg/s/m^2

Ctl: radiative-convective equilibrium
Prt: with a warm anomaly (0.3K) that peaks at 700 hPa

Conditional instability



Stevens, 2005

How does cumulus convection restore convective neutrality?

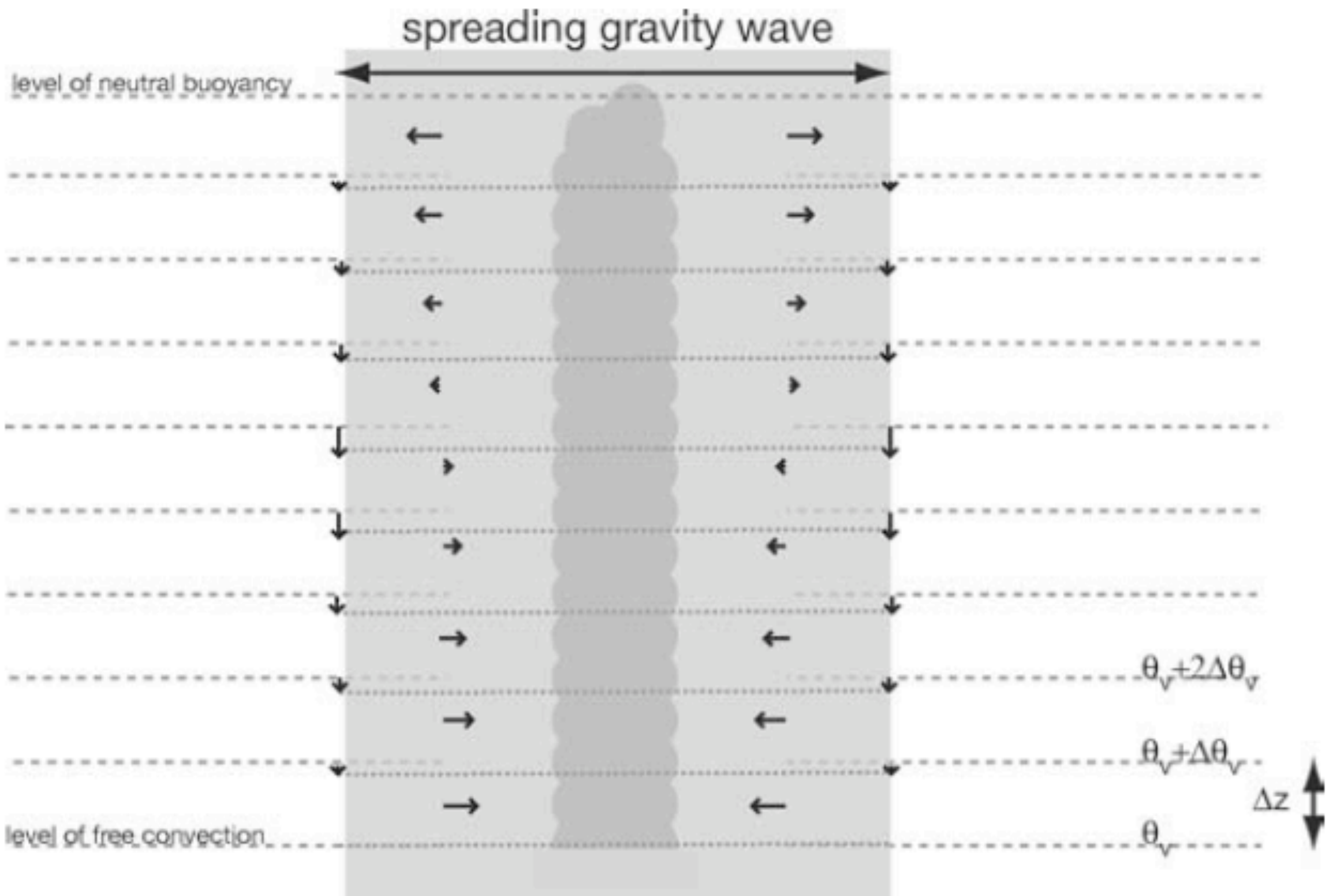
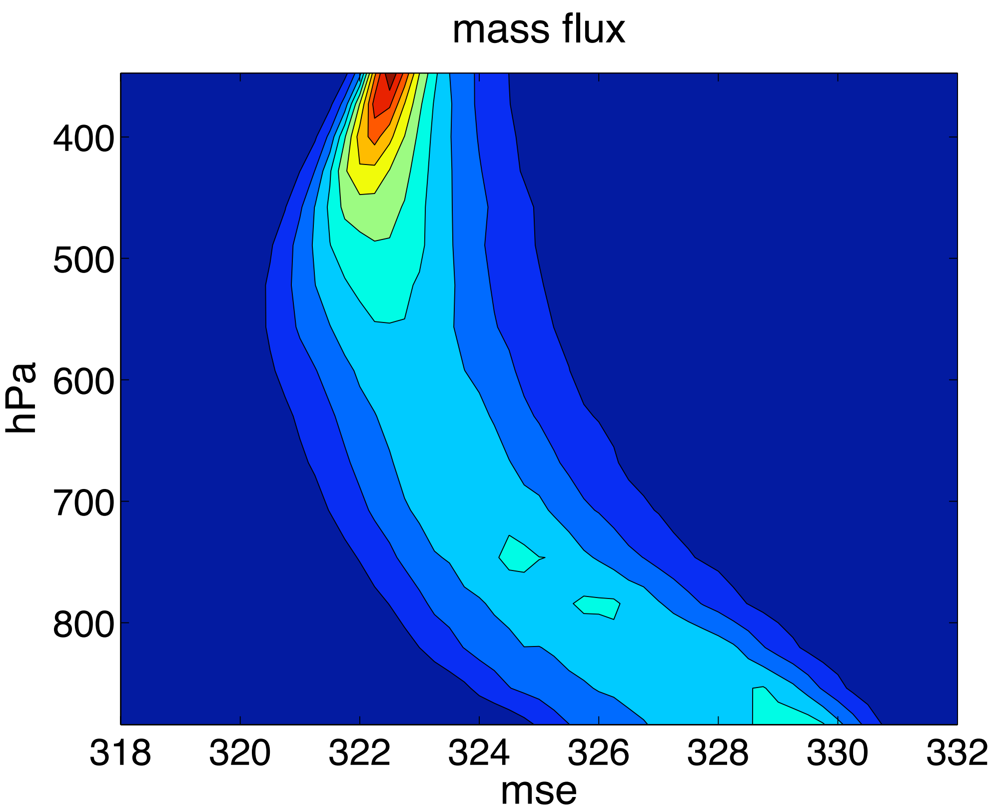


Figure 10 Schematic of adjustment owing to cumulus heating following Bretherton & Smolarkiewicz (1989). Here the transient adjustment to the moist-adiabatic lapse

Mass flux distribution on moist static energy (mse):

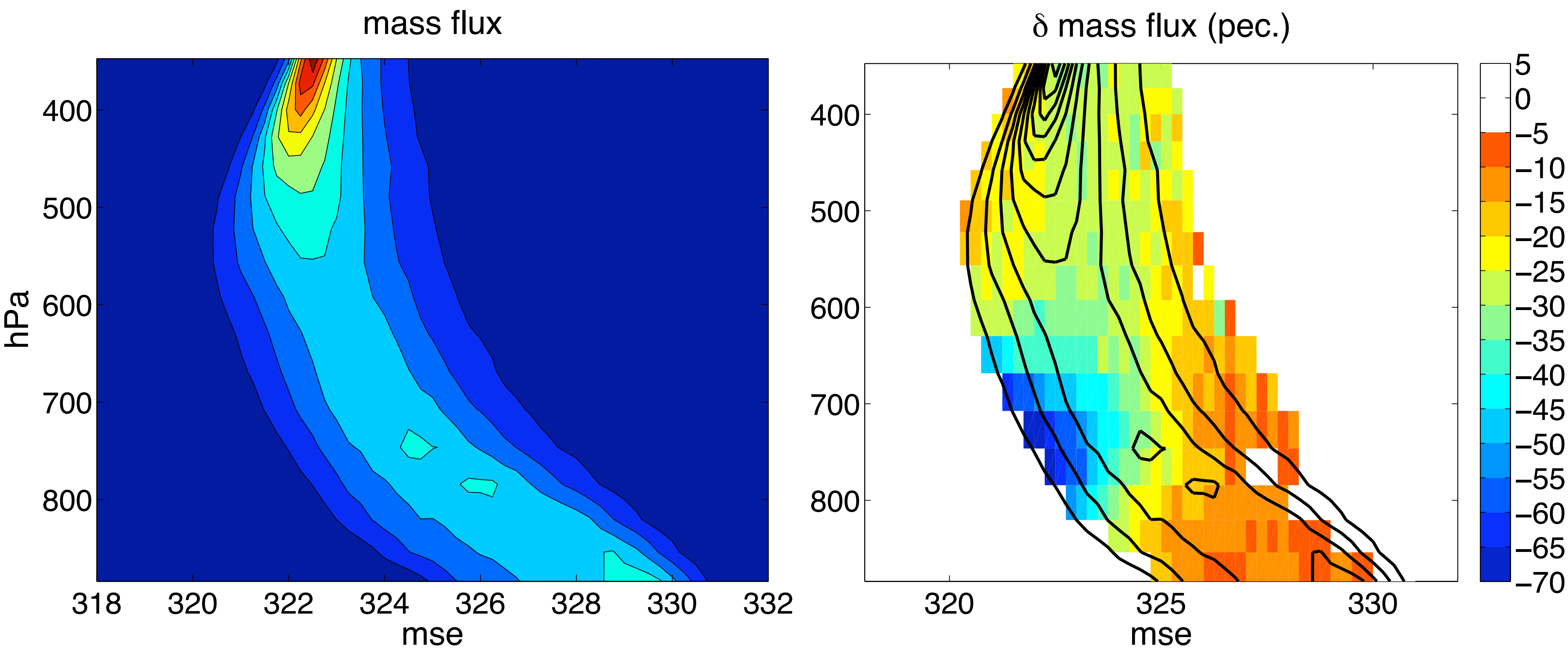
Ctl:



Mass flux distribution on moist static energy (mse):

