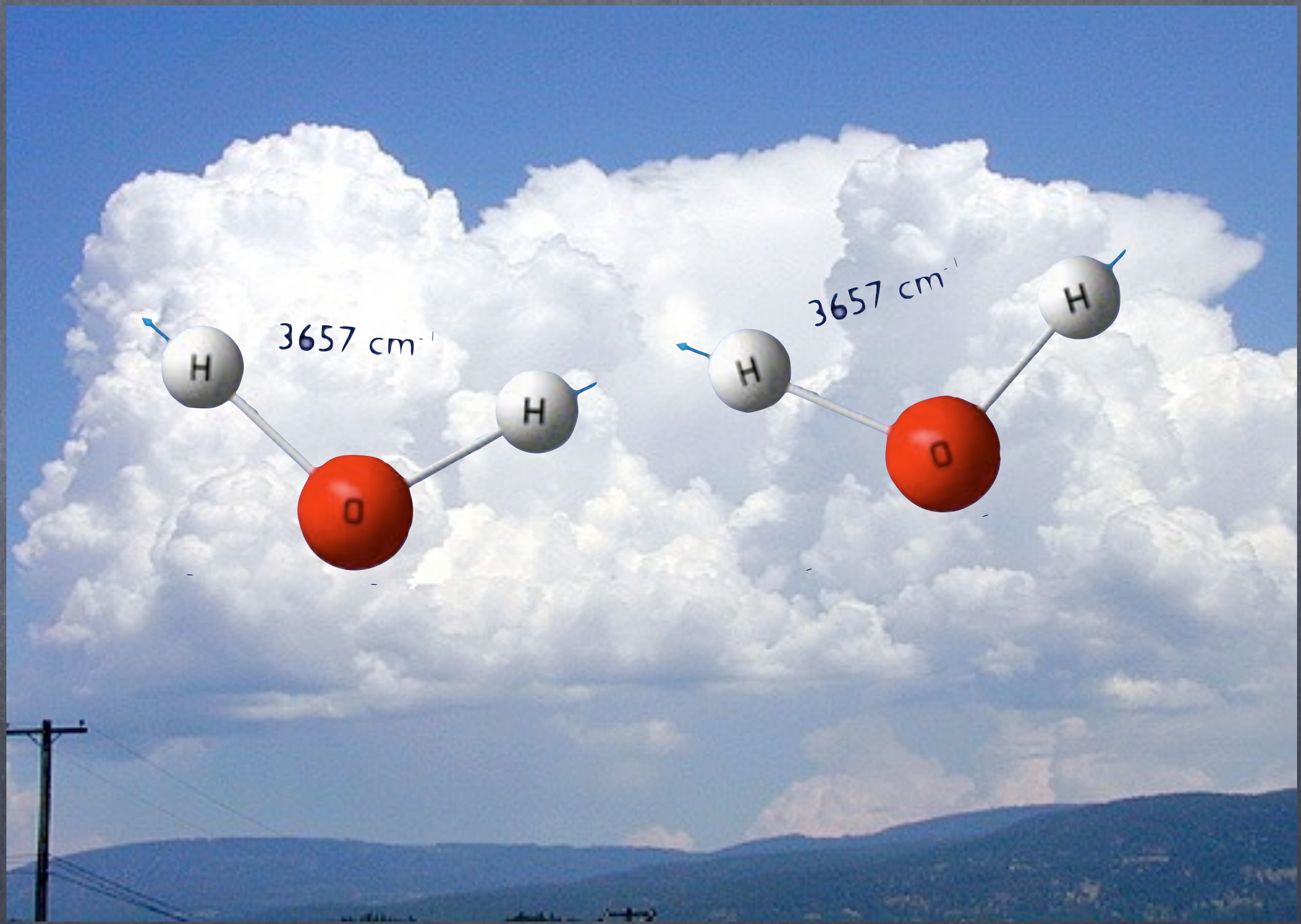
Recent Advances in Understanding Cloud Feedbacks



