Cloud mixing and cloud mixing feedbacks

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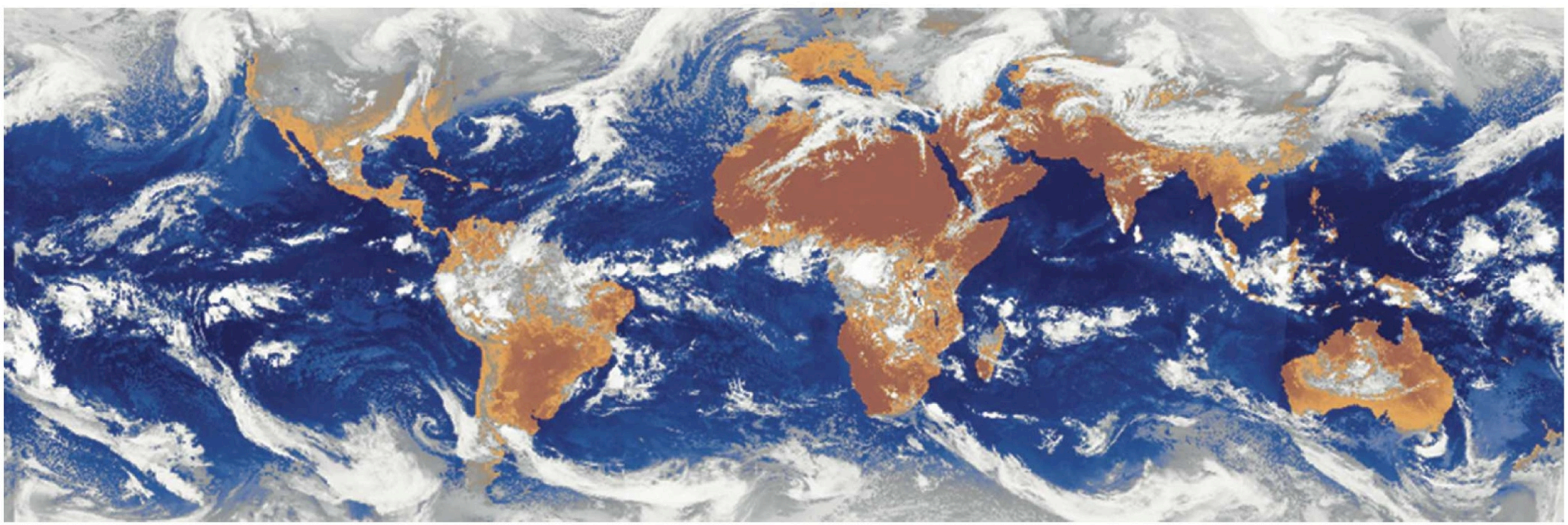


Introduction

- Focus on small scale convection (cloud tops < 700 hPa) at scales from ocean-wide (GCM) to GCM gridcell (SCM), to individual clouds (25 meters)

- **Questions**

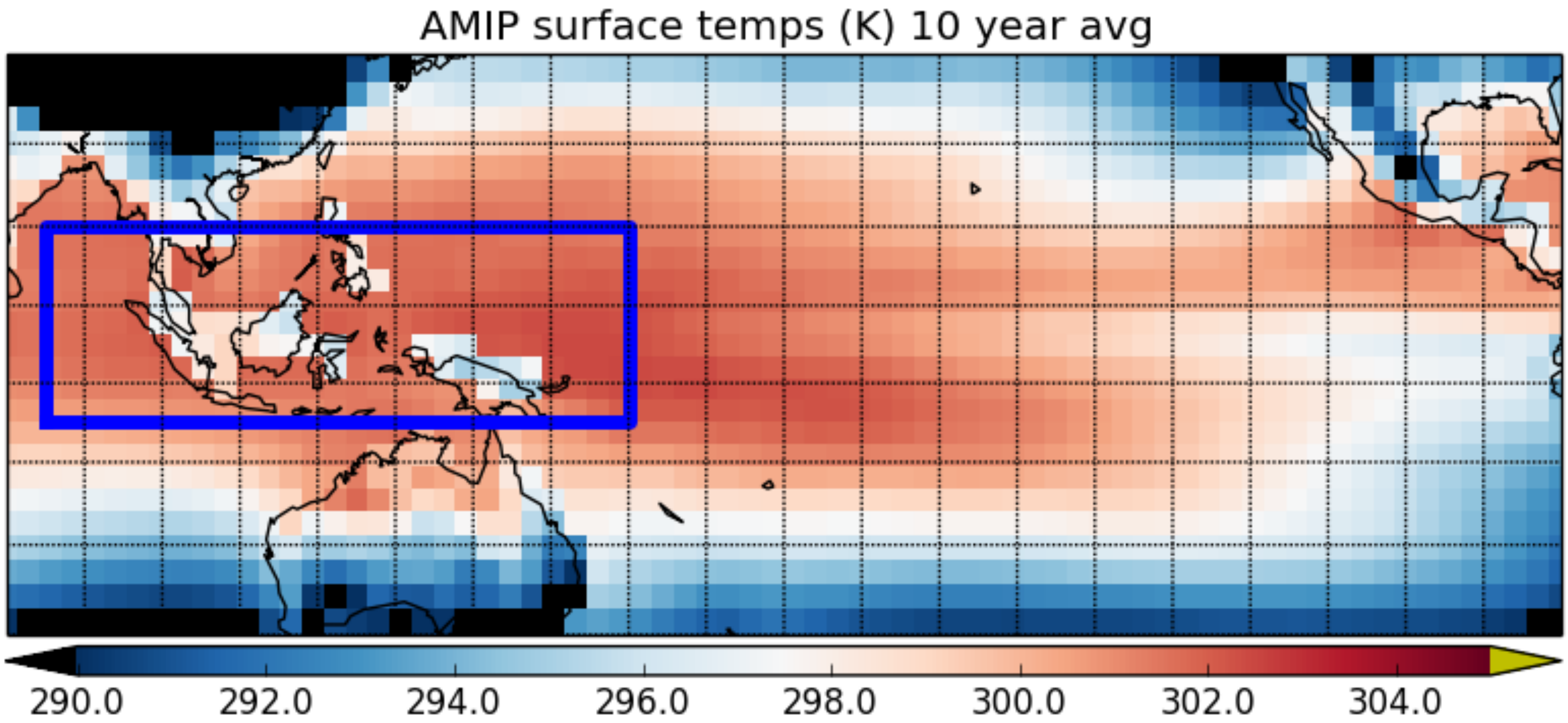
- How does the parameterization of convective transport in large scale models contribute to their equilibrium climate sensitivity?
- What can we learn about convective mixing from high resolution cloud models, and how can this inform parameterization development?

- **Three sections**:

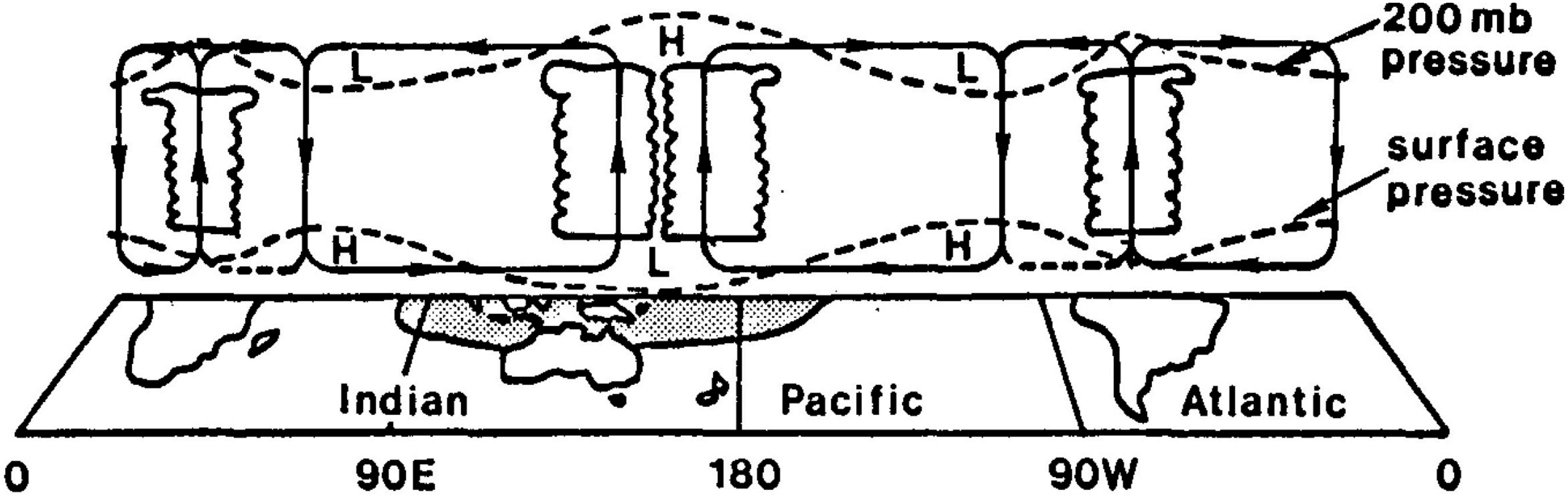
- Moisture transport and climate sensitivity in CMIPS5 models (after Sherwood, Bony and Dufresne, Nature, Jan 2, 2014)
- Results from the CGILS single column model and large eddy intercomparison of shallow convection (Zhang and 33 co-authors (incl. KvS and PHA), JAMES, vol. 5, Dec. 2013.
- High resolution LES of entrainment and detrainment in shallow cumulus (Dawe and Austin 2011a,b, 2012, 2013), papers at http://www.cafc.ubc.ca

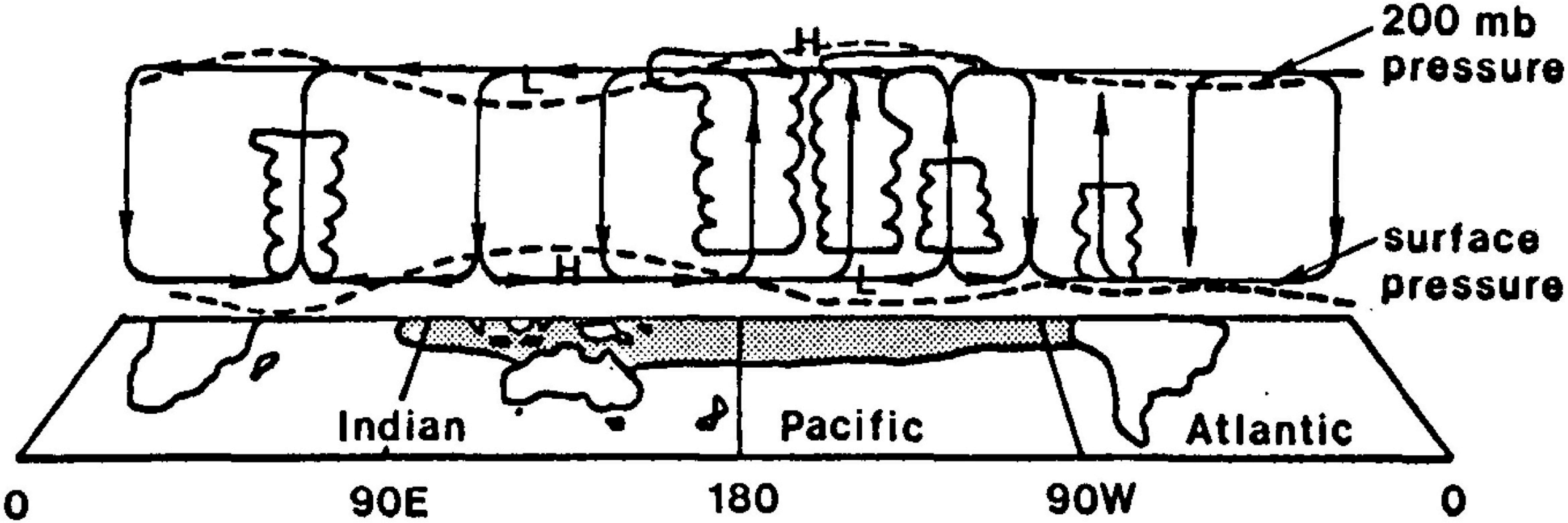
Part 1: Linking boundary layer mixing to cloud feedback

Deep convection in the tropical warm pool is tightly coupled to boundary layer clouds in the subtropics



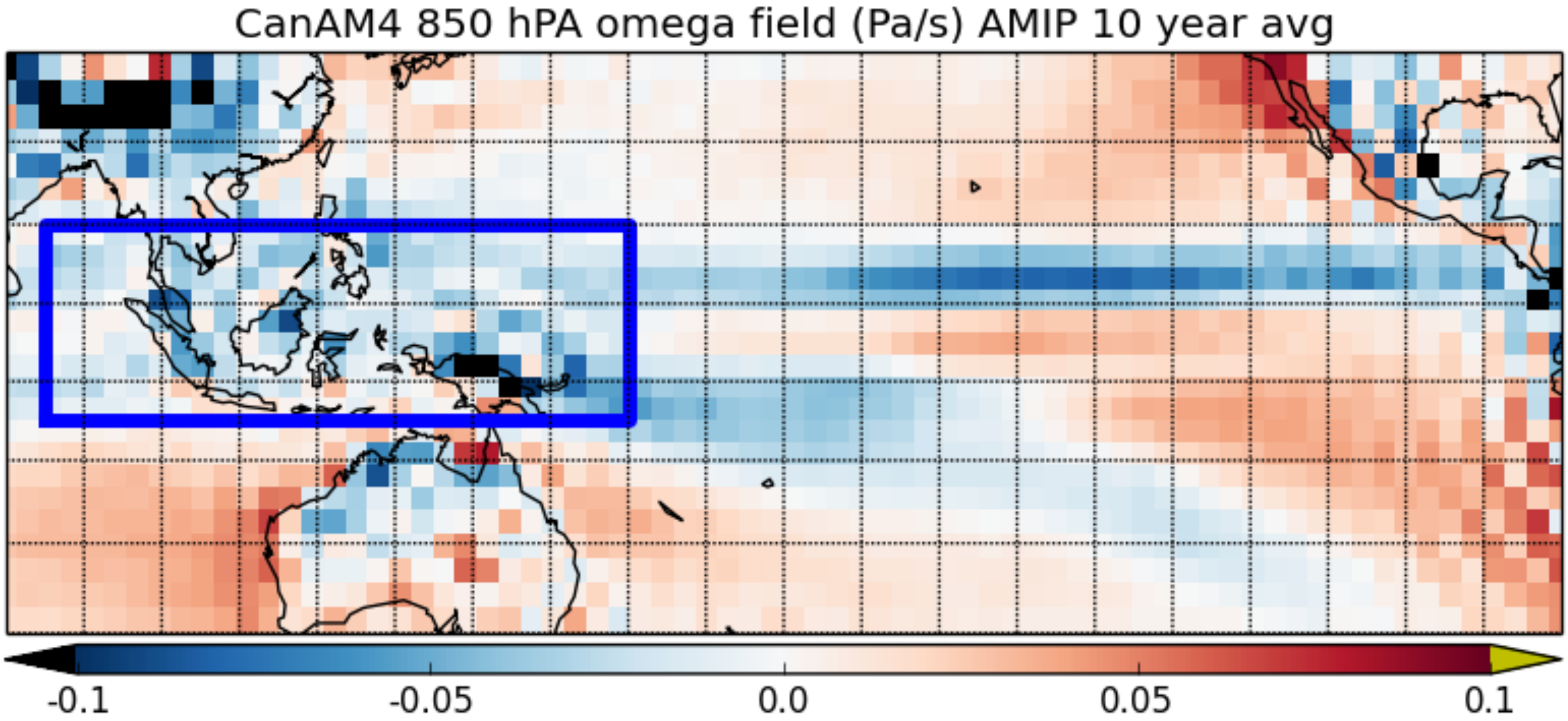
Walker circulation connects the west/east Pacific