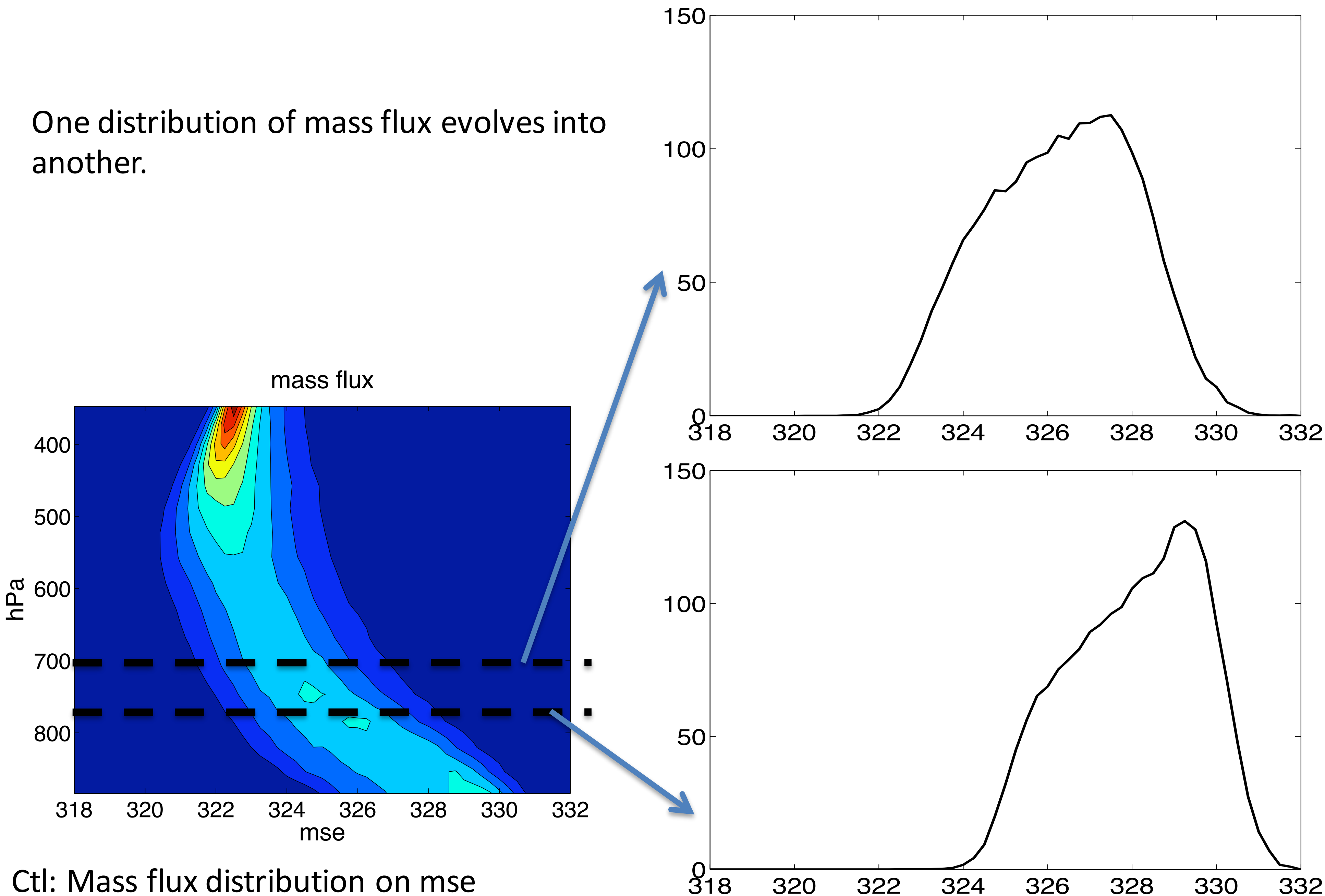
Ctl:

Prt – Ctl:



A new diagnostic framework:

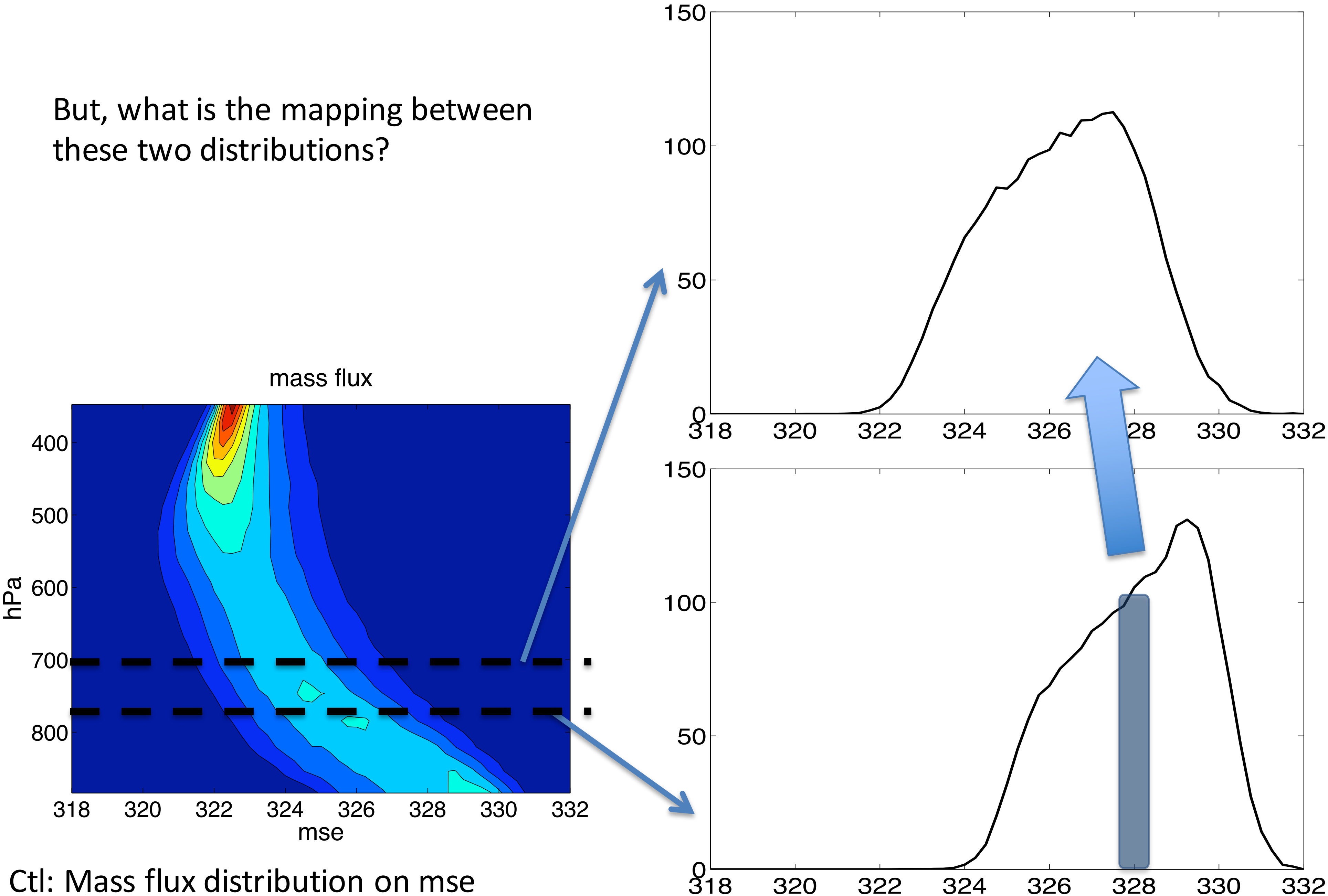
One distribution of mass flux evolves into another.



Ctl: Mass flux distribution on mse

A new diagnostic framework:

But, what is the mapping between these two distributions?

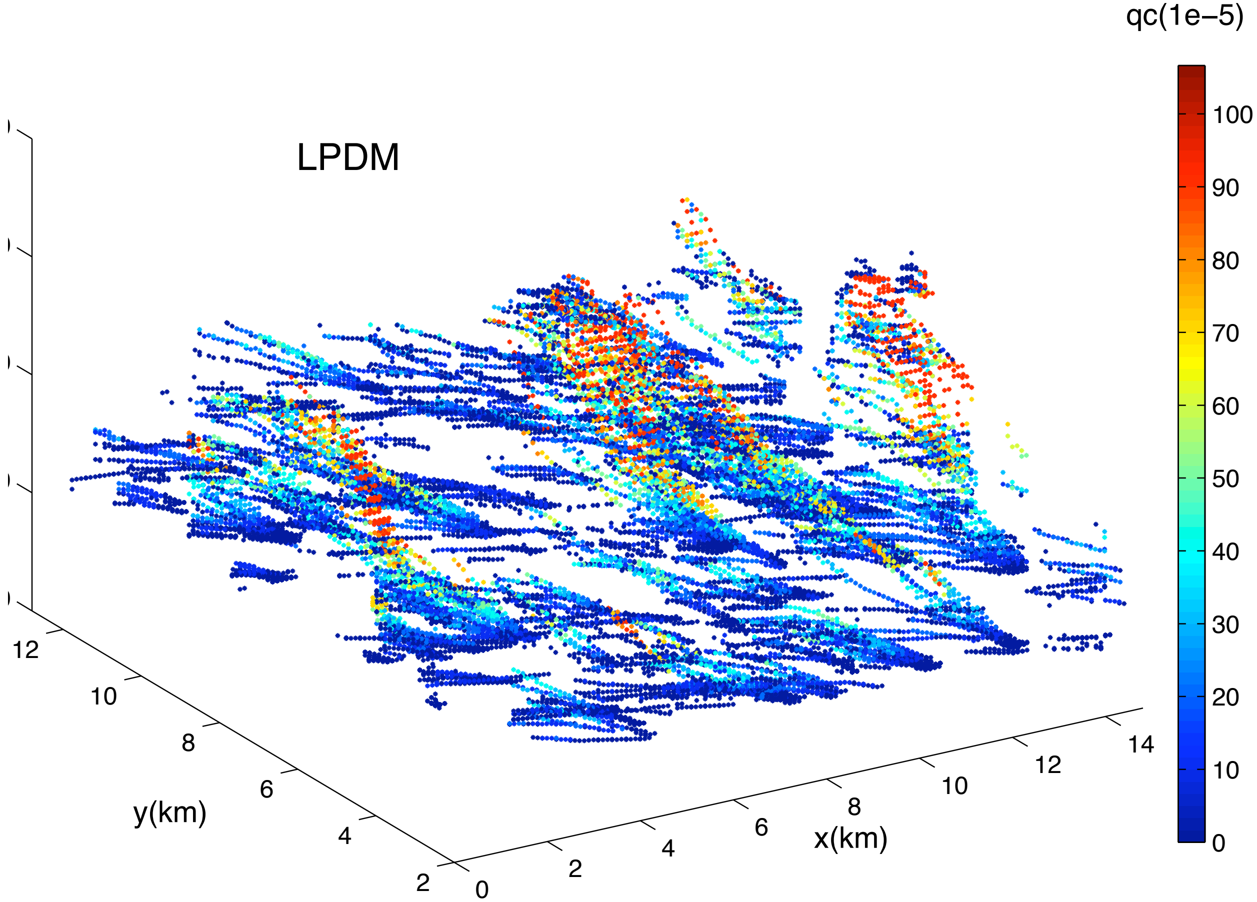


Ctl: Mass flux distribution on mse

Lagrangian Particle Dispersion Model (LPDM):