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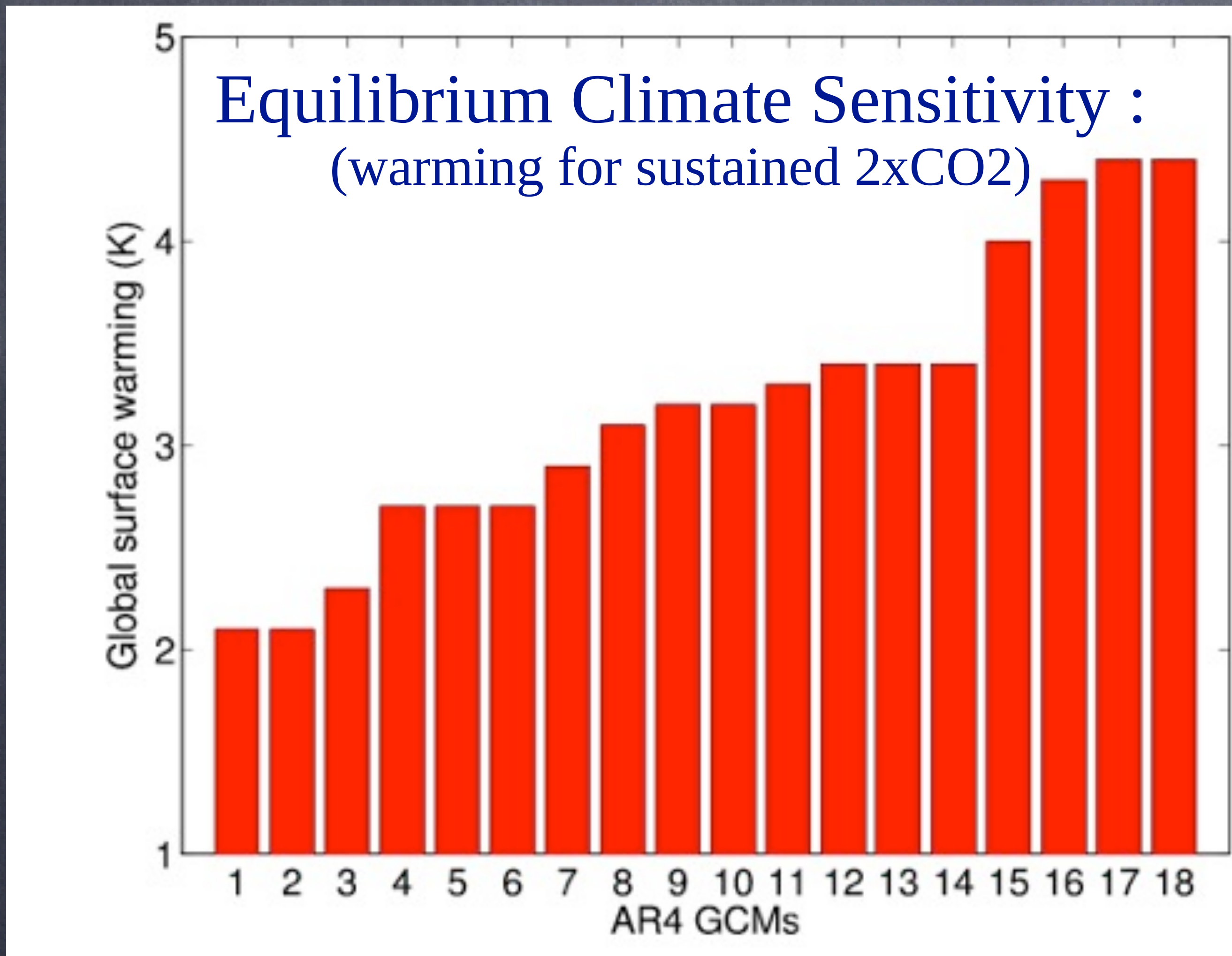