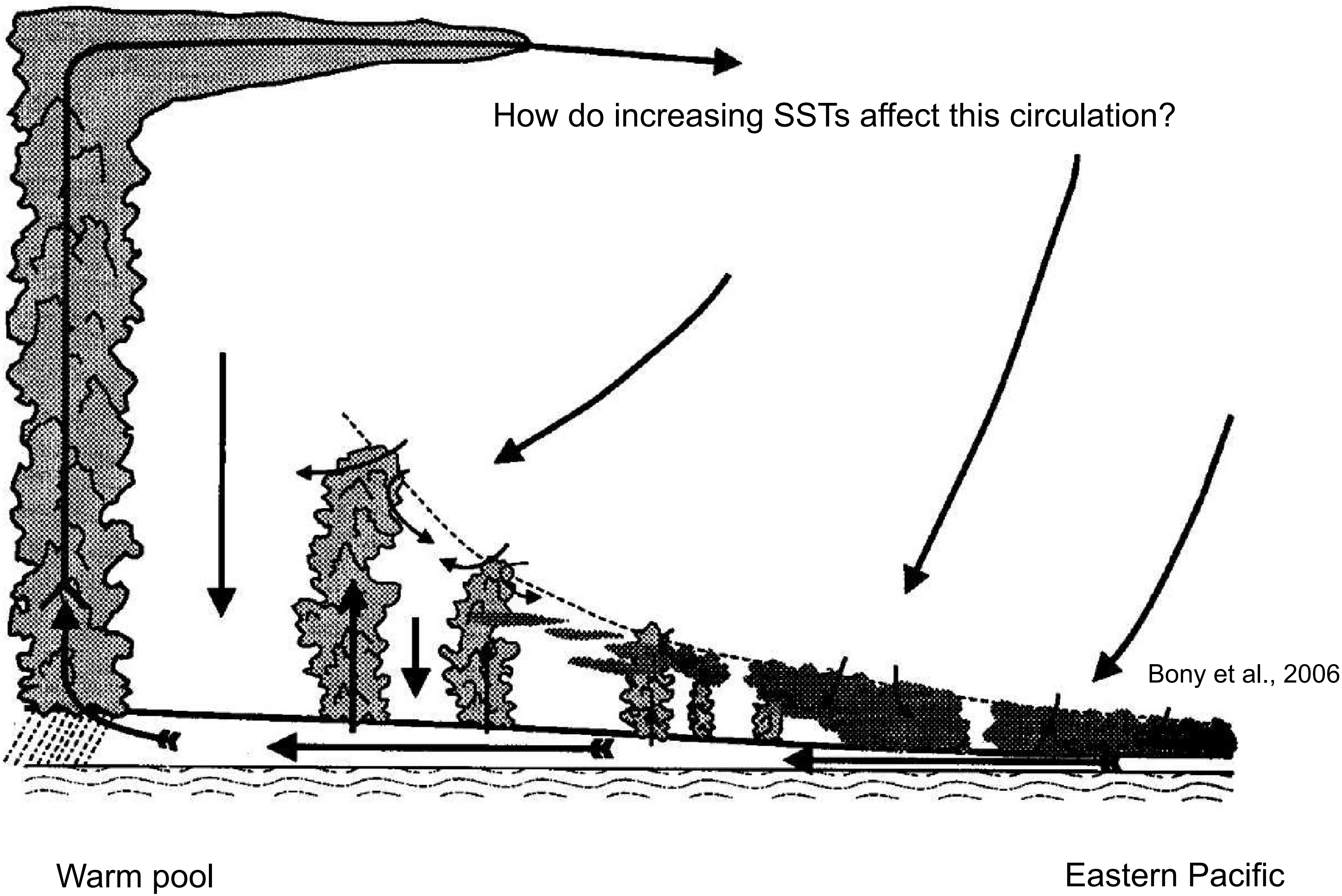


Webster, 1983

Large scale vertical velocity at 850 hPa, CanAM4, current climate

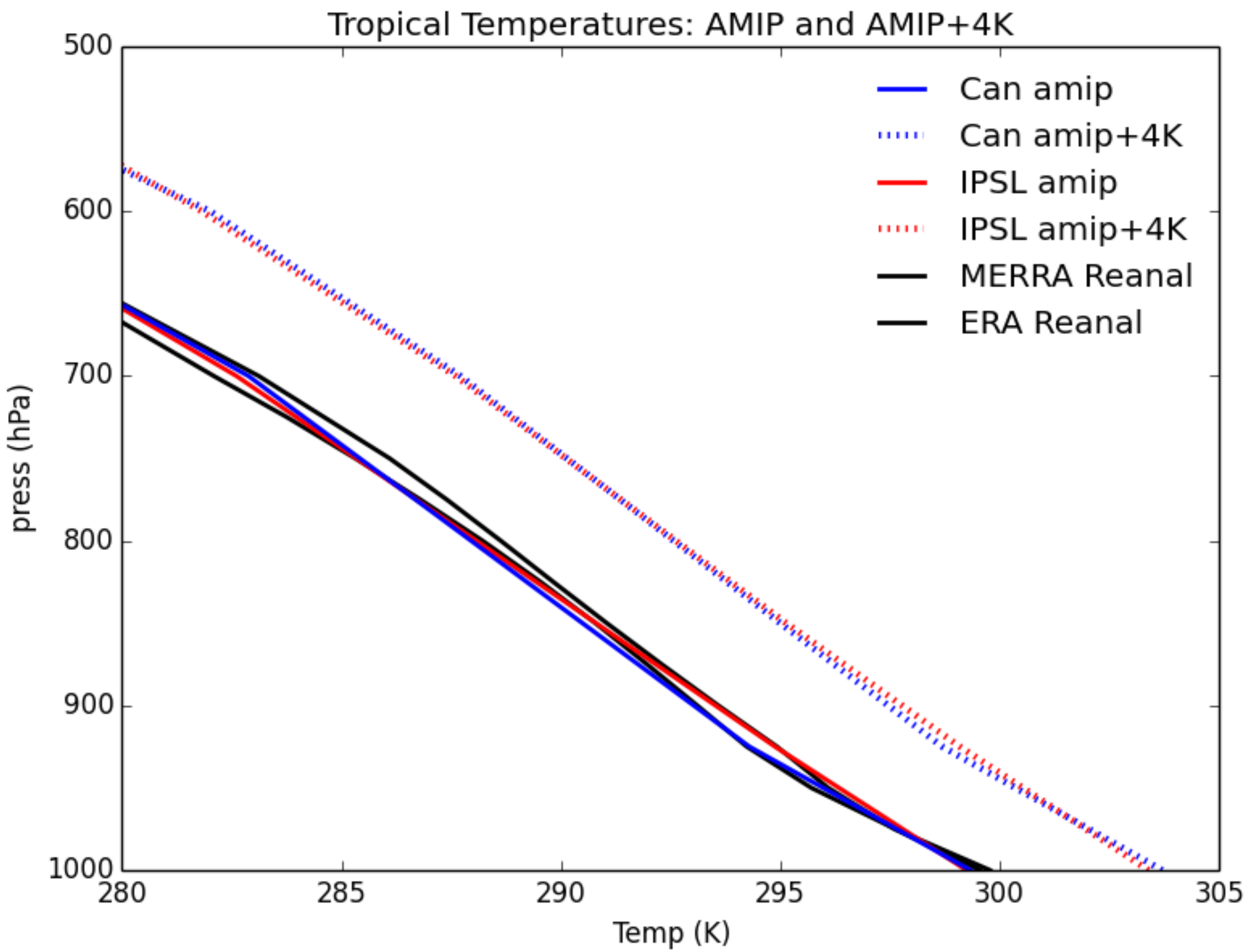


Two box model of the tropical circulation

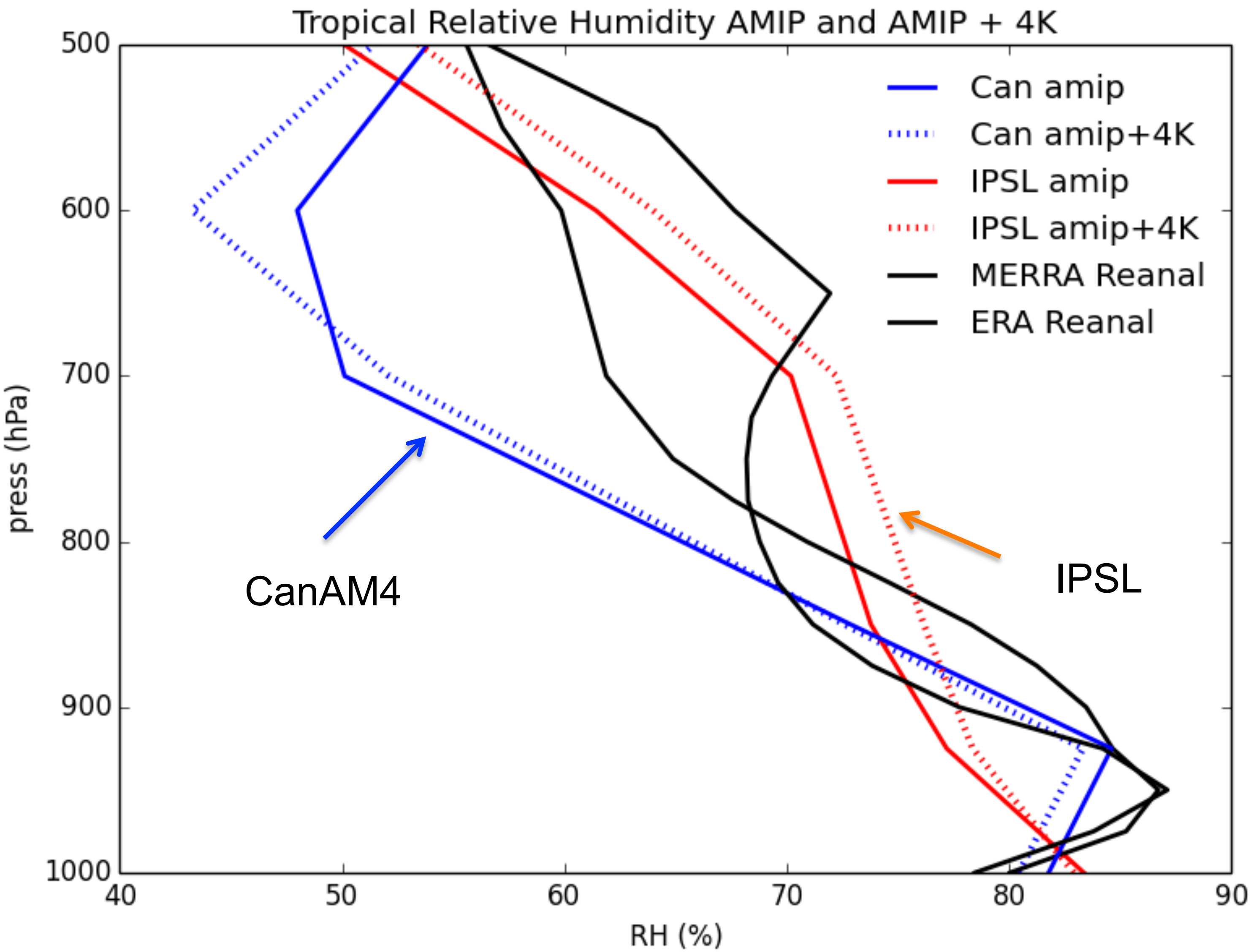


Decreasing large scale subsidence will affect cloud cover, feedback on net radiation

Vertical temperature structure in tropics: CanAM4 and IPSL agree with reanalysis



Relative humidity: CanAM4 significantly drier than reanalysis at 700 hPa

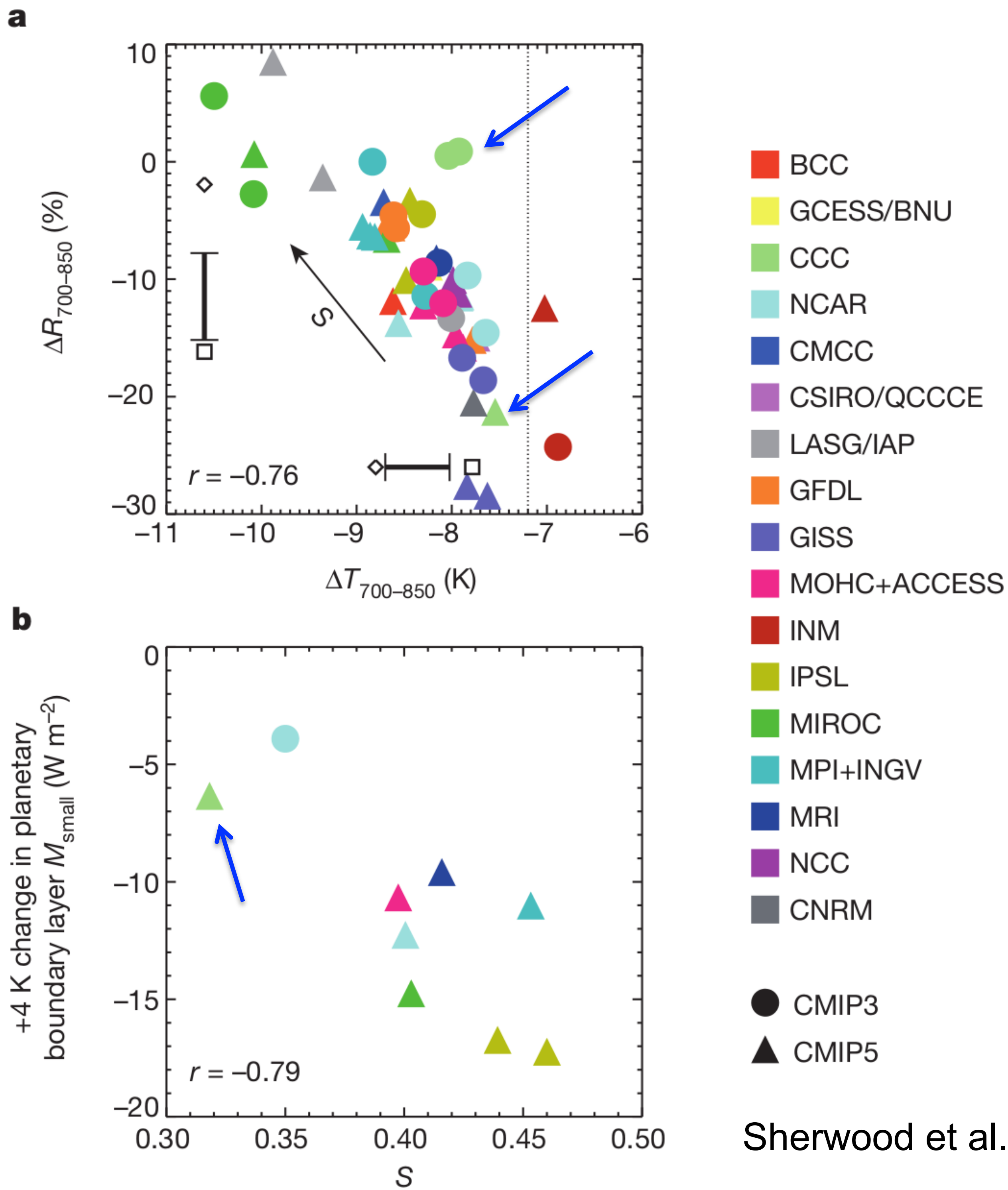


Sherwood et al. define a metric of "mixing strength" S in the tropics as:

$$S = (\Delta RH_{700-850} - \Delta T_{700-850}/9.)/2.$$

Models with large S have higher T and/or higher RH At 700 hPa. The hypothesis Is that this is because of active vertical mixing.