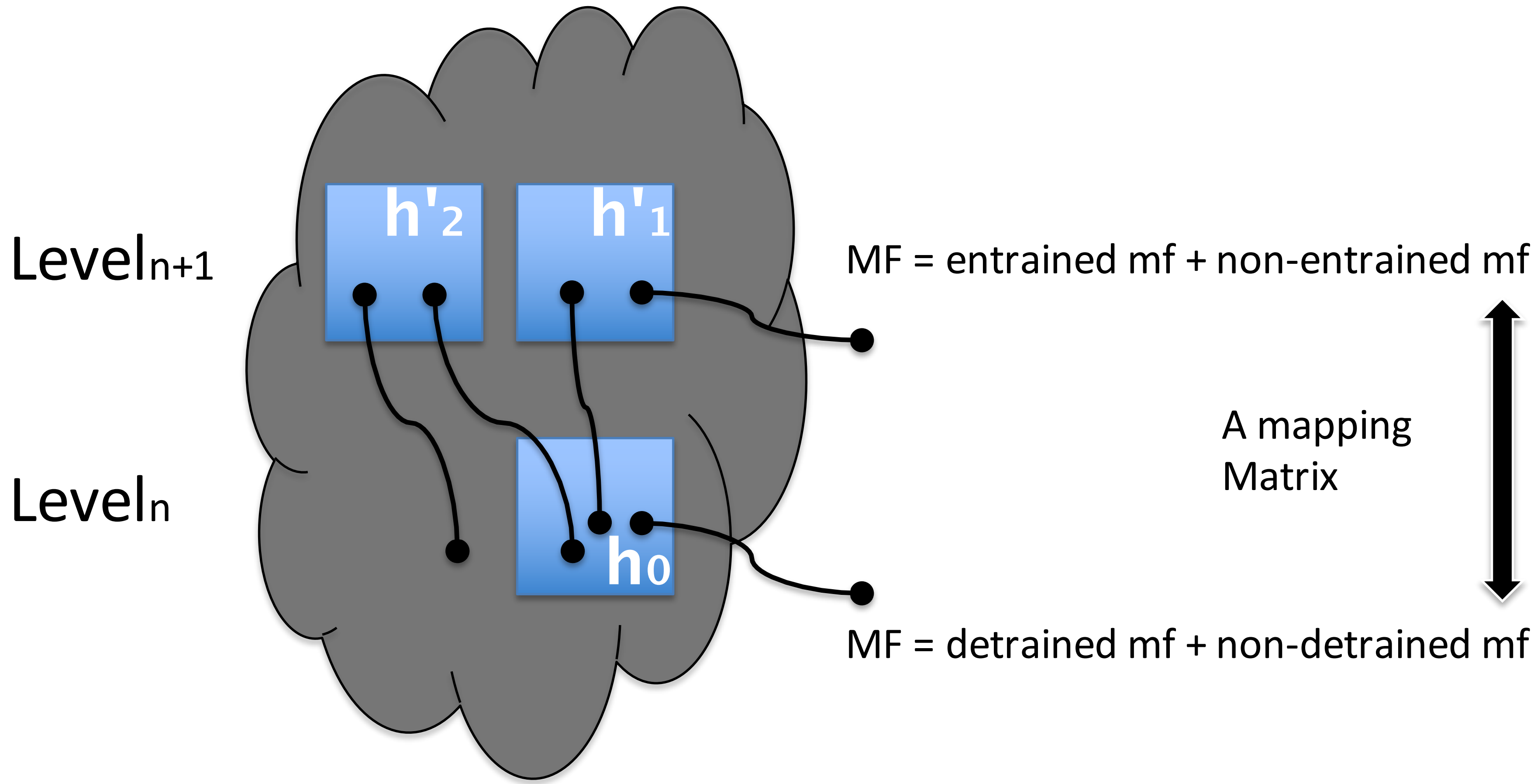
Many massless particles are randomly released in each grid box and then advected around by the CRM winds.

The trajectories of these particles, and the thermodynamics and dynamics properties reveal information of cumulus dynamics.

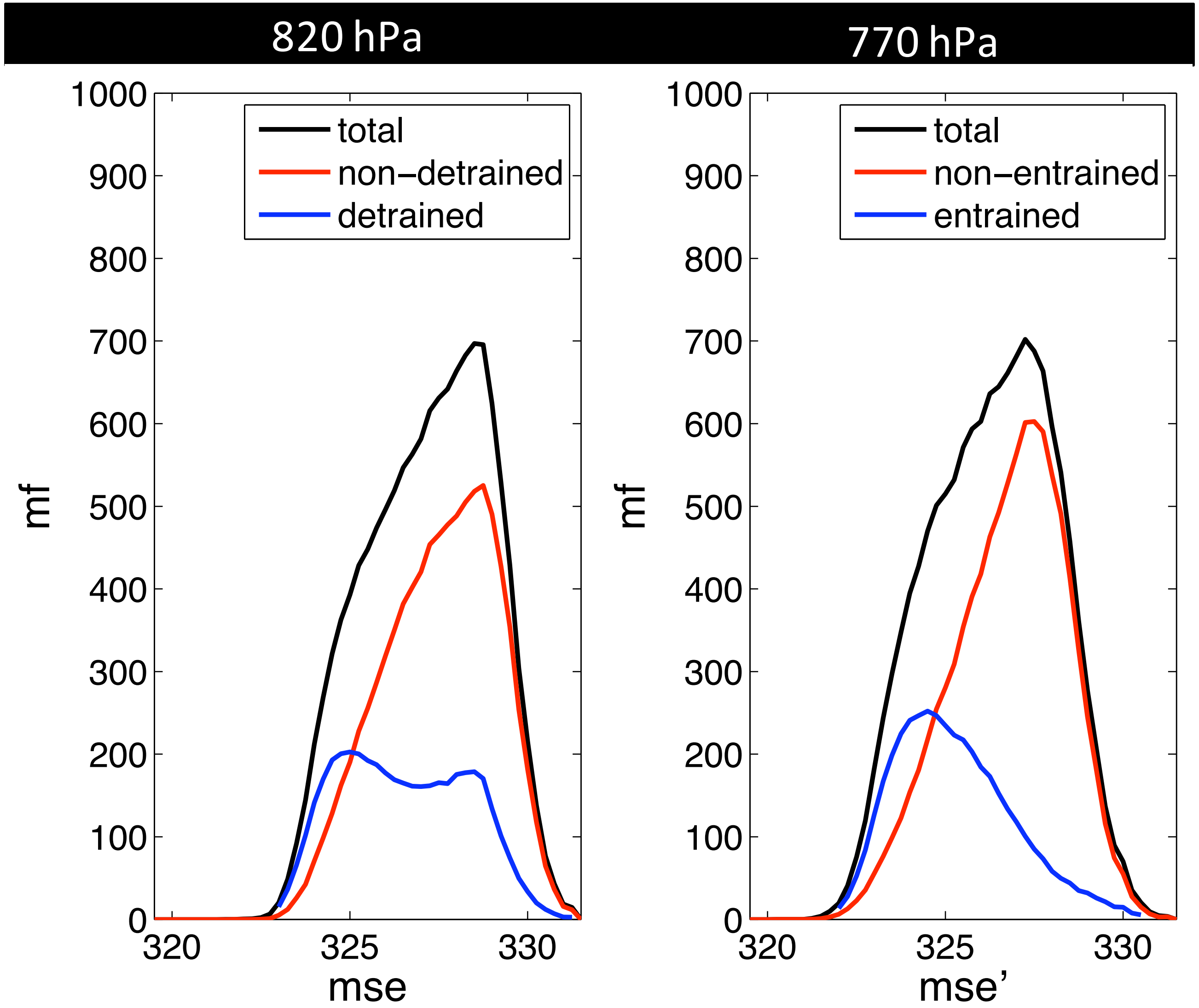


Its applications in research of convection:
Weil et. al. 2004, Heus et. al. 2008

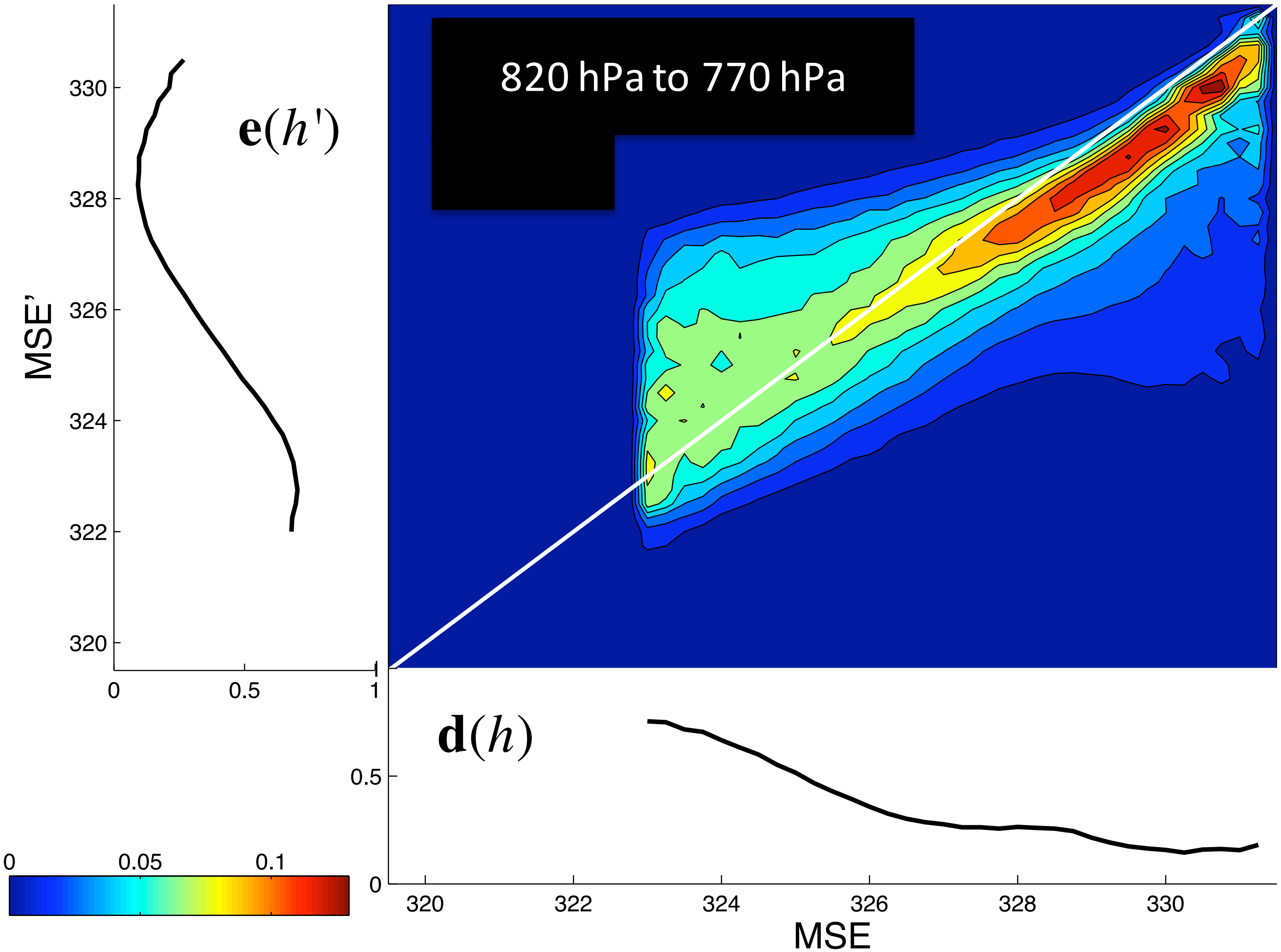
Constructing the mapping matrix using the LPDM:



[redacted]


820 hPa
770 hPa
total
non−detrained
detrained
mf
mse
total
non−entrained
entrained
mf
mse’
0
100
200
300
400
500
600
700
800
900
1000
320
325
330

[redacted]

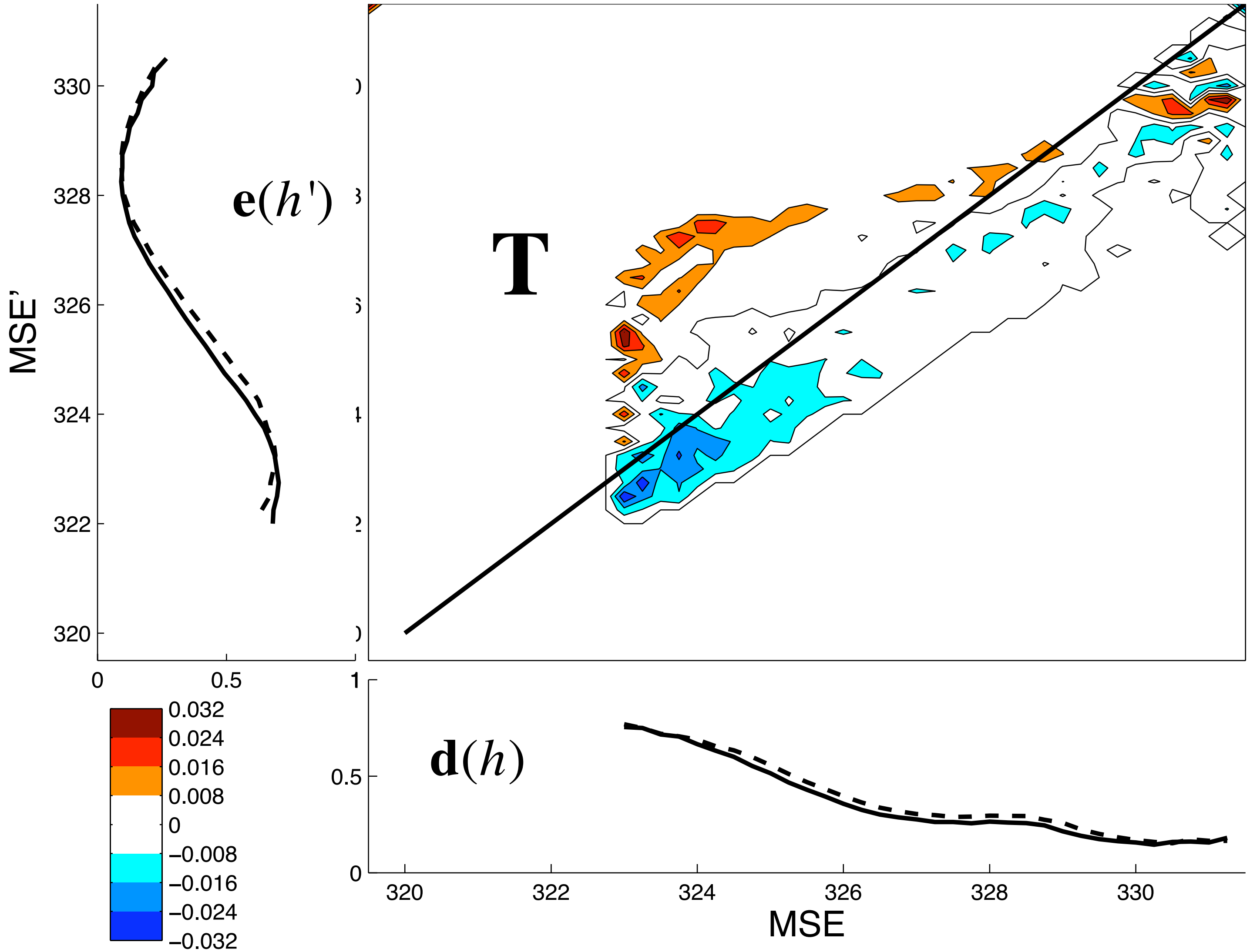


820 hPa to 770 hPa
e(h')
d(h)
MSE'
MSE
330
328
326
324
322
320
0
0.5
1
0
0.05
0.1

Apply the diagnostic framework on linear perturbation problems:

Prt – Ctl:

Solid line: Ctl
Dash line: Prt



[redacted]

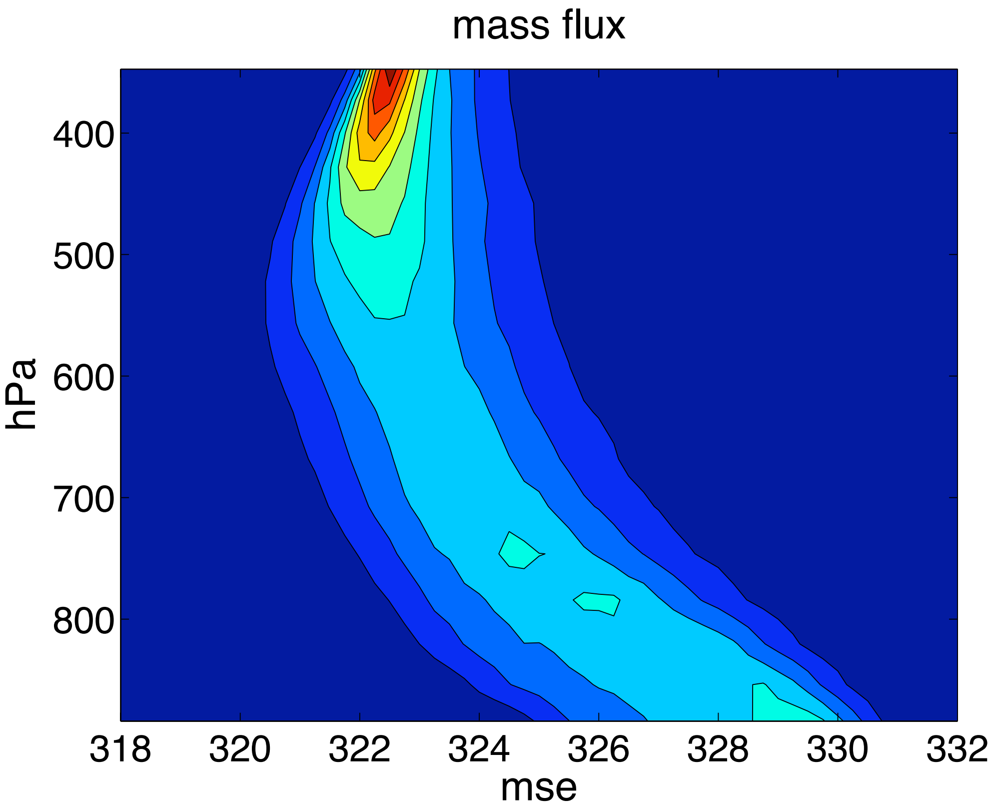
With a perturbation, the change of mass flux can be separated into 4 different terms:

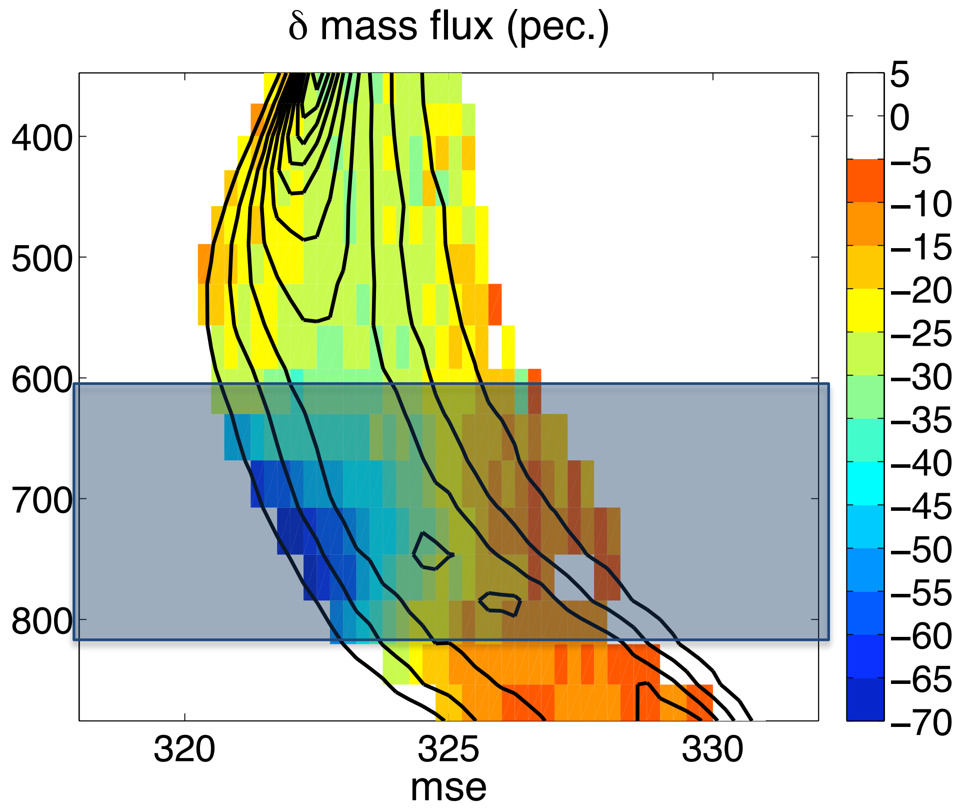
Total change =
passive + detrained + entrained + mapping