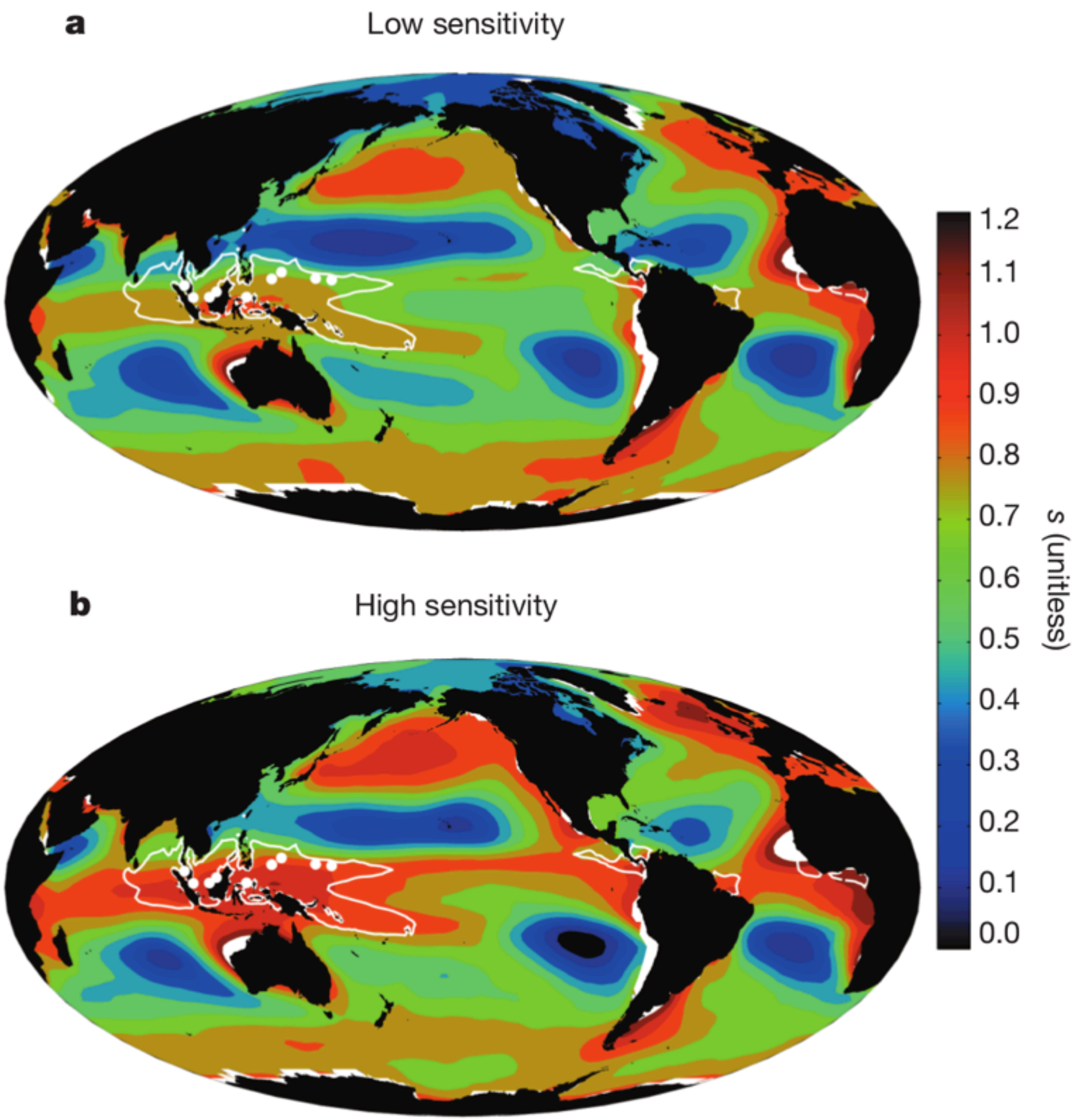
Models with active mixing tend to mix less in the AMIP+4K pcenario – this reduces low-level cloud fraction and produces a positive cloud feedback



Sherwood et al.

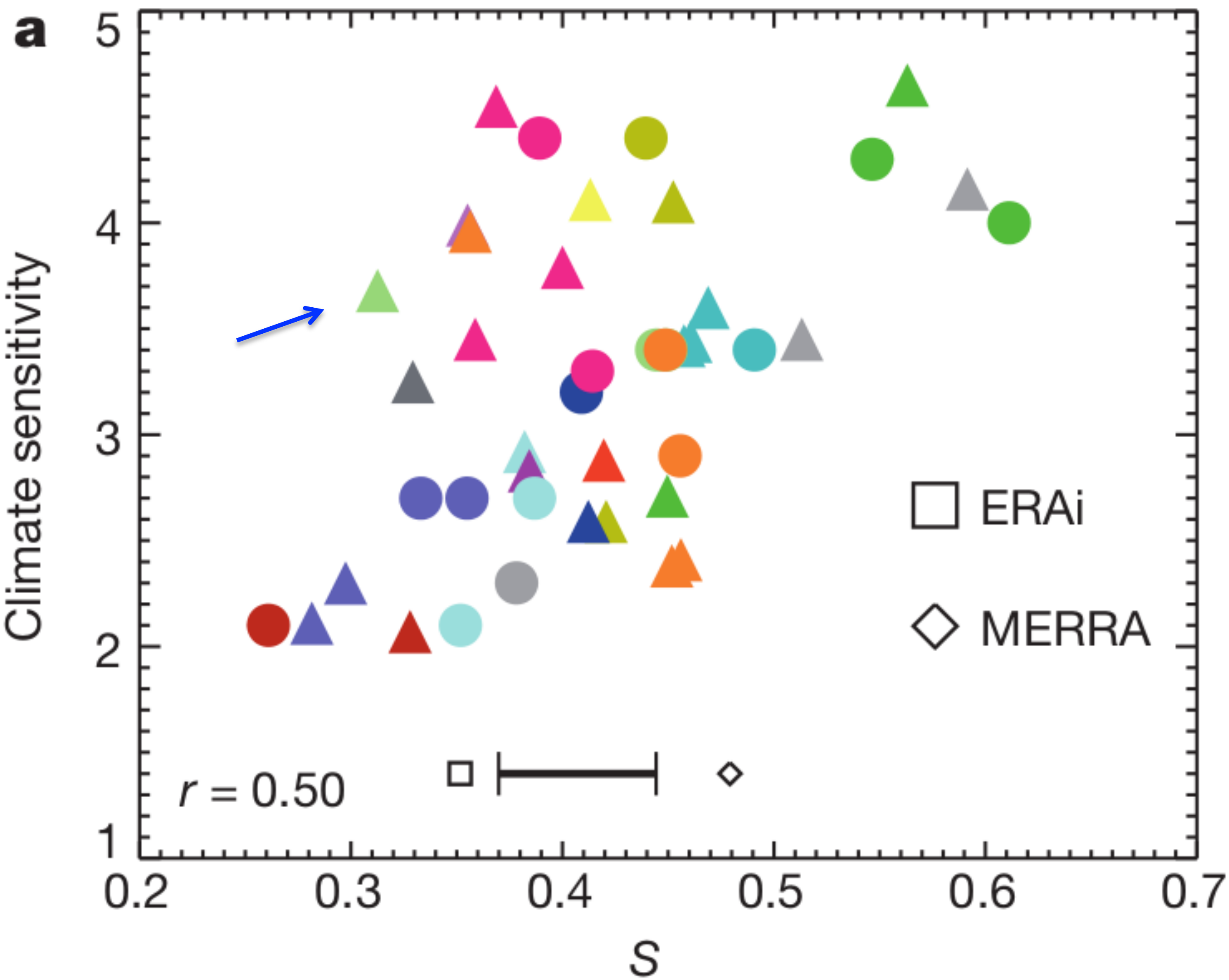
Segment models into low (ECS < 3 K/doubling) and high (ECS > 3.5 K/doubling) groups

Major difference is strength of mixing in the tropics



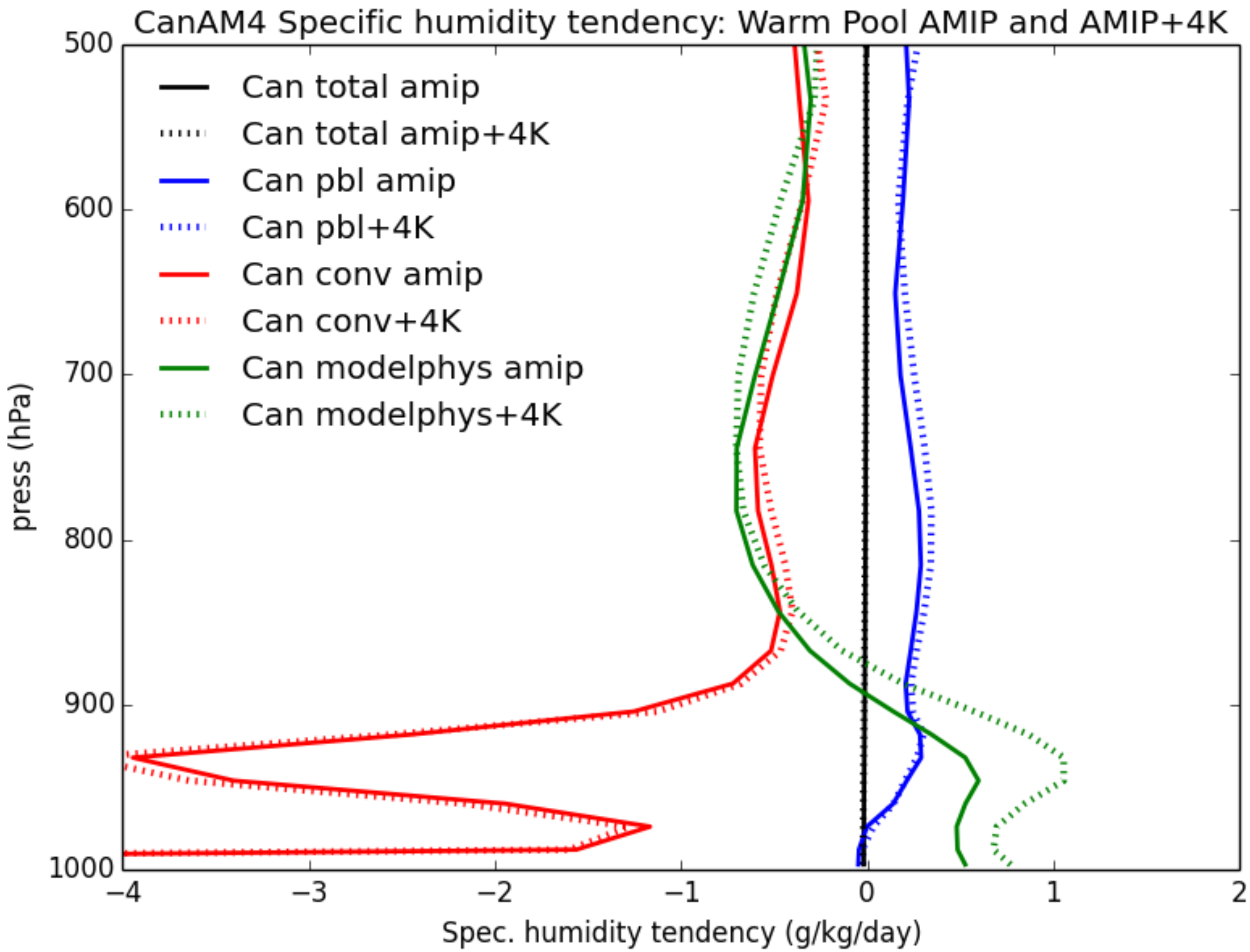
Sherwood et al.

CanAM4 is atypical in the sense that it is weakly mixing but sensitive

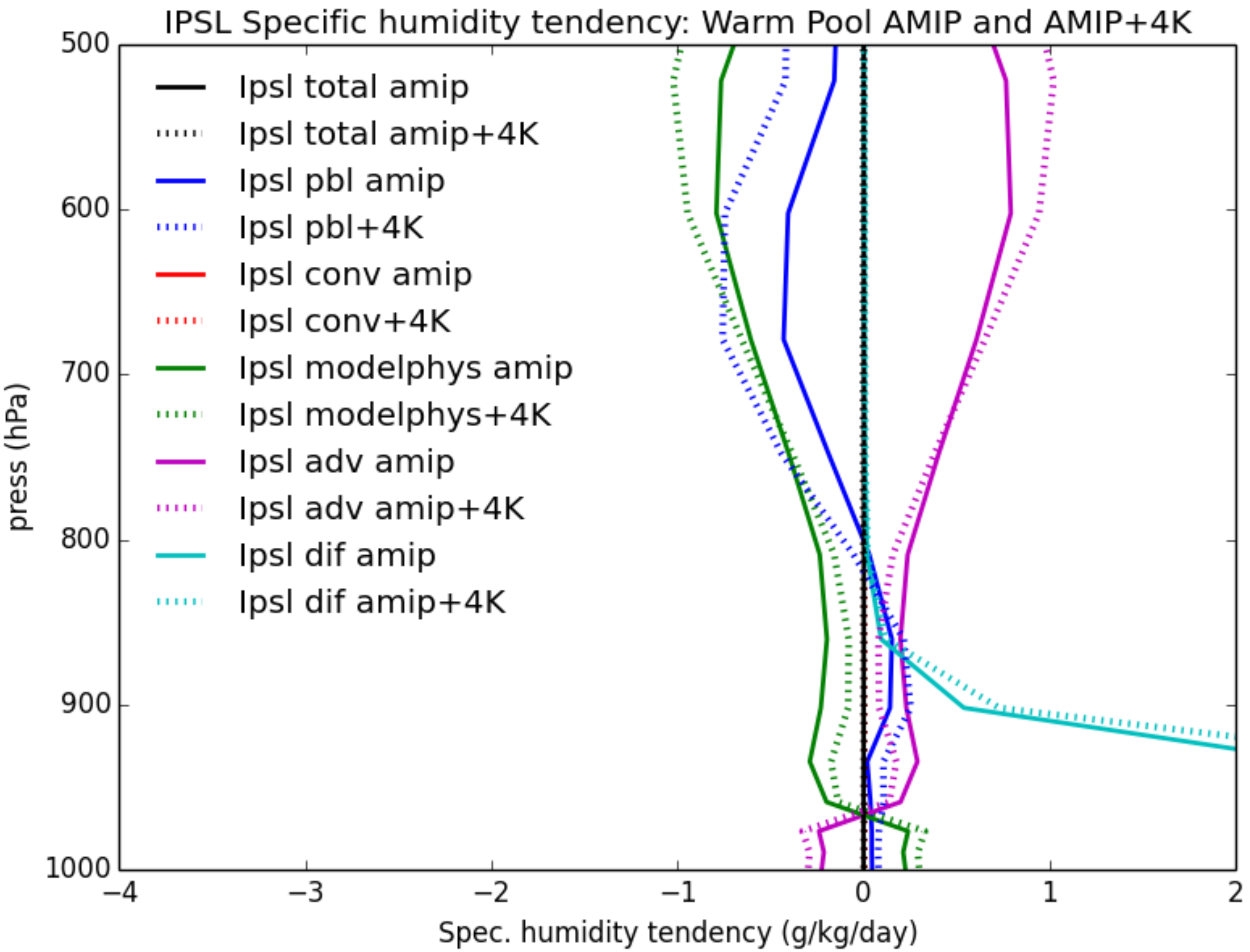


Sherwood et al.