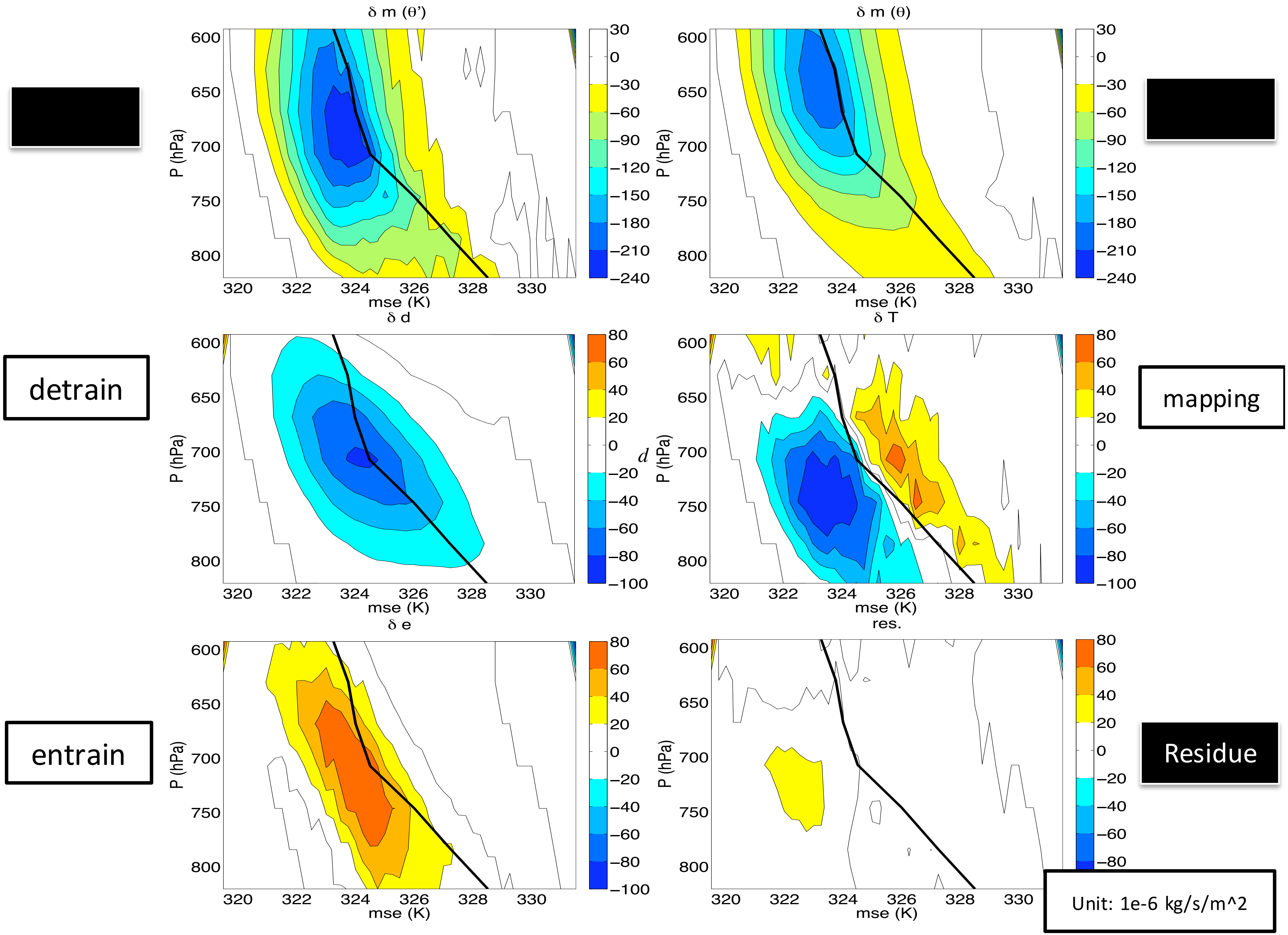
Mass flux distribution on moist static energy (mse):

Ctl:

Prt – Ctl:






δ m (θ')
δ m (θ)
δ d
δ T
δ e
res.
P (hPa)
mse (K)
[redacted]
[redacted]
detrain
mapping
entrain
Residue
Unit: 1e-6 kg/s/m^2

Summary and Conclusions:

•The motivation is to better understand the linear response function, which can help the understanding of convective dynamics and development of convective parameterization.

•A new diagnostic framework, which utilizes the LPDM, is proposed.
It views the evolution of mass flux as a mapping processes. Entrainment, detrainment, and other mixing can be quantified for ensemble of updrafts with certain properties.

•The diagnostic framework is applied on one case of the linear response problem.
With a lower troposphere temperature perturbation, the buoyancy barrier eliminates more updrafts. Meanwhile, the entrainment is enhanced in the perturbed layer. The effects of entraining warmer air is that decreasing mass flux of updrafts with low mse and increasing mass flux of updrafts with high mse.

Thanks !!

Different organization

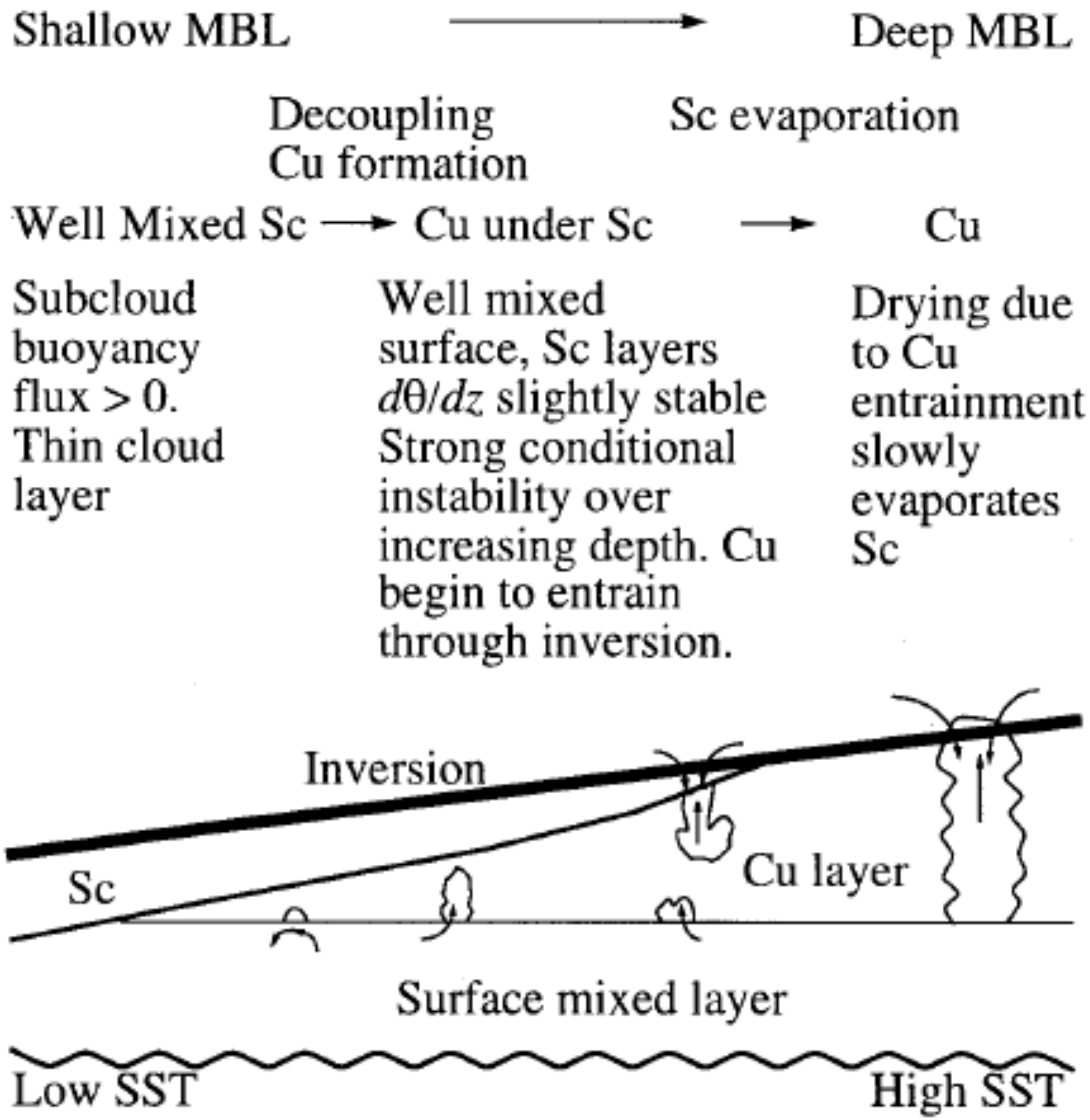


Figure 8. A conceptual model of the entire transition from subtropical stratus to cumulus capped CTBLs, from Wyant et al. (1997)

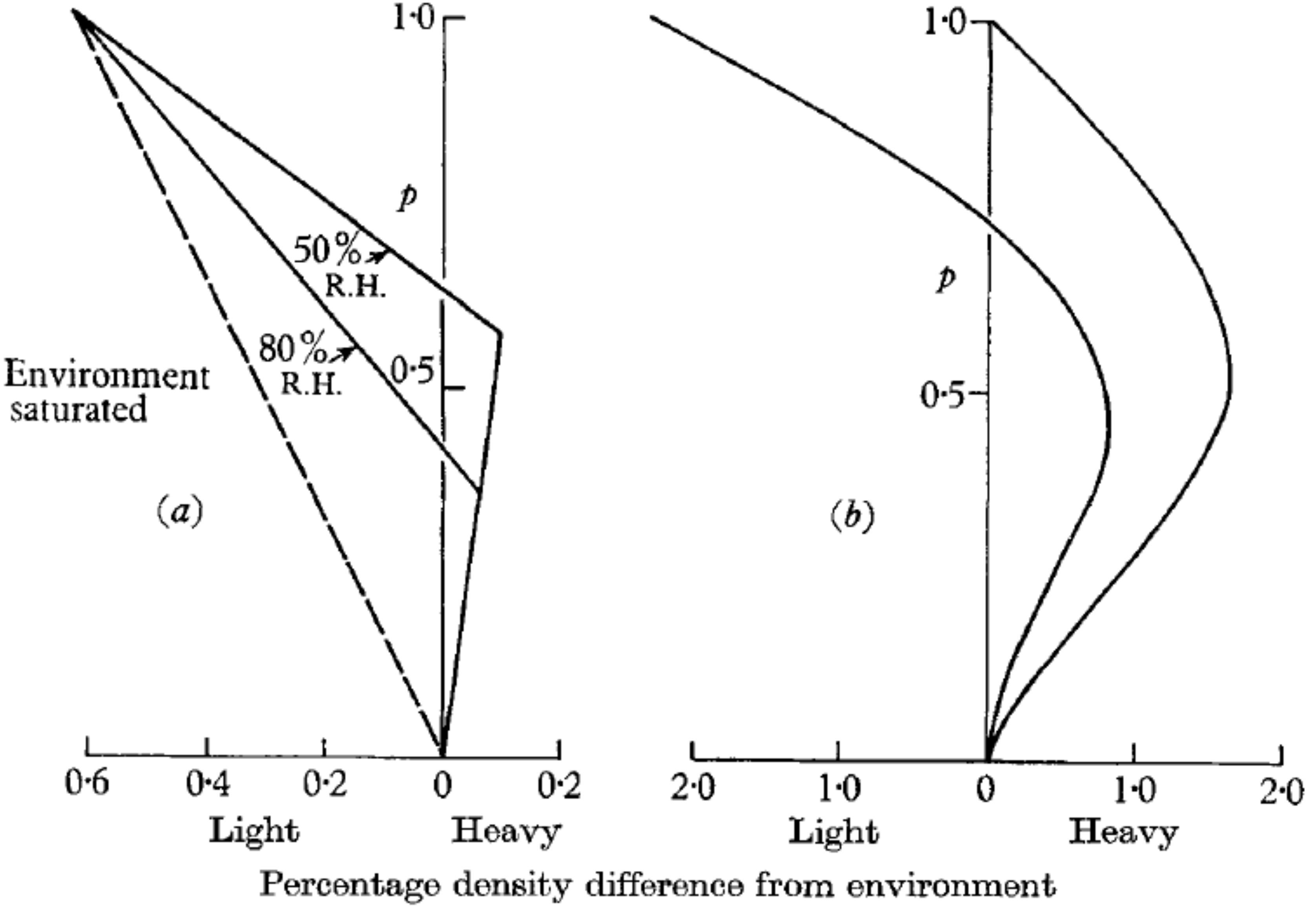


FIGURE 2. The non-linear density behaviour produced when a fraction p of 'cloud' fluid is mixed with its environment. (*a*) Cloudy air containing 1 g/kg of liquid water mixing with an environment 2 °C cooler having various relative humidities (denoted by R.H. on the figure). Cloud at 2 °C and 700 mb. (*b*) The experimental plume fluid, consisting of alcohol with ethylene glycol in various proportions, mixing with water.

Linear response functions of shallow convection from large-eddy simulations and two parameterizations

Zhiming Kuang and Ji Nie

Harvard University

The linear response functions

- Consider an atmospheric column (or a limited-domain model) that contains a cumulus ensemble. Define the state vector to include profiles of T and q anomalies in the current case, we seek **M** so that

$$\frac{d\vec{x}}{dt} = \mathbf{M}\vec{x}$$

- Such functions for a LES (or CRM) can be constructed reliably (Kuang 2010)

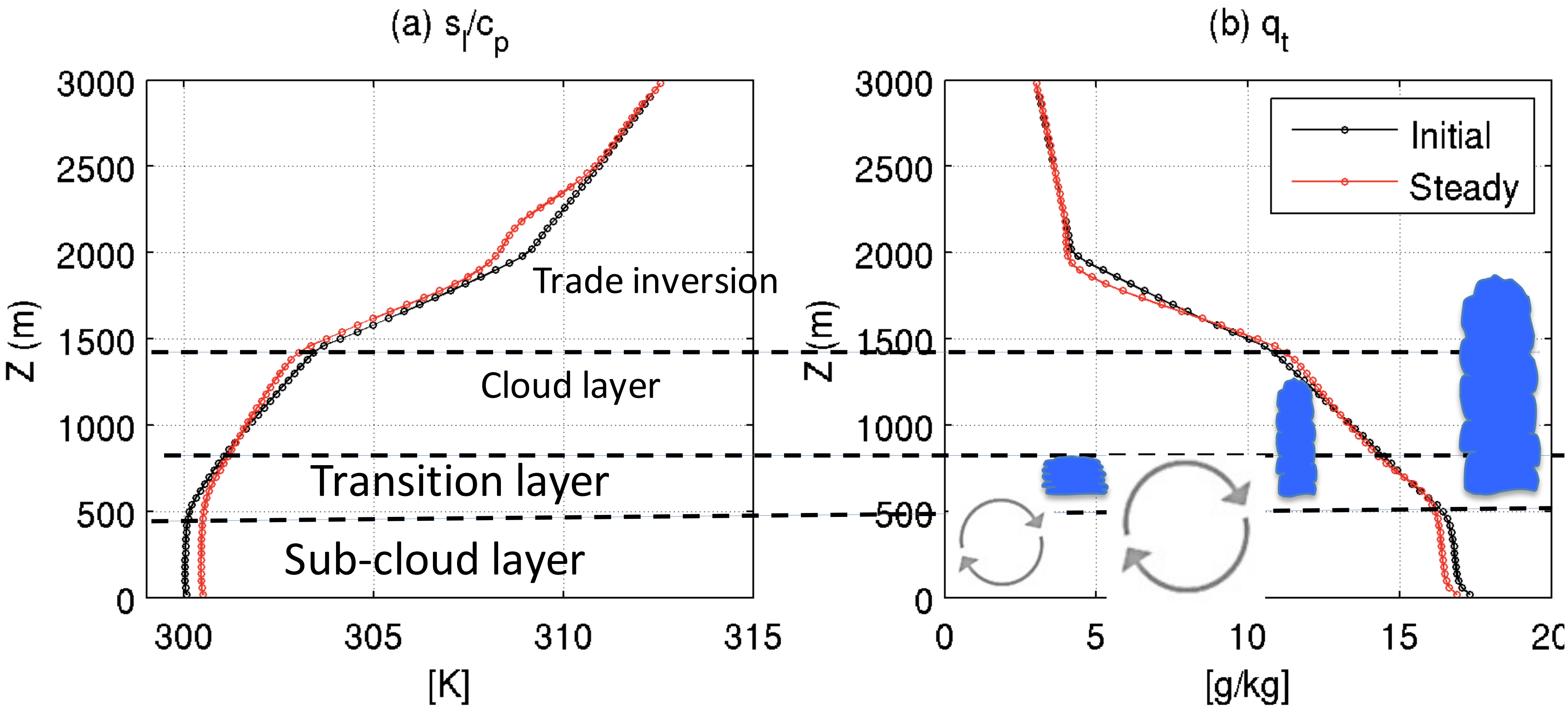
Motivations

- These functions summarize the macroscopic behaviors of the cumulus ensemble around a reference state and facilitate comparisons between LES and convection schemes
- A way to probe dynamics of convection
- Timescales of the system
  - Slow manifolds (Bretherton, Uchida, Blossey, 2011)
  - Understand the response of the buffered cloud system (e.g. Steven and Feingold, 2009; Lee, Feingold, Chuang, submitted)

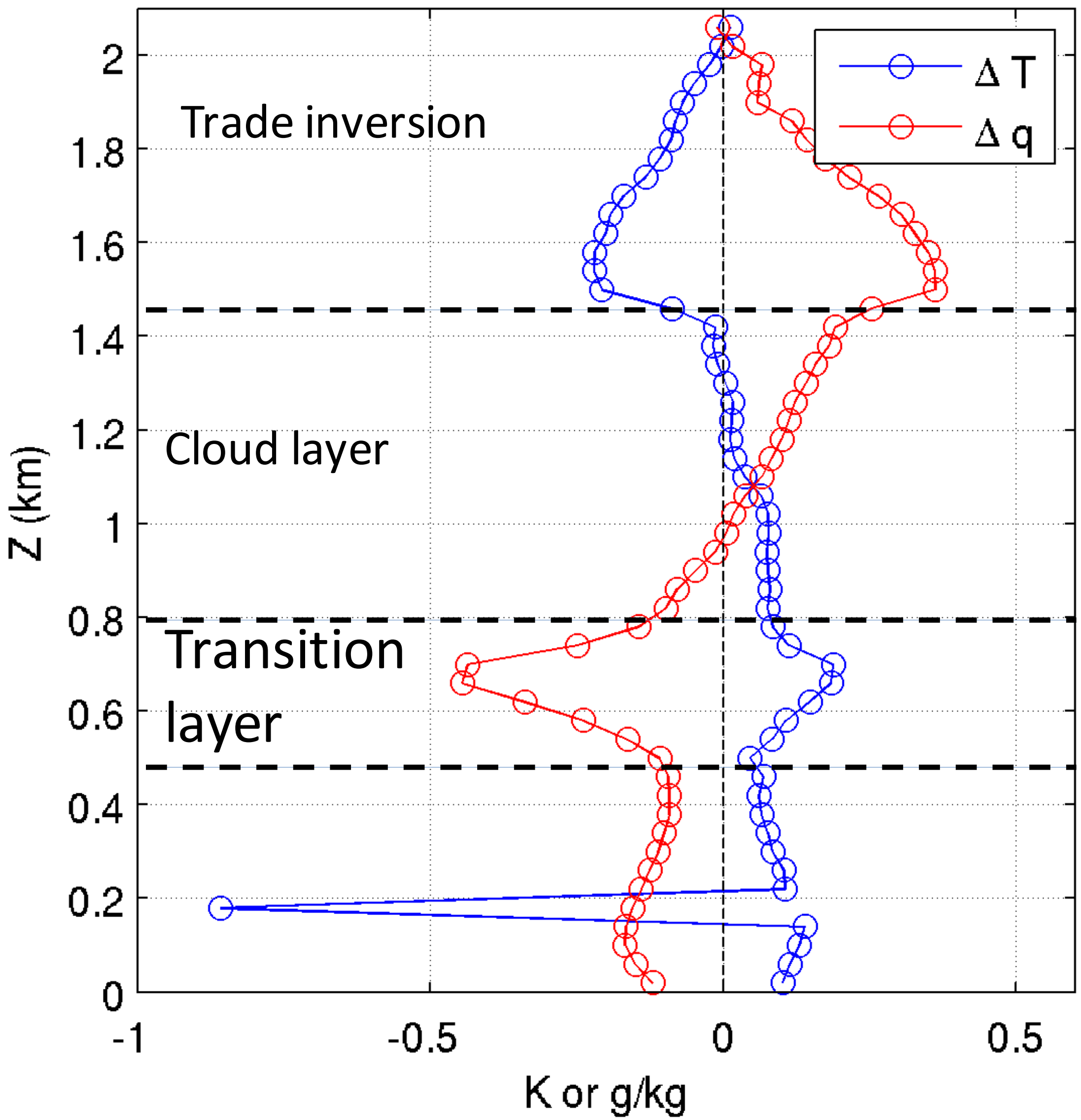
LES setup

- SAM by Marat Khairoutdinov
- Domain size 6.4kmx6.4kmx3km
- dx=dy=100m and dz=40m
- BOMEX case setup (Siebesma et al., 2003) with a 1-day nudging to initial profiles