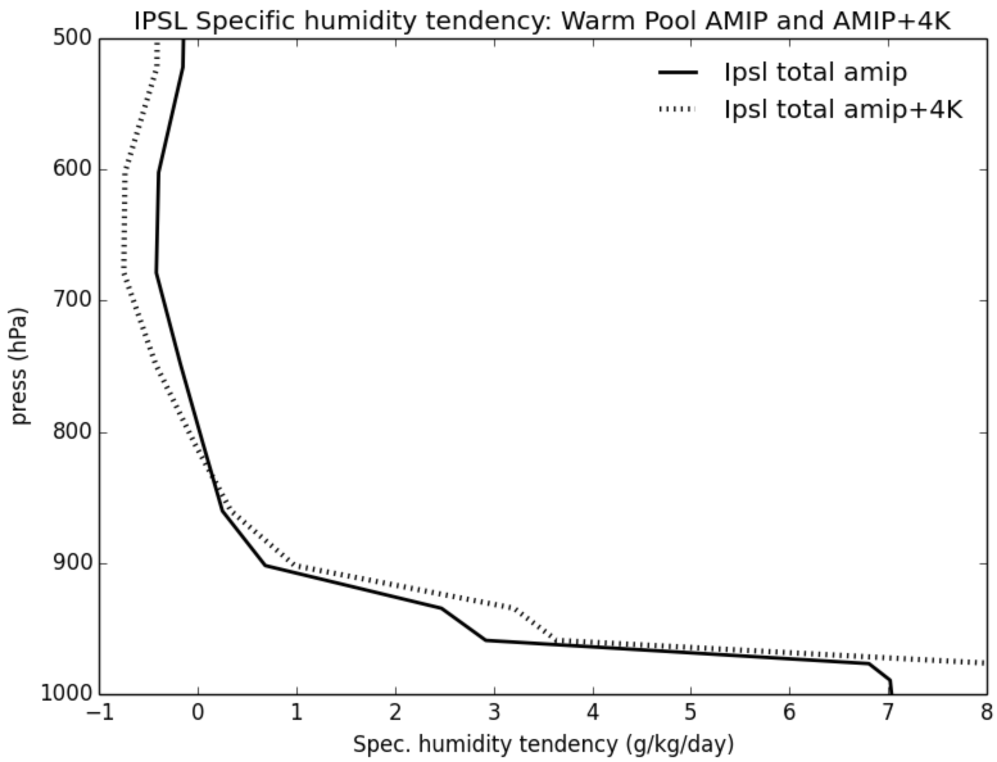
Specific humidity tendency indicates drying due to convection/turbulence dominates

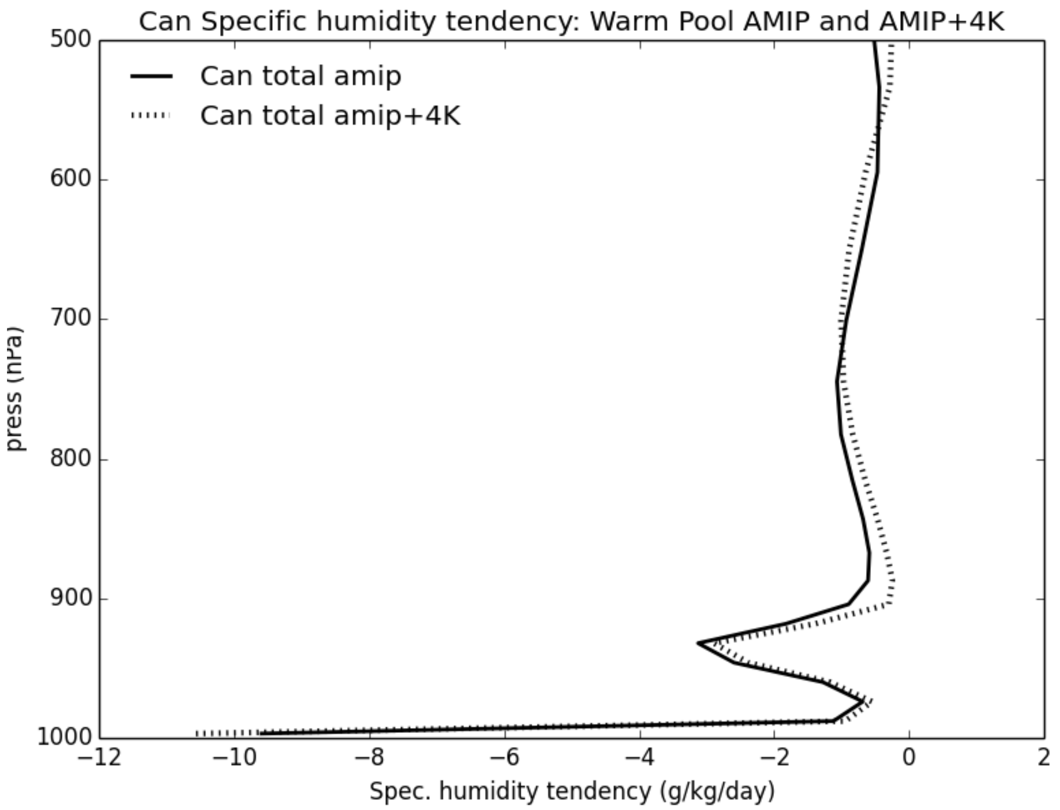


IPSL shows larger response/increased drying in AMIP+4K



Total specific humidity tendencies, CanAM4 and IPSL

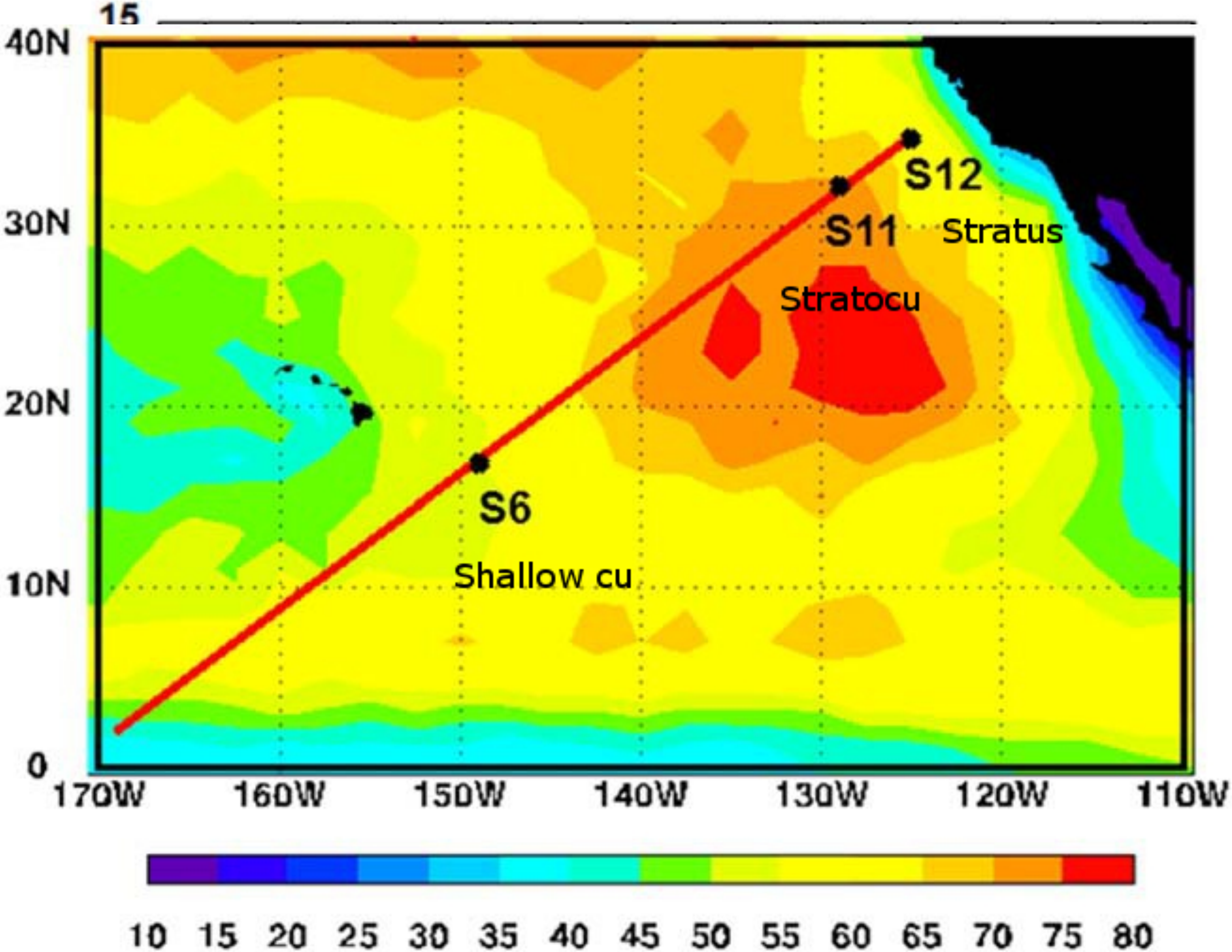




Part 1 summary

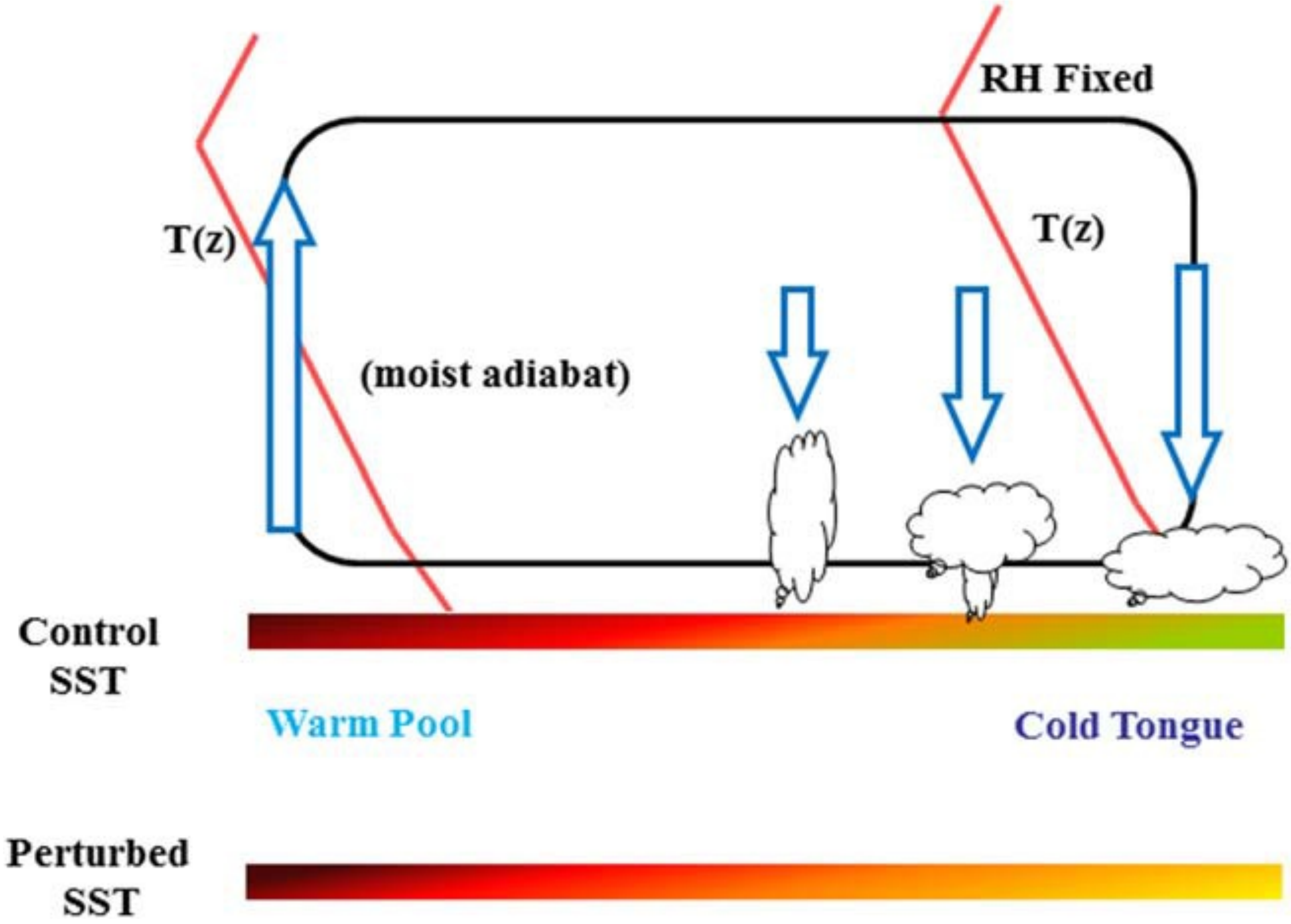
- In the absence of a mixing feedback in CanAM4, what is producing the large climate response? (Feedback analysis with Jason and Knut using ISCCP simulator output)
- How should boundary layer/convection be modified in CanAM4 to get more accurate moisture profiles in the tropics? (new SCM/CRM tropical convection intercomparison with Norm and Yanping)

CGILS intercomparison of single column models and large eddy simulations



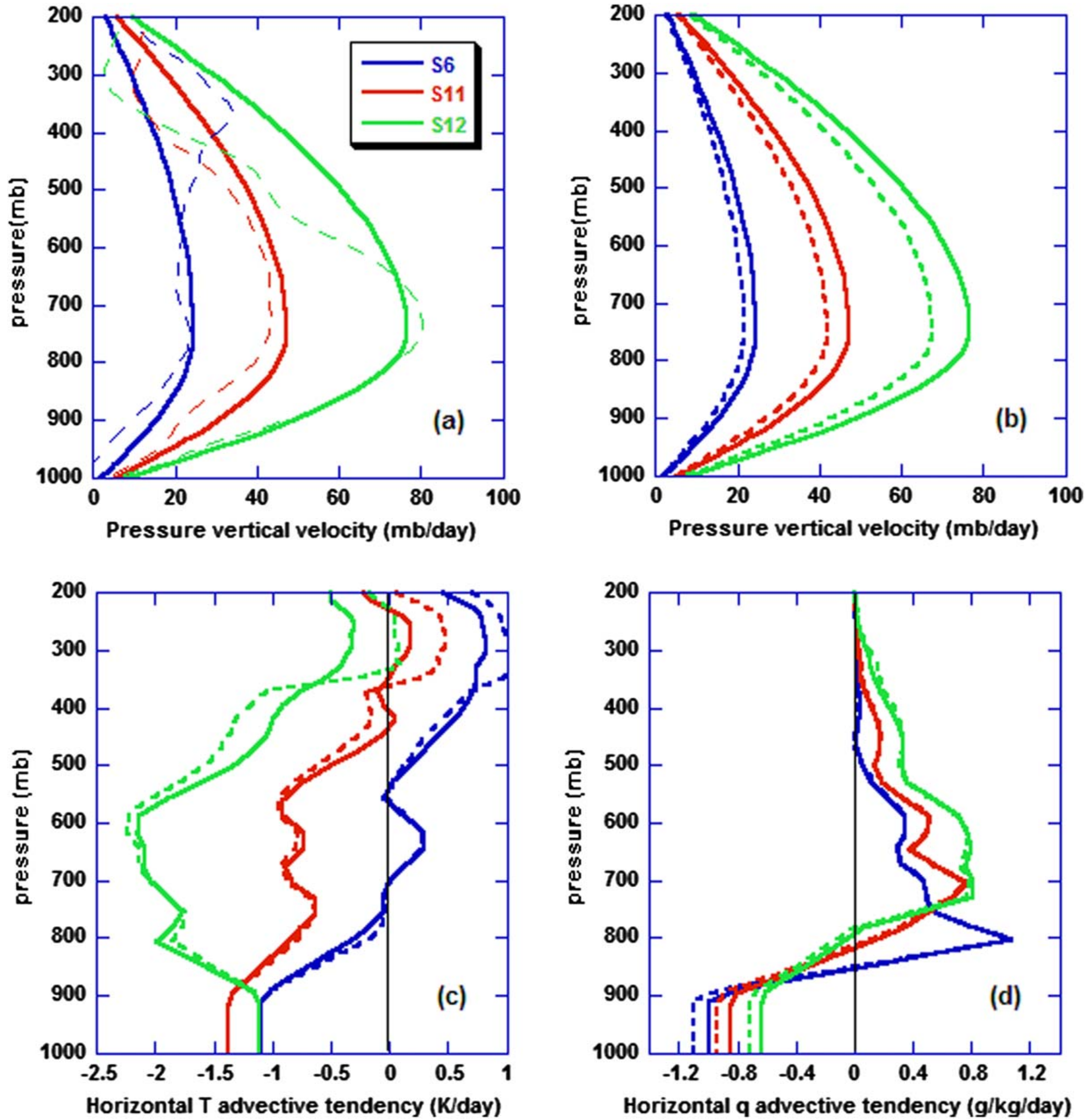
Zhang et al., 2013

Basic idea -- simulate AMIP+4K in a single column assuming weak temperature gradient



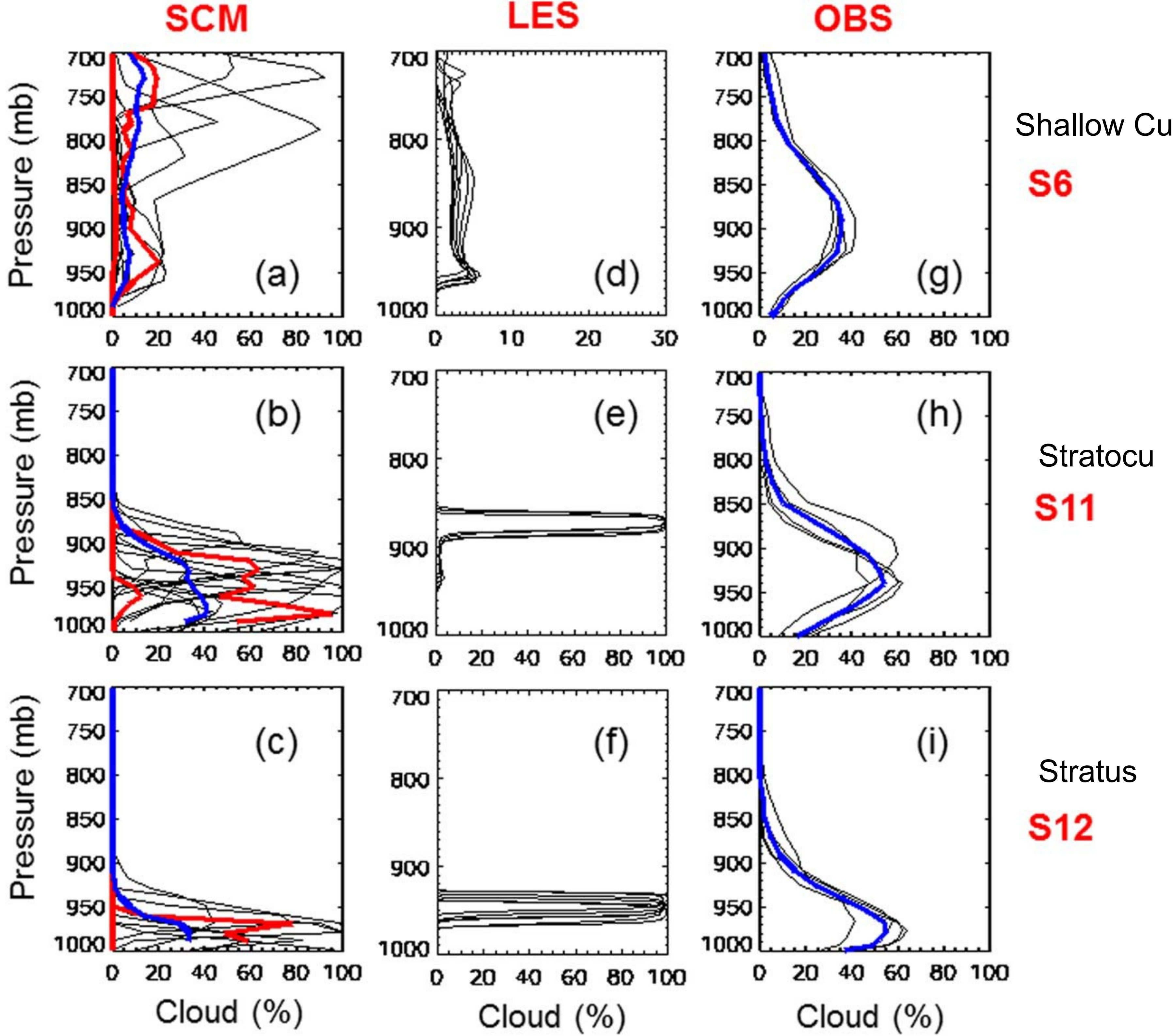
Subsidence in Current climate

Subsidence in +4K climate (dashed)



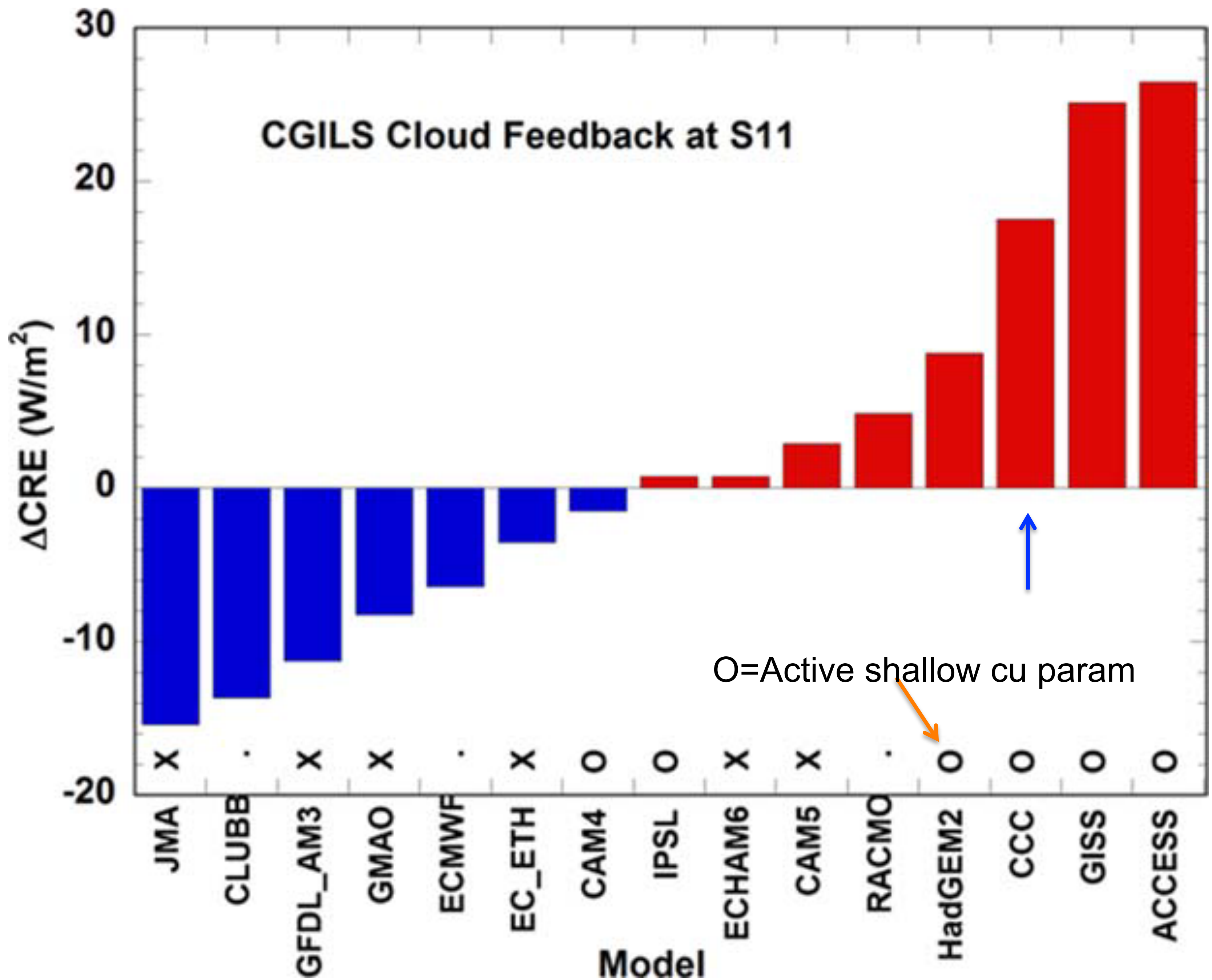
Specified large scale temperature tendency

Specified large scale moisture tendency

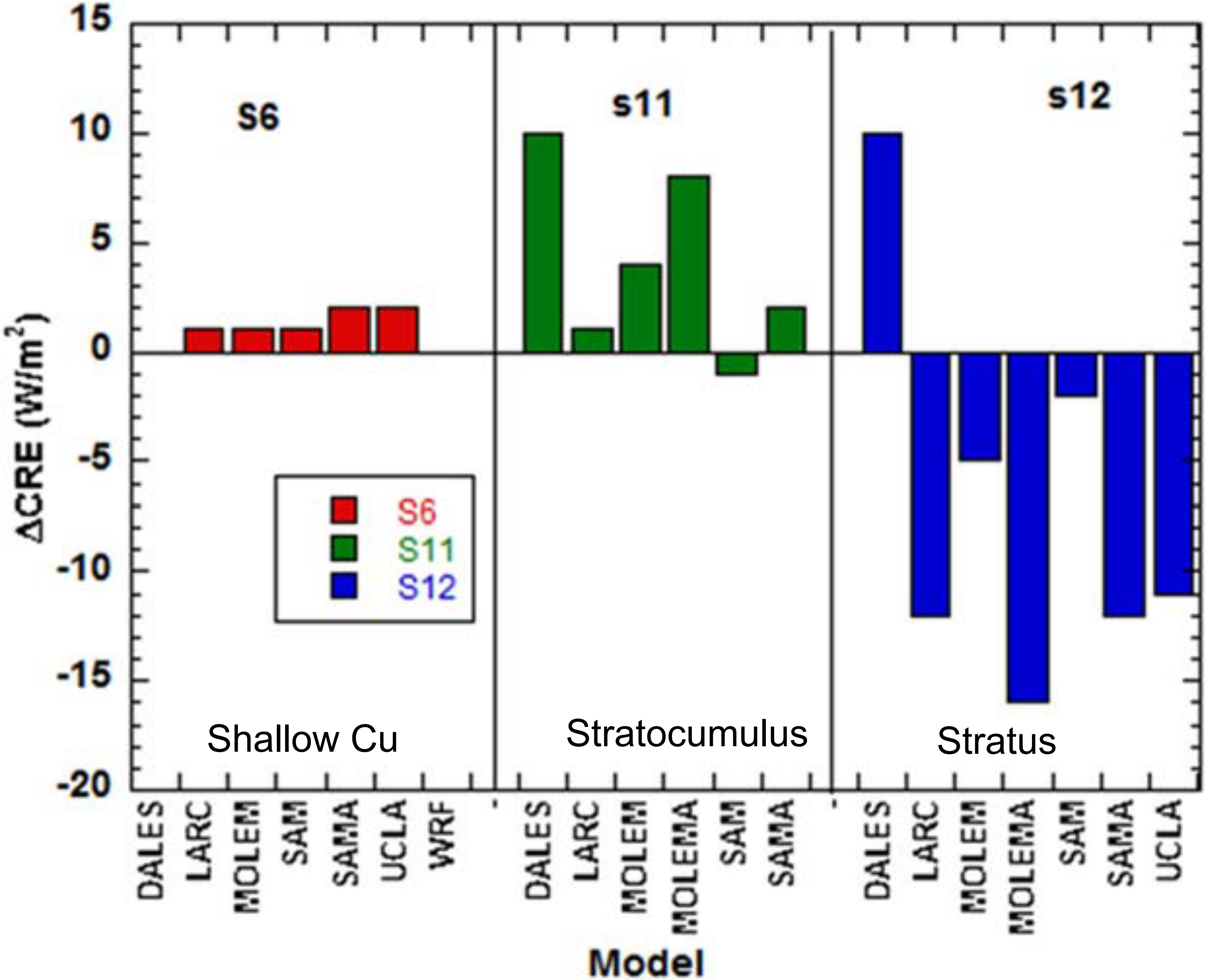


SCM
LES
OBS
Shallow Cu
S6
Stratocu
S11
Stratus
S12
Pressure (mb)
Cloud (%)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)

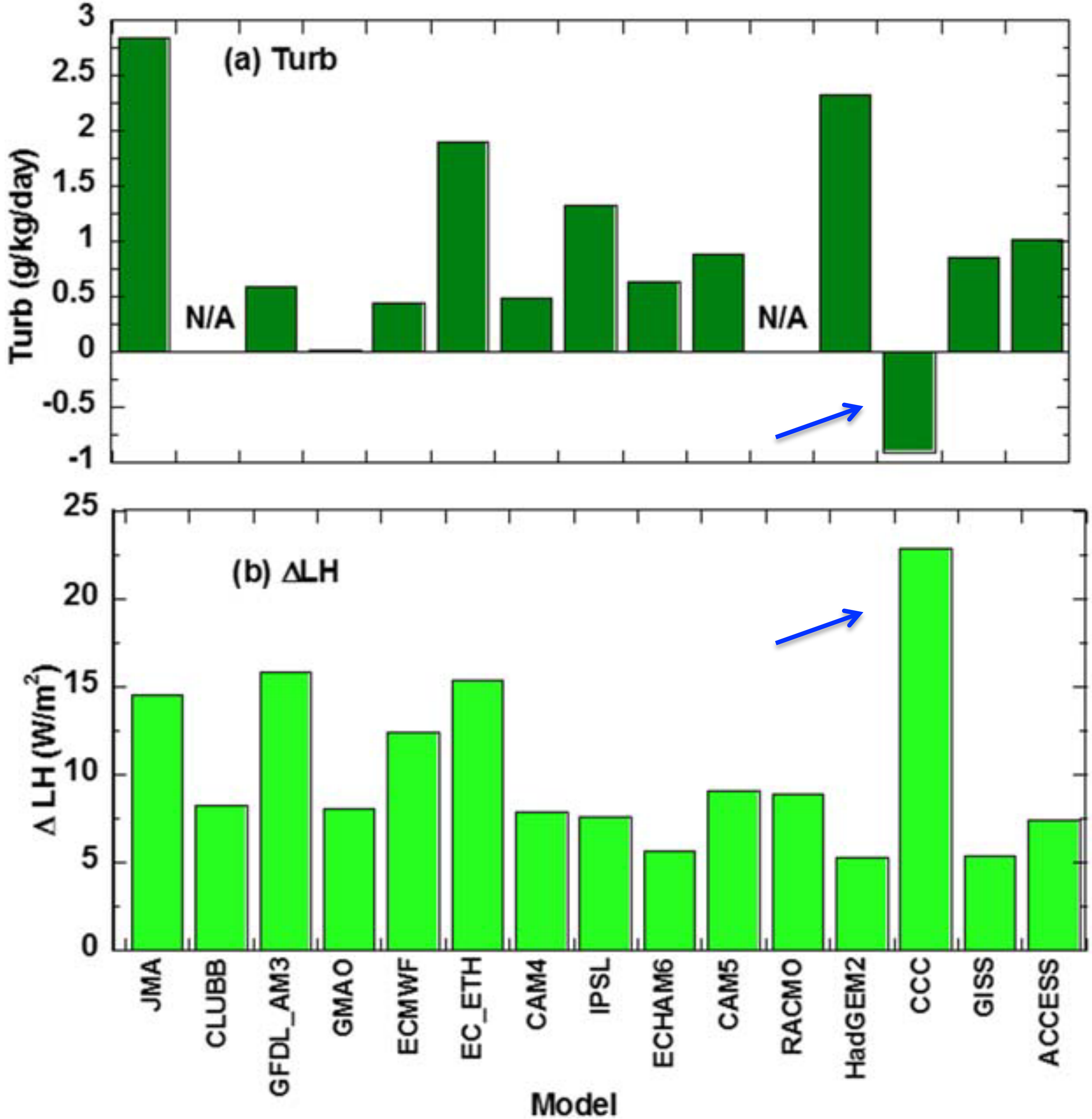
No consensus on sign or magnitude of stratocumulus cloud feedback