LES mean state



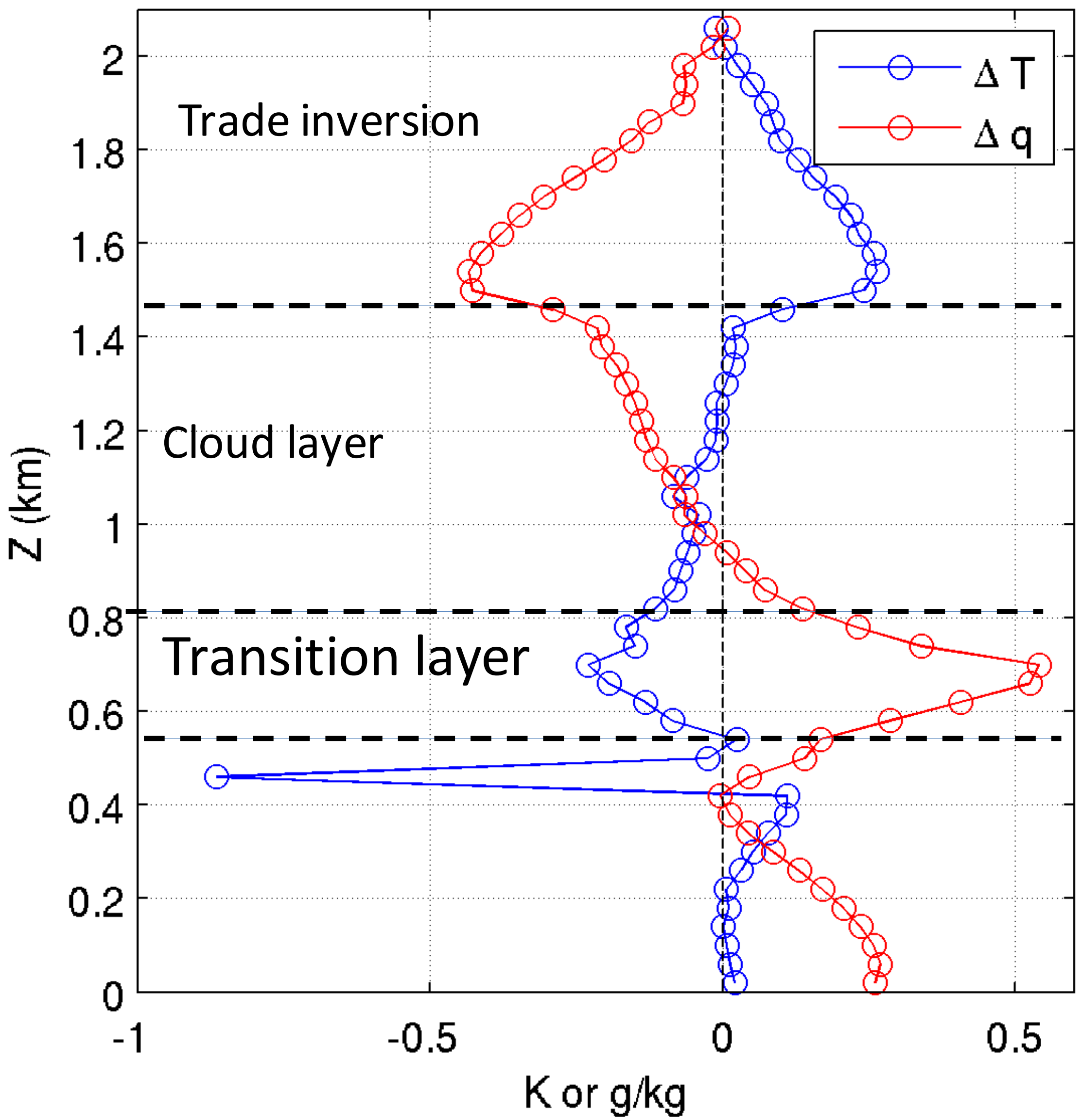
10-min responses to a warm anomaly in the lower half of the sub-cloud layer



Stronger boundary layer turbulence → more mass flux through the transition layer → warming and drying around the cloud base

Also more penetration into the trade inversion → cooling and moistening of the trade inversion

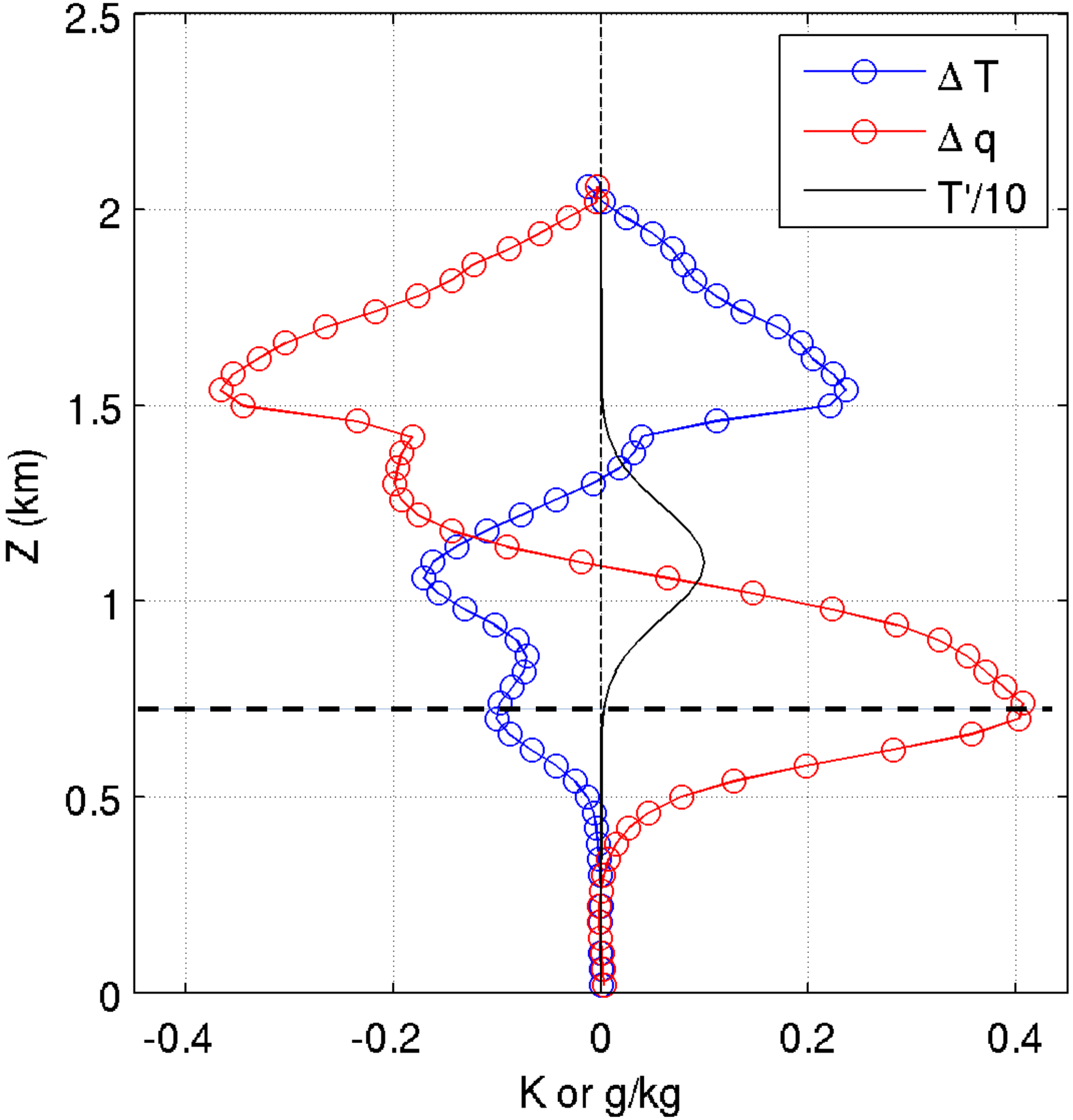
10-min responses to a warm anomaly in the upper half of the sub-cloud layer



Weaker BL turbulence → less mass flux through the transition layer → cooling and moistening around the cloud base

Also less penetration into the trade inversion → warming and drying of the trade inversion

30-min response to a cloud layer warm anomaly



There is local cooling and less penetration into (and hence warming and drying of) the trade inversion.

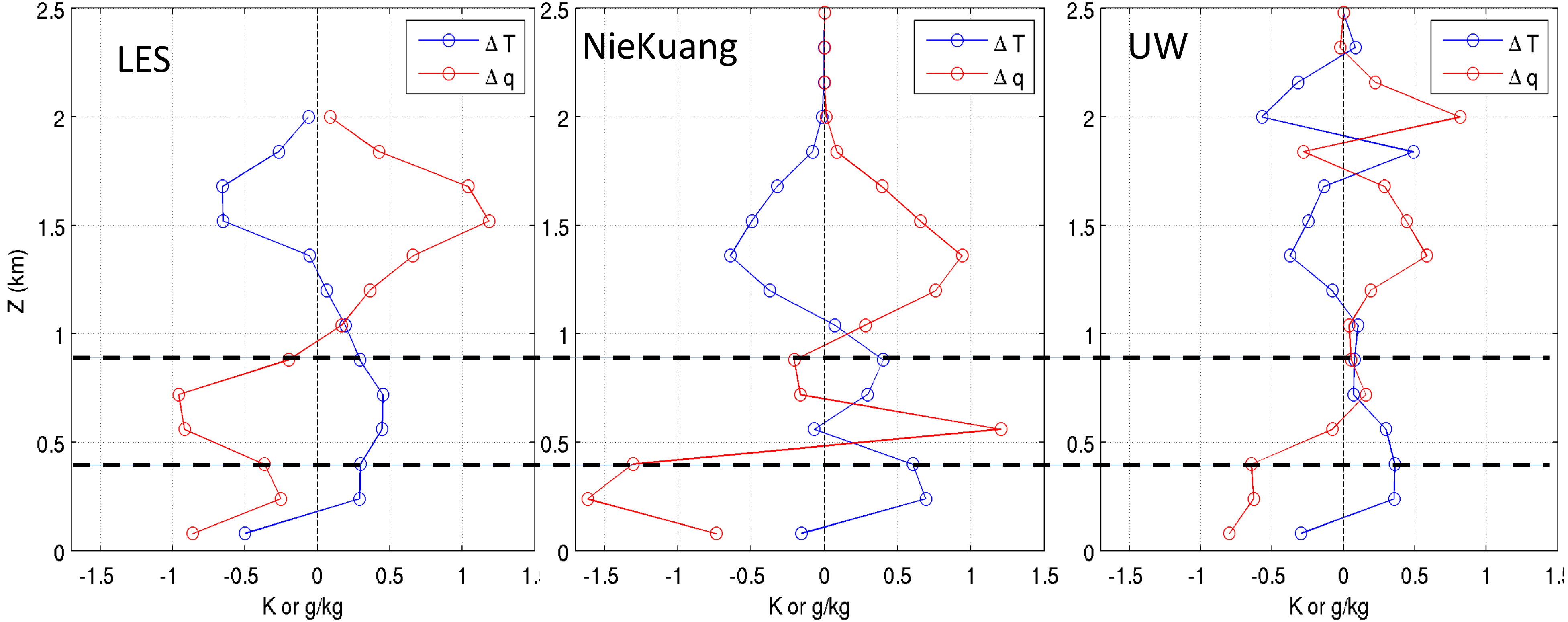
There is also cooling and moistening below the warm anomaly, because of the finite size of in-cloud eddies. Stronger evaporation of cloud water, and hence moister downdrafts, may also play a role.