Most large eddy simulations have postive feedback at S11 (although significantly smaller)



Warming response for CanAM4 is to reduce turbulence and significantly Increase surface vapor flux

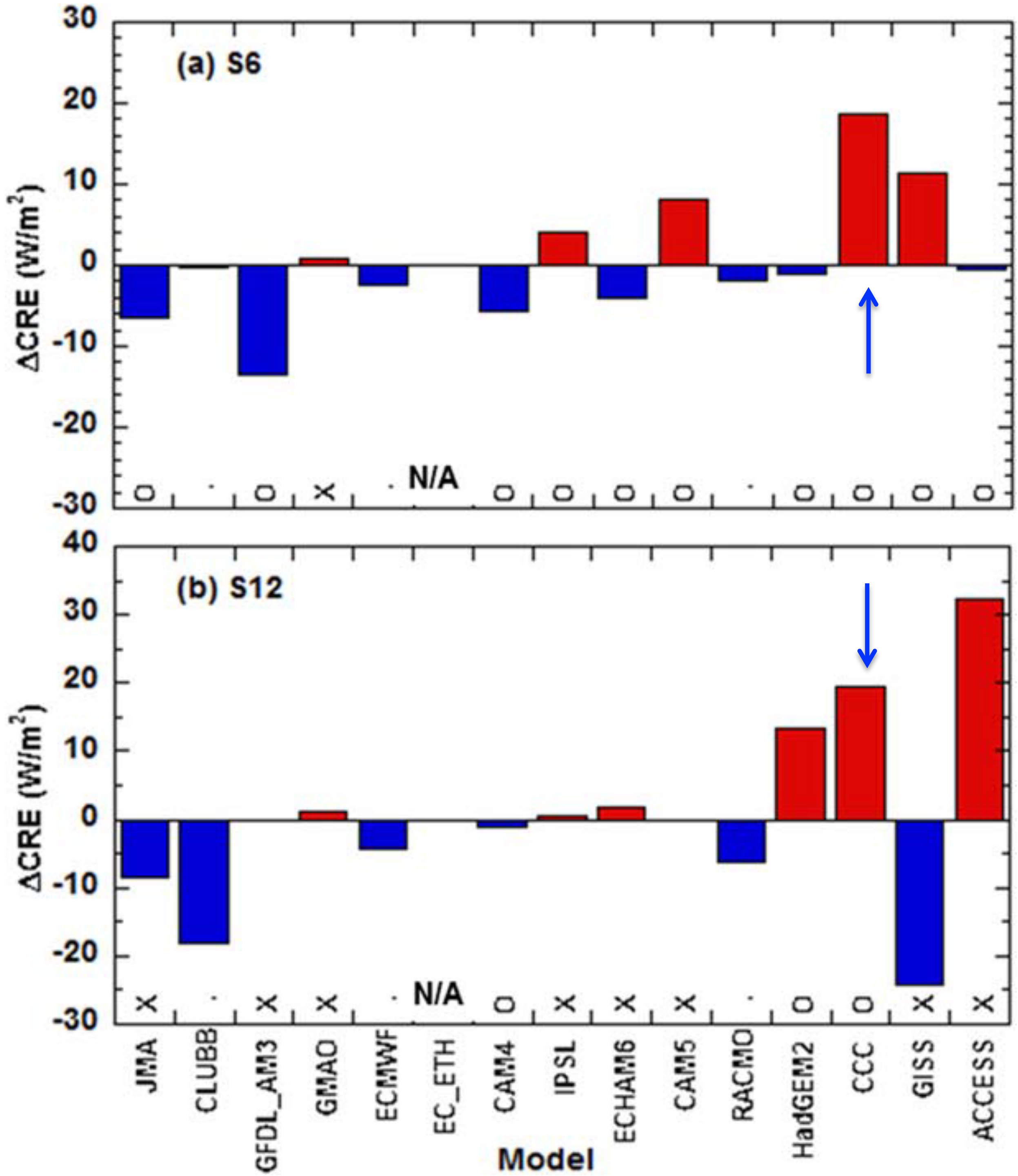


CanAM4 exhibits large
positive feedback for
Both Shallow Cu regime
And for stratus

LES have small positive
feedback for shallow cu,
large negative feedback
for stratus.

Part II summary: SCM shows
Significant low cloud feedbacks
In all cloud categories in the
subsidence regime in the
Eastern subtropical Pacific.

Next steps: return CGILS
cases with new TKE bounary
Layer parameterization



Entrainment: Some definitions and a simple mixing parameterization:

$$E = -\frac{1}{A}\oint_{\hat{\mathbf{n}}\cdot(\mathbf{u}-\mathbf{u_i})<0} \rho\hat{\mathbf{n}}\cdot(\mathbf{u}-\mathbf{u_i})dl \;\; (kg\, m^{-3}\, s^{-1})$$

Entrainment rate

$$D = \frac{1}{A}\oint_{\hat{\mathbf{n}}\cdot(\mathbf{u}-\mathbf{u_i})>0} \rho\hat{\mathbf{n}}\cdot(\mathbf{u}-\mathbf{u_i})dl(kg\, m^{-3}\, s^{-1})$$

Detrainment rate

$$M = \rho w \;\; (kg\, m\, s^{-2})$$

Vertical mass flux

$$M_{core}\frac{\partial \phi_{core}}{\partial z} = E(\phi_{env} - \phi_{core})$$

Cloud core tracer plume budget, constant cloud fraction

$$\rho\frac{\partial \phi_{env}}{\partial t} = D(\phi_{core} - \phi_{env})$$

Environment tracer budget

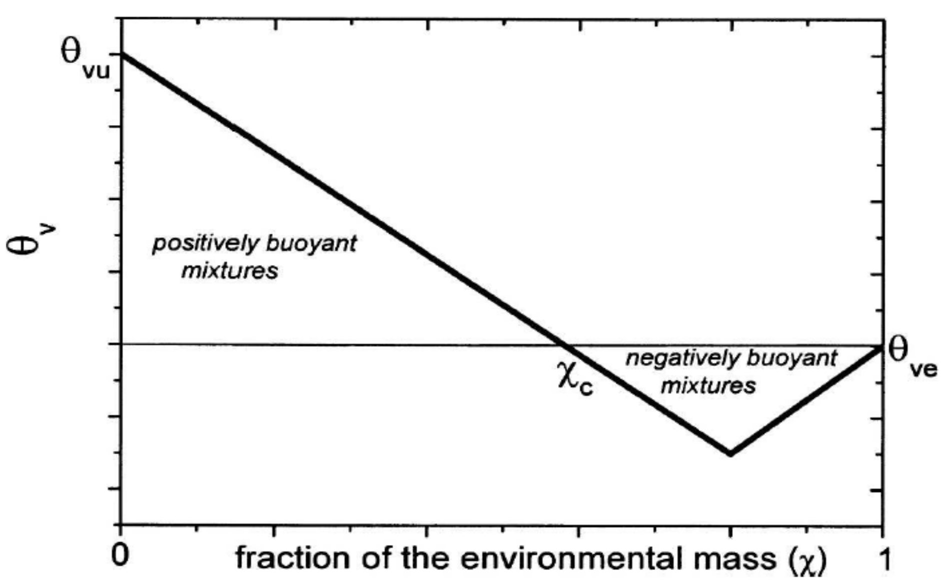
$$\epsilon = E/M_{core}, \quad \delta = D/M_{core} \;\; (s^{-1})$$

Fractional entrainment and detrainment rates

Background

- BOMEX and ARM-diurnal simulations with SAM 6.8.2 LES
- 25 m grid size in x,y,z on ~ 6 km x 6 km horizontal domain
- One minute snapshots
- 4362 tracked clouds over 12 simulation hours
- Filter out clouds smaller than 16 gridcells (50% of population, 5% of mass flux)
- 120,000 individual samples of entrainment and detrainment rates with coincident samples of buoyancy, vertical velocity, environmental stability, critical mixing fraction χ_c

χ_c



Movie: Cloud tracking for life-cycle measurements of entrainment/detrainment in the UBC-SAM LES

- Question: Do LES measurements of direct entrainment/detrainment provide constraints on parameterizations of ε and δ, e.g:

$$\epsilon = \frac{\alpha B}{w^2} - \frac{1}{w}\frac{\partial w}{\partial z}$$

$$\epsilon = \epsilon_0$$

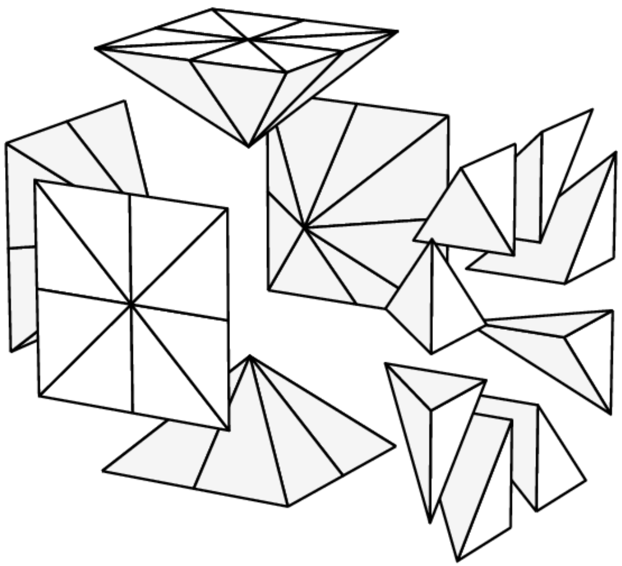
$$\epsilon = c_e z^{-1}$$

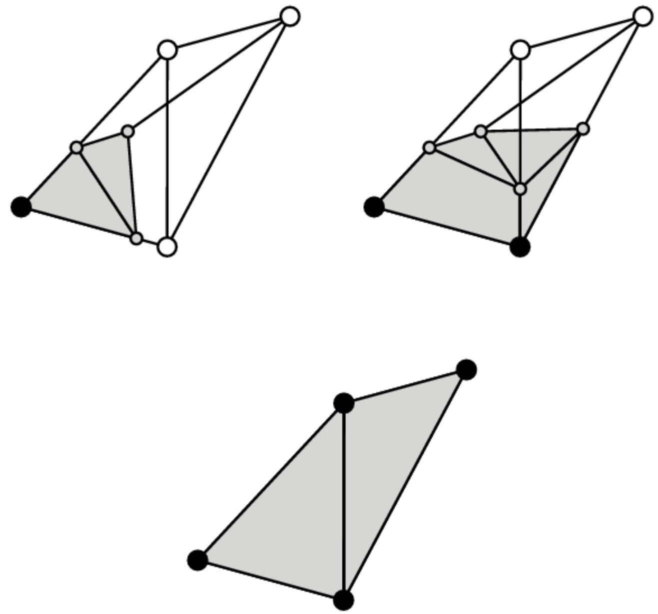
$$\epsilon = \frac{\eta}{\tau_p}\frac{1}{w_p}$$