U. Washington shallow cumulus scheme

(Bretherton et al. 2004; Park and Bretherton, 2009)

- A mass flux scheme based on a bulk buoyancy-sorting, entrainment-detrainment plume model
- A CIN closure for cloud base mass flux (Mapes 2000)
- Coupled to a moist TKE-based eddy-diffusion PBL scheme (Bretherton and Park, 2009)
- Enhanced penetrative mixing at the LNB

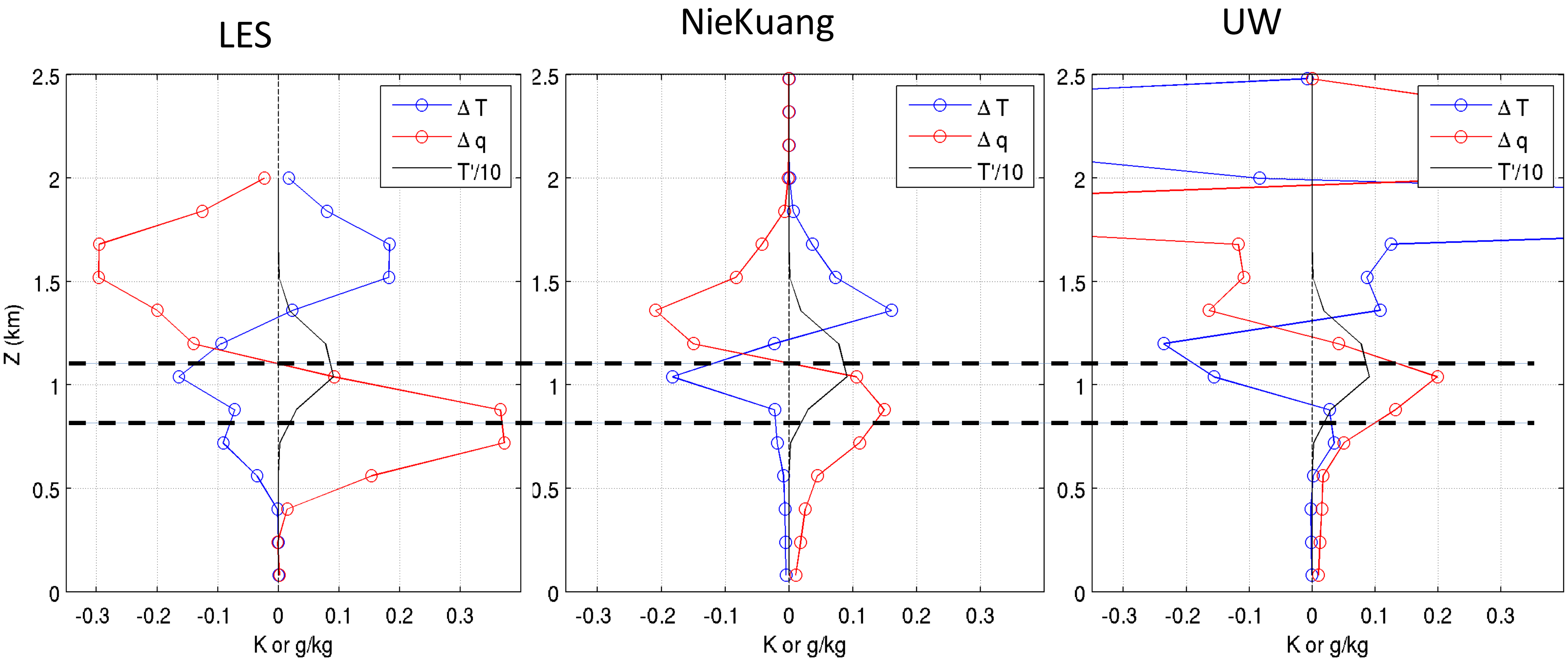
10-min responses to a 1-K near surface anomaly



Nie and Kuang have too large an increase in subcloud mass flux and detrain too much near the cloud base.

UW has little change in the transition layer (pointing to its diffusive PBL scheme), and is off in the trade inversion (pointing to its enhanced penetrative mixing at LNB).

30-min response to a 1-K cloud-layer anomaly



UW scheme has too little change below the anomaly (pointing to the missing finite eddy sizes and downdrafts).

Nie and Kuang are a little better but still not sufficient.

Concluding remarks

- The linear response functions from LES provide a valuable depiction of the convective adjustment process
- They can be directly compared to those from convection schemes to reveal issues
- Results may have some dependence on the LES used
- For a discussion on deep convection, see Mike Herman's talk later today.

Thanks to Sungsu Park for help with the UW scheme

Some variations in formulation

Cloud base properties:

- Use mean surface air plus a specified perturbation - ZM
- Use mean of lowest 50 mb plus perturbation (possibly convergence-dept.) - KF

Triggering

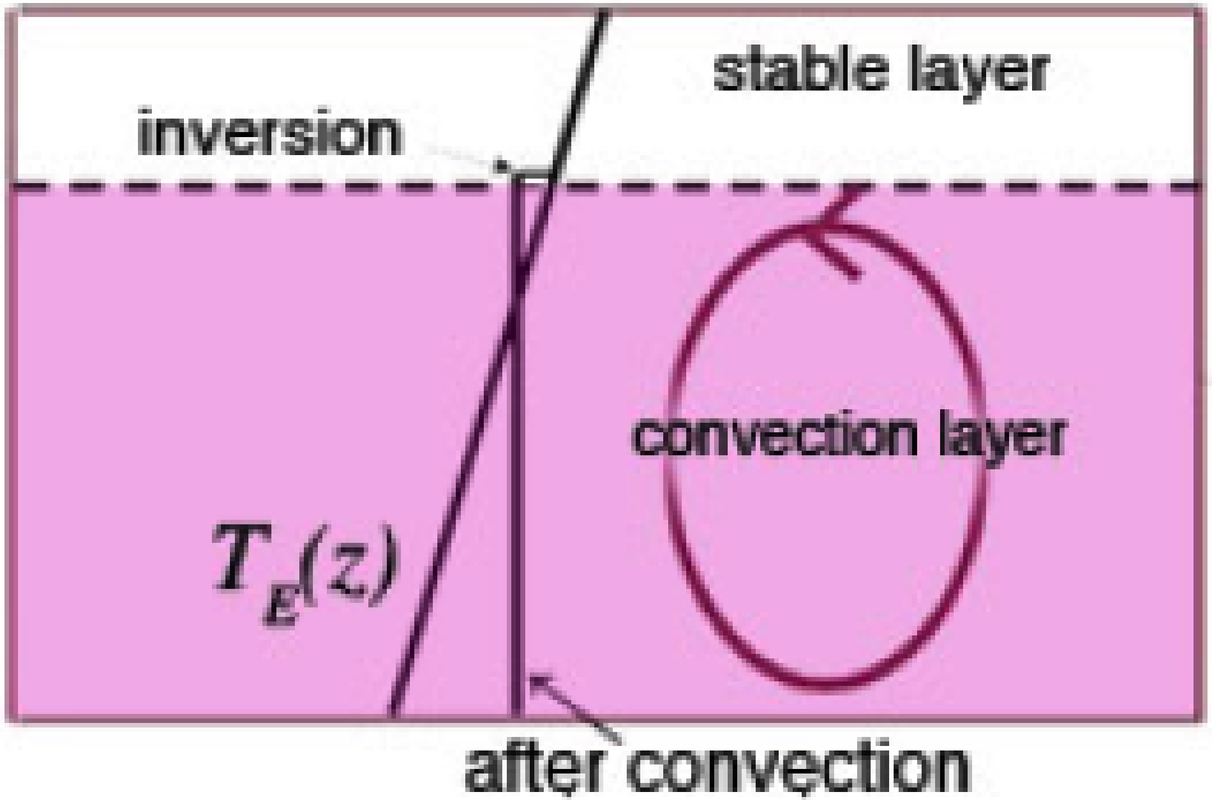
- Convection if undilute cloud-base parcel has CAPE (CIN not considered) - ZM.
- Convection if undilute parcel with initial W keeps going up above cloud base (overcomes CIN) - RAS
- Convection if entraining parcel has CAPE and overcomes CIN -KF.

Cloud models:

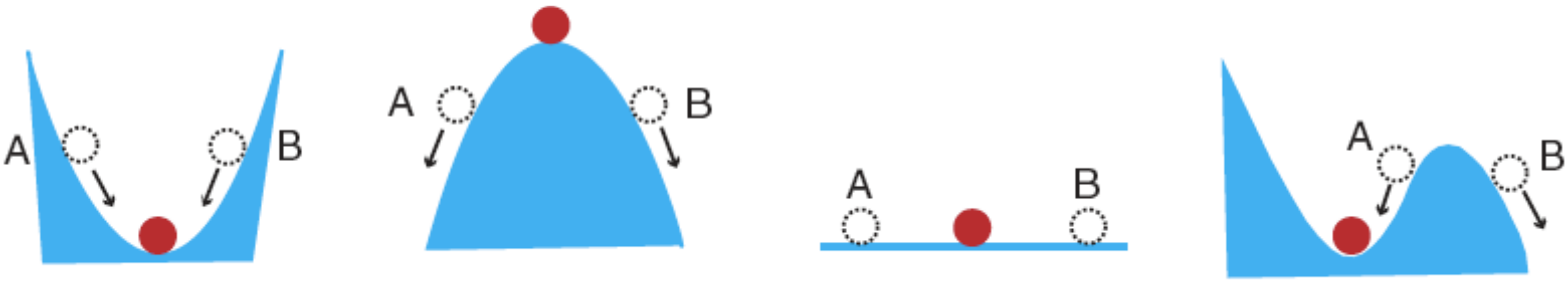
- Ensembles of entraining plumes incl. undilute (partitioning?) - AS
- Bulk entraining/detraining plumes (buoyancy sorting?) -KF
- ‘Banana-peel’ (discrete mixing events) - Emanuel

Mass-flux closure:

- CAPE or entraining CAPE-regulating – RAS, KF, ZM
- Moisture convergence – Kuo, Tiedtke
- Boundary-layer quasi-equilibrium –Emanuel (now CIN-regulating).


stable layer
inversion
convection layer
$T_E(z)$
after convection

Finite amplitude instability



(a) (b) (c) (d)

How does convection restore neutral stability?