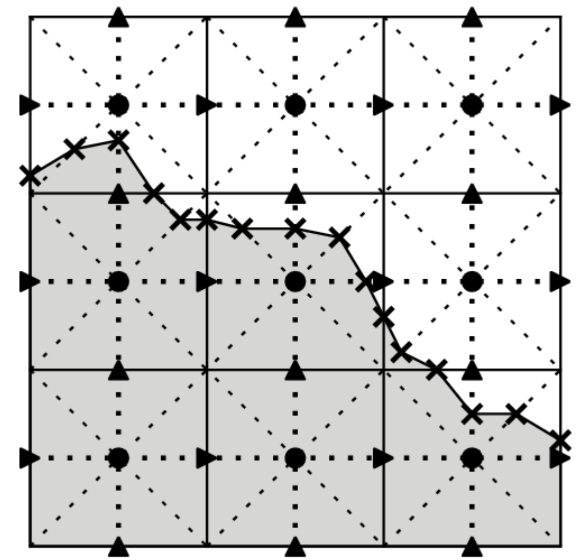
$$\epsilon = \epsilon_0 \chi_c^2$$

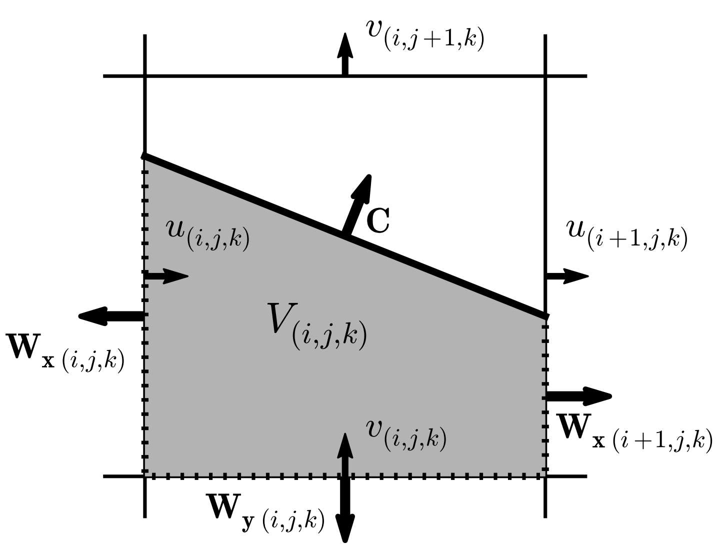
$$\delta = \epsilon_0 (1 - \chi_c)^2$$

Tetrahedral interpolation and the direct entrainment calculation

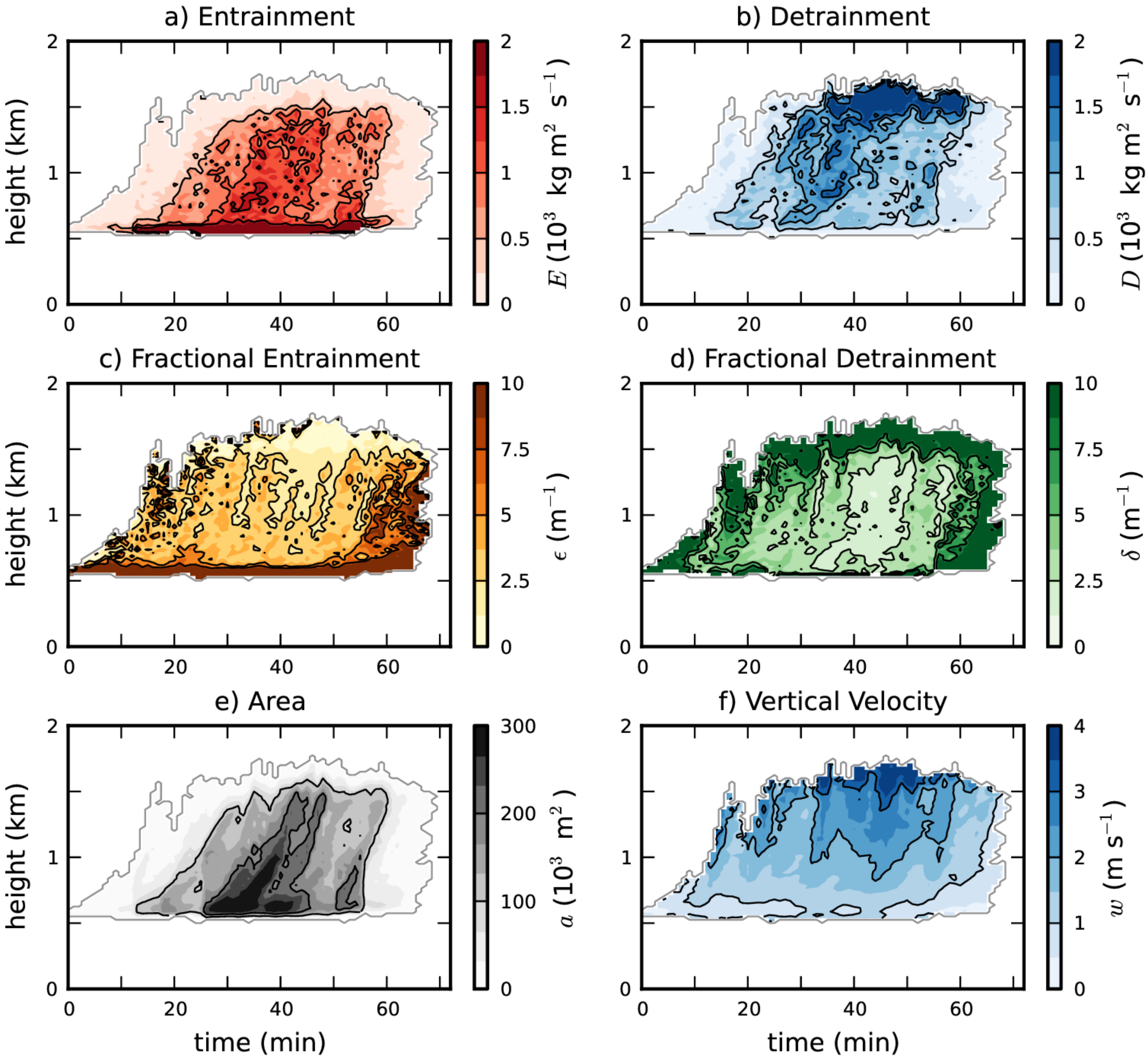






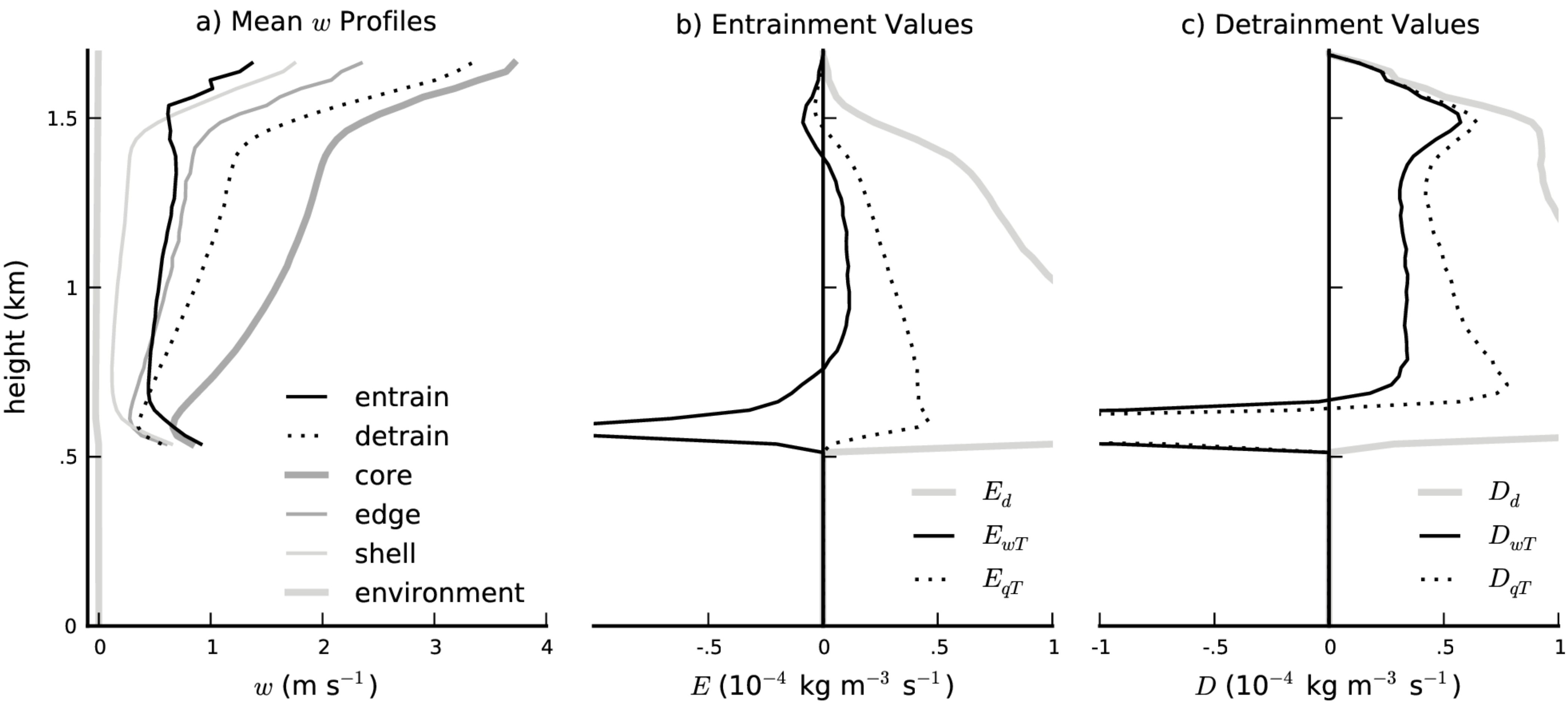


Dawe and Austin, MWR 2011



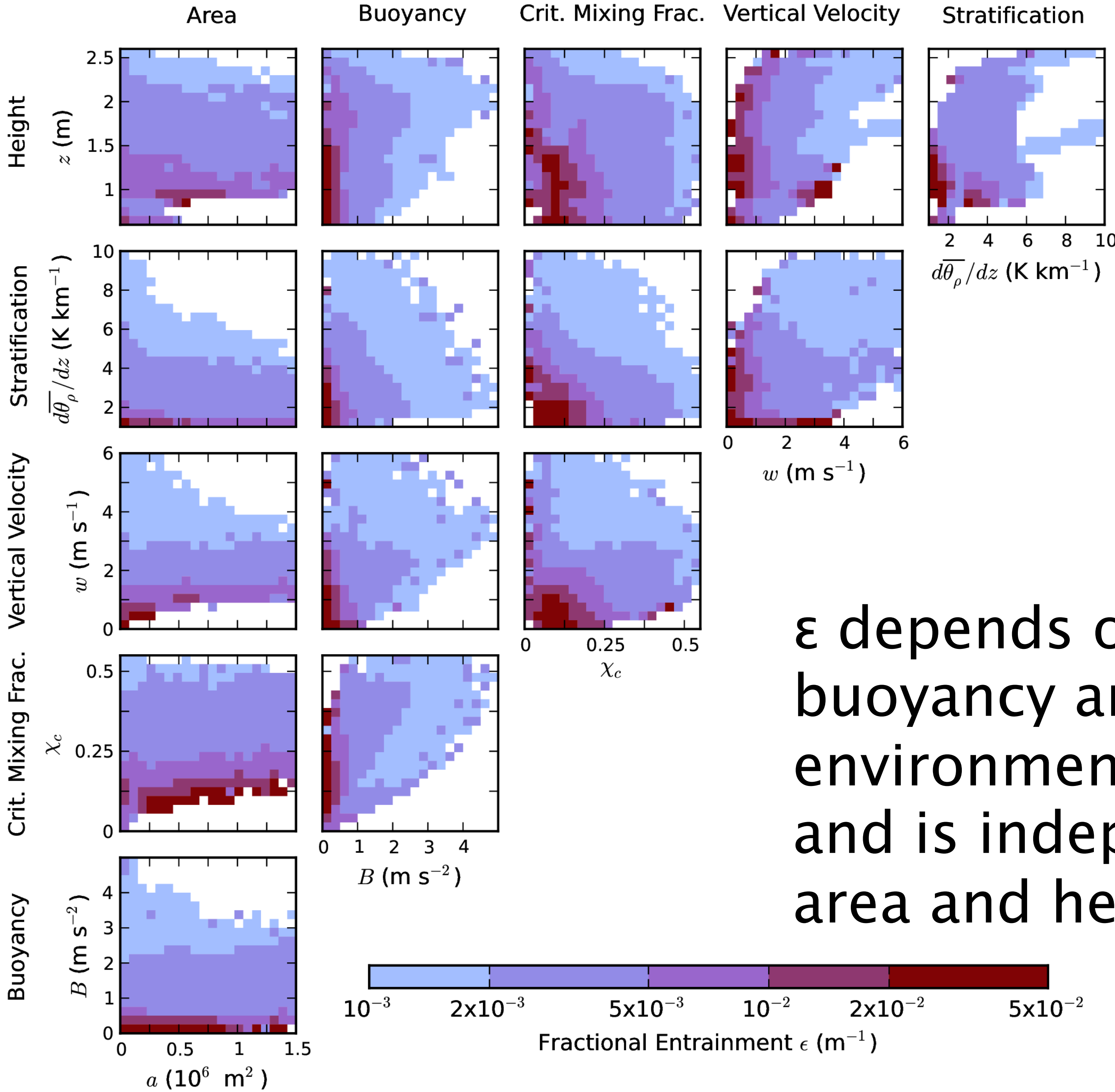
a) Entrainment
b) Detrainment
c) Fractional Entrainment
d) Fractional Detrainment
e) Area
f) Vertical Velocity
height (km)
time (min)
E (10^3 kg m^2 s^-1)
D (10^3 kg m^2 s^-1)
ϵ (m^-1)
δ (m^-1)
a (10^3 m^2)
w (m s^-1)
0
20
40
60
0.5
1
1.5
2
2.5
5
7.5
10
100
200
300
3
4

Direct vs. bulk thermodynamic entrainment

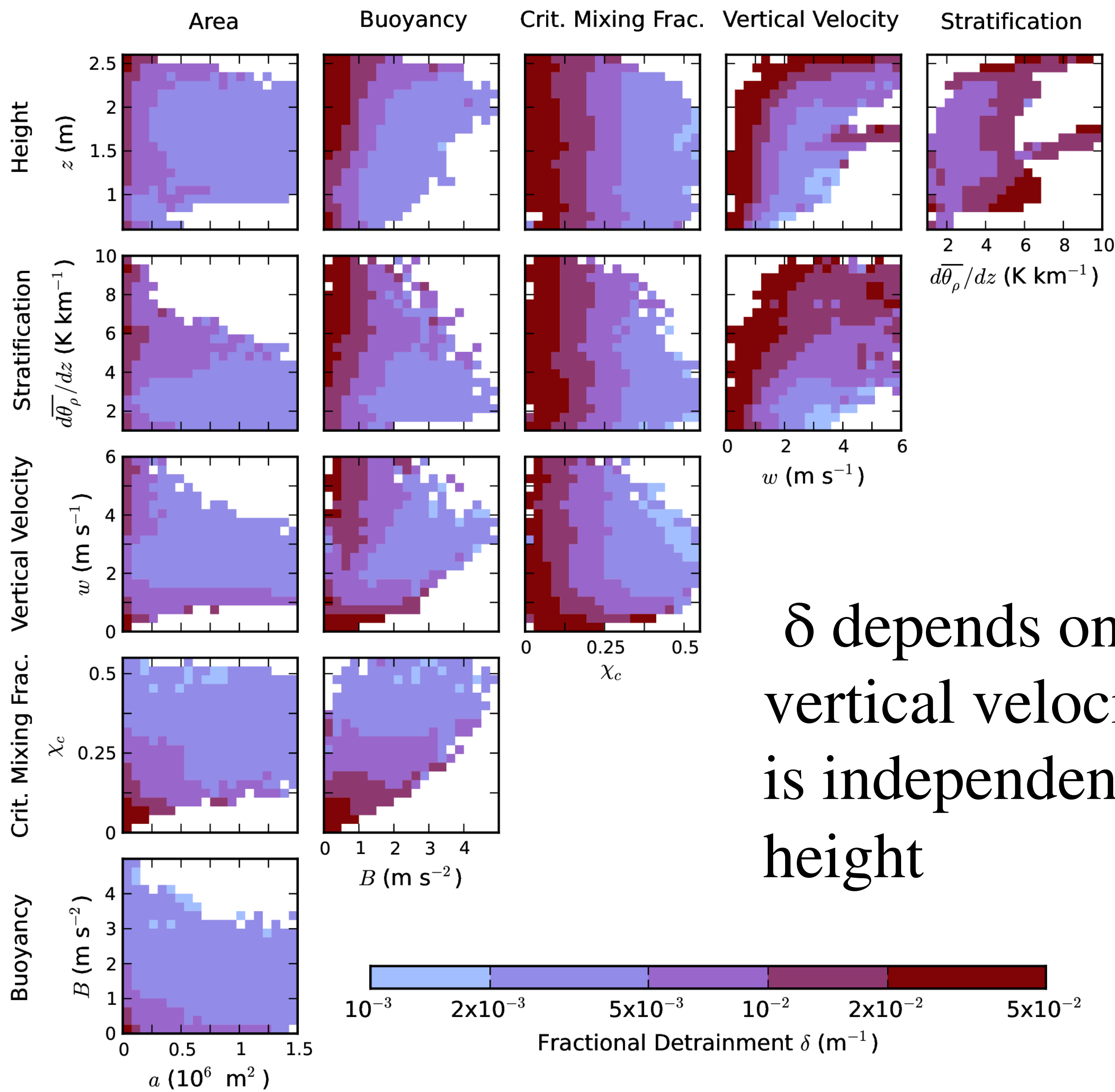


Dawe and Austin, JAS, 2011

Direct entrainment rates more than twice those calculated by budget calculations that assume mixing between mean cloud and environment (and note difference between tracer and momentum entrainment rates)



ε depends on buoyancy and local environmental stability and is independent of area and height



δ depends on mean vertical velocity and χ_c and is independent of area and height

Quantify this with the mutual information, I(X;Y)

$$I(X) = \ln\left(\frac{1}{P(x)}\right) = -\ln\big(P(x)\big)$$

Self information

$$H = -\int P(x)\ln\big(P(x)\big)dx$$

Entropy

$$I(X;Y) = H(X) - H(X\,|\,Y)$$

Mutual information

$$I(X;Y) = \int P(x,y)\ln\left(\frac{P(x,y)}{P(x)P(y)}\right)dxdy$$

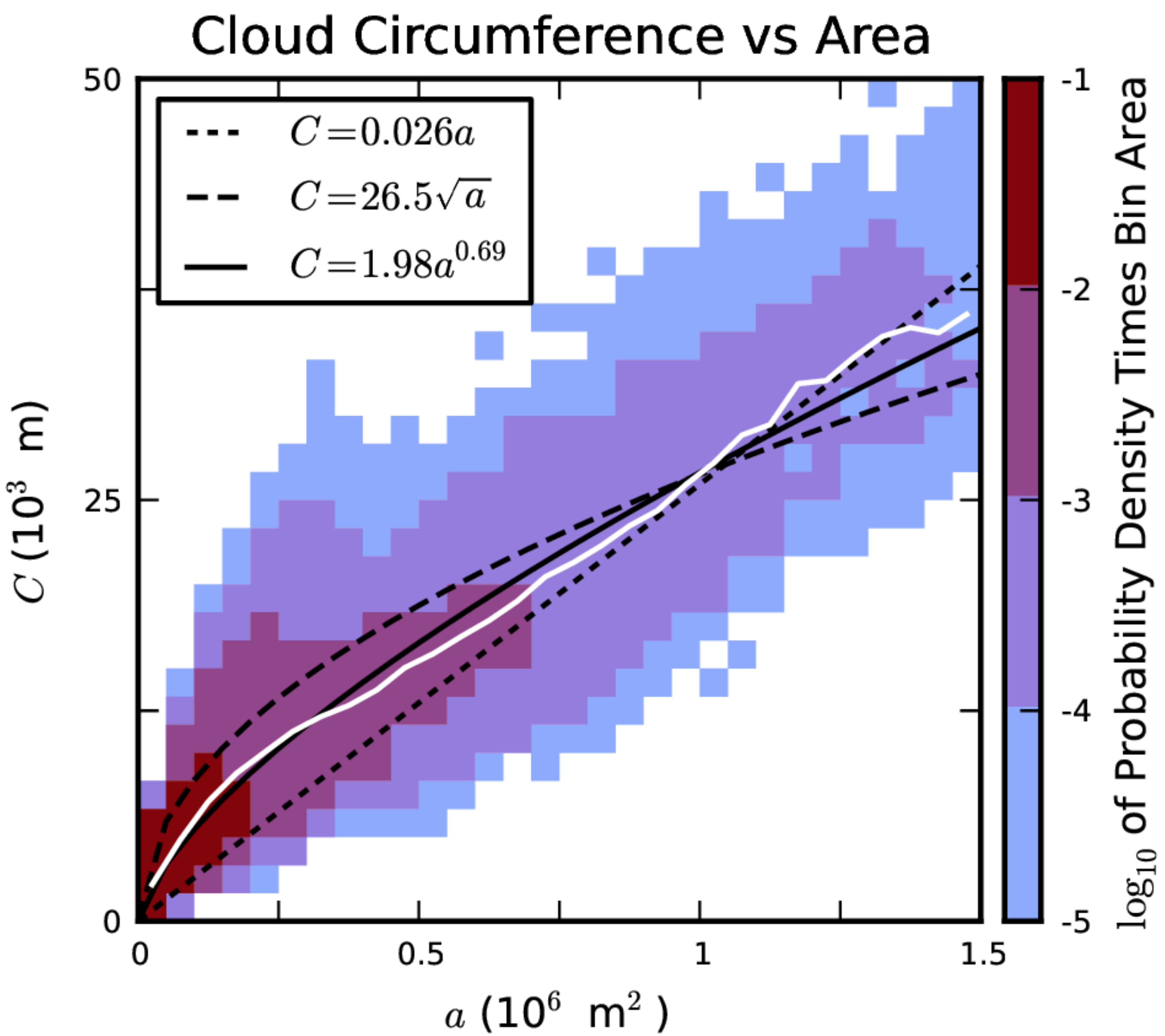
Mutual information

Entrainment

Variable	MI	Noise
$I(\log_{10}\epsilon; z)$	0.104	0.002
$I(\log_{10}\epsilon; w)$	0.214	
$I(\log_{10}\epsilon; a)$	0.036	
$I(\log_{10}\epsilon; B)$	0.419	
$I(\log_{10}\epsilon; \chi_c)$	0.259	
$I(\log_{10}\epsilon; d\overline{\theta_\rho}/dz)$	0.130	
$I(\log_{10}\epsilon; z\|B)$	0.07	0.01
$I(\log_{10}\epsilon; w\|B)$	0.06	
$I(\log_{10}\epsilon; a\|B)$	0.03	
$I(\log_{10}\epsilon; \chi_c\|B)$	0.07	
$I(\log_{10}\epsilon; d\overline{\theta_\rho}/dz\|B)$	0.13	
$I(\log_{10}\epsilon; z\|B, d\overline{\theta_\rho}/dz)$	0.12	0.10
$I(\log_{10}\epsilon; w\|B, d\overline{\theta_\rho}/dz)$	0.08	0.07
$I(\log_{10}\epsilon; a\|B, d\overline{\theta_\rho}/dz)$	0.09	0.07
$I(\log_{10}\epsilon; \chi_c\|B, d\overline{\theta_\rho}/dz)$	0.11	0.09

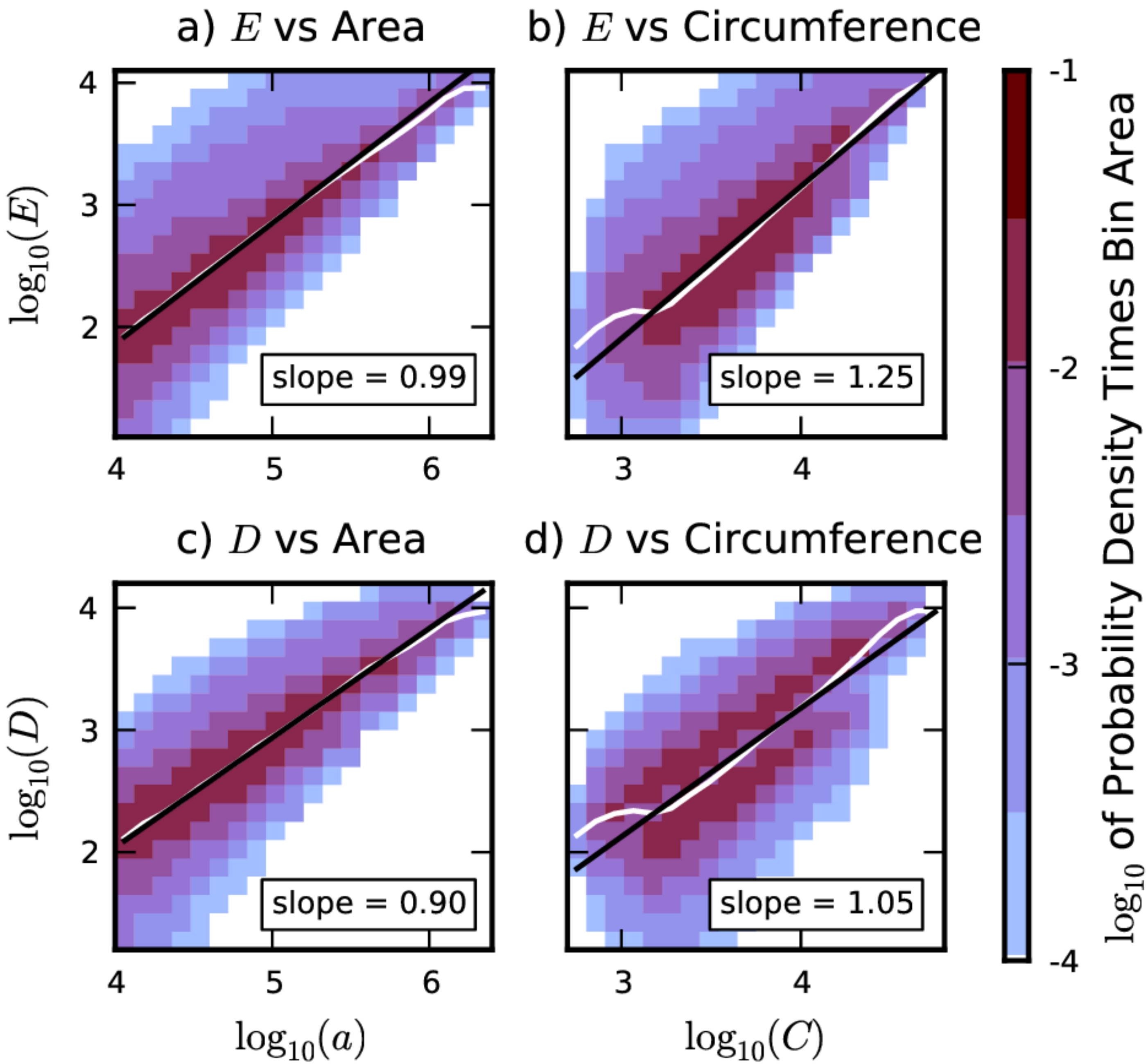
Detrainment

Variable	MI	Noise
$I(\log_{10}\delta; z)$	0.027	0.002
$I(\log_{10}\delta; w)$	0.216	
$I(\log_{10}\delta; a)$	0.152	
$I(\log_{10}\delta; B)$	0.184	
$I(\log_{10}\delta; \chi_c)$	0.353	
$I(\log_{10}\delta; d\overline{\theta_\rho}/dz)$	0.054	
$I(\log_{10}\delta; z\|\chi_c)$	0.04	0.02
$I(\log_{10}\delta; w\|\chi_c)$	0.17	
$I(\log_{10}\delta; a\|\chi_c)$	0.08	
$I(\log_{10}\delta; B\|\chi_c)$	0.03	
$I(\log_{10}\delta; d\overline{\theta_\rho}/dz\|\chi_c)$	0.04	
$I(\log_{10}\delta; z\|\chi_c, w)$	0.27	0.13
$I(\log_{10}\delta; a\|\chi_c, w)$	0.11	0.09
$I(\log_{10}\delta; B\|\chi_c, w)$	0.12	0.08
$I(\log_{10}\delta; d\overline{\theta_\rho}/dz\|\chi_c, w)$	0.17	0.09



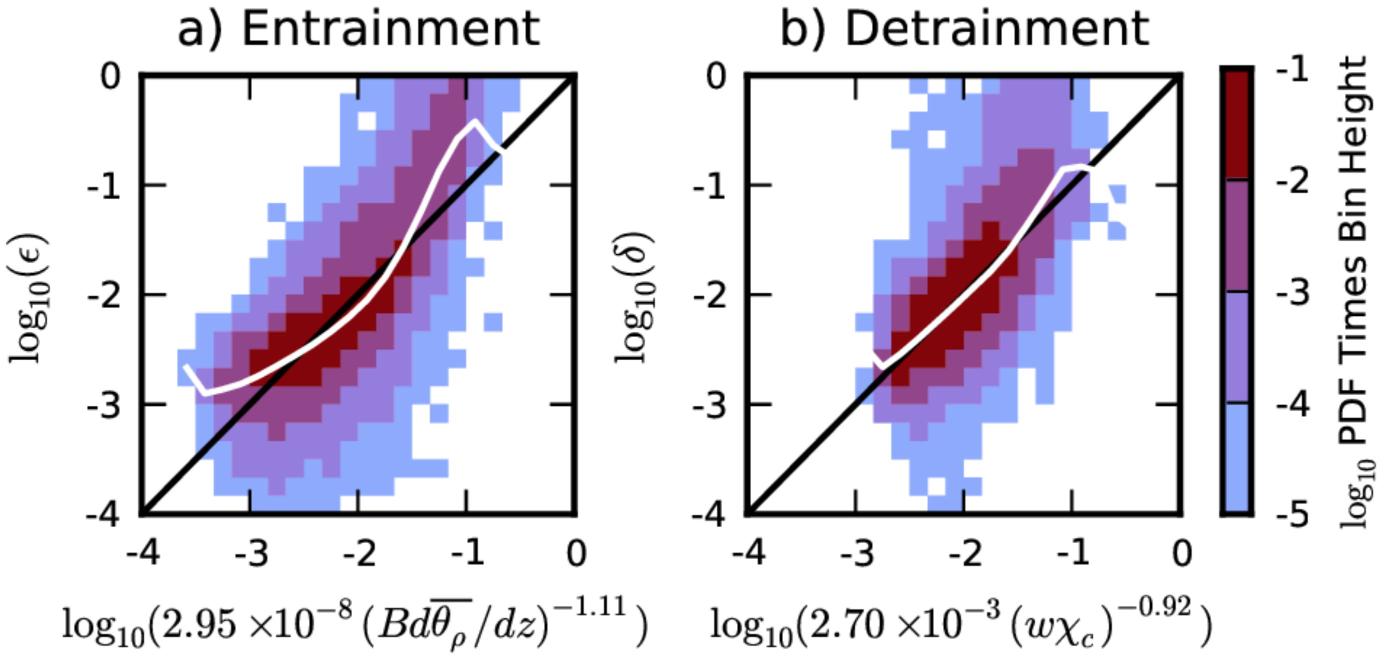
Best fit functional relationships

Clouds are not cylinders, but Circumference and Area have a scaling relationship: $C \sim a^{0.7}$



Dimensional entrainment E and detrainment D

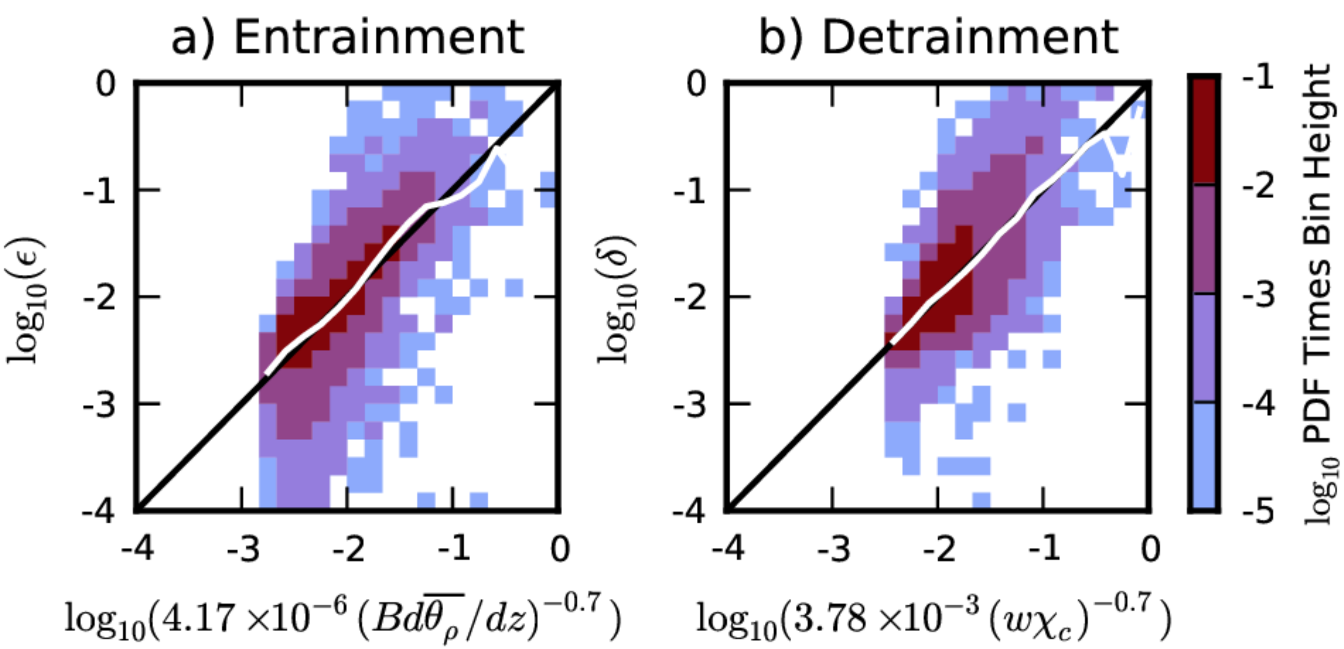
E ~ Area while D ~ Circumference



Fit to individual values of ε,δ

$$\epsilon \propto (Bd\theta / dz)^{-1.11}$$

$$\delta \propto (w\chi_c)^{-0.92}$$



Fit to ensemble average ε,δ

$$\epsilon \propto (Bd\theta / dz)^{-0.7}$$

$$\delta \propto (w\chi_c)^{-0.7}$$

To Summarize:

$\epsilon \propto (B d\theta / dz)^{-0.7}$ $\delta \propto (w \chi_c)^{-0.7}$ LES

$$\epsilon = \frac{\alpha B}{w^2} - \frac{1}{w}\frac{\partial w}{\partial z}$$

$$\epsilon = \epsilon_0$$

$$\epsilon = c_e z^{-1}$$

$$\epsilon = \frac{\eta}{\tau_p}\frac{1}{w_p} \qquad \epsilon = \epsilon_0 \chi_c^2 \qquad \delta = \epsilon_0 (1 - \chi_c)^2$$

Tropical simulations with the UBC SAM model (radiative-convective equilibrium and weak temperature gradient approximation as part of the GASS-WTG SCM/CRM intercomparison

Next steps: move from shallow to deep convection

Cloud Entrainment vs Area

Entrainment is often parameterized by:

$$E = k\frac{M}{R} = k\frac{\rho a w}{R}$$

The rationale for this is simple.

$$C = 2\pi R = 2\frac{a}{R} \qquad v_E = v_o w \qquad E = \rho C v_E = 2v_o\frac{\rho a w}{R}$$

However, we find $E = k\rho a$. This implies $\rho C v_E = k\rho a$

There are two possibilities:

1. If the cloud is a cylinder, then

$$v_E = kR/2$$

2. If the cloud is not a cylinder, then

$$C = \frac{ka}{v_o w}$$