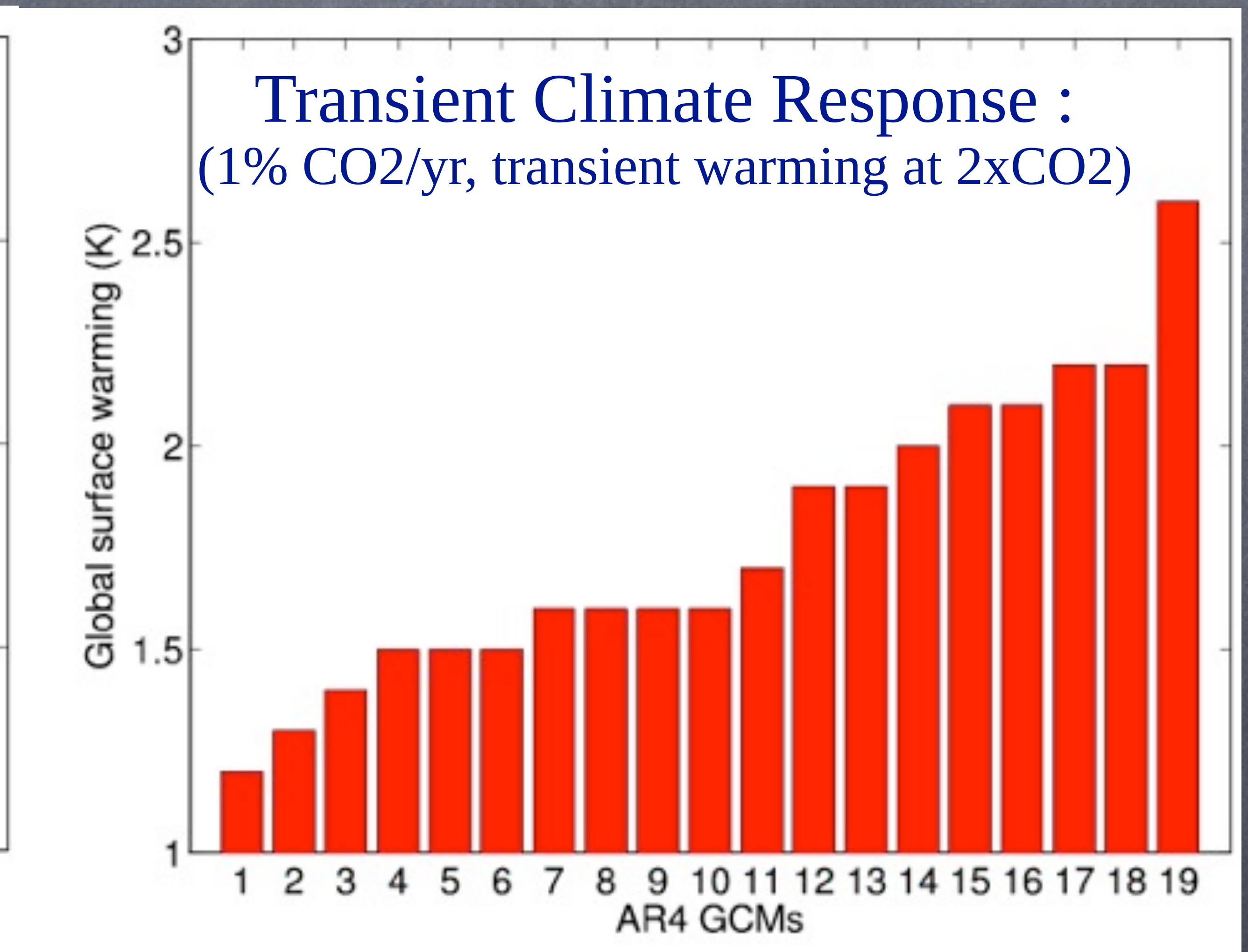
Climate sensitivity estimates from CMIP3 GCMs participating in the IPCC AR4 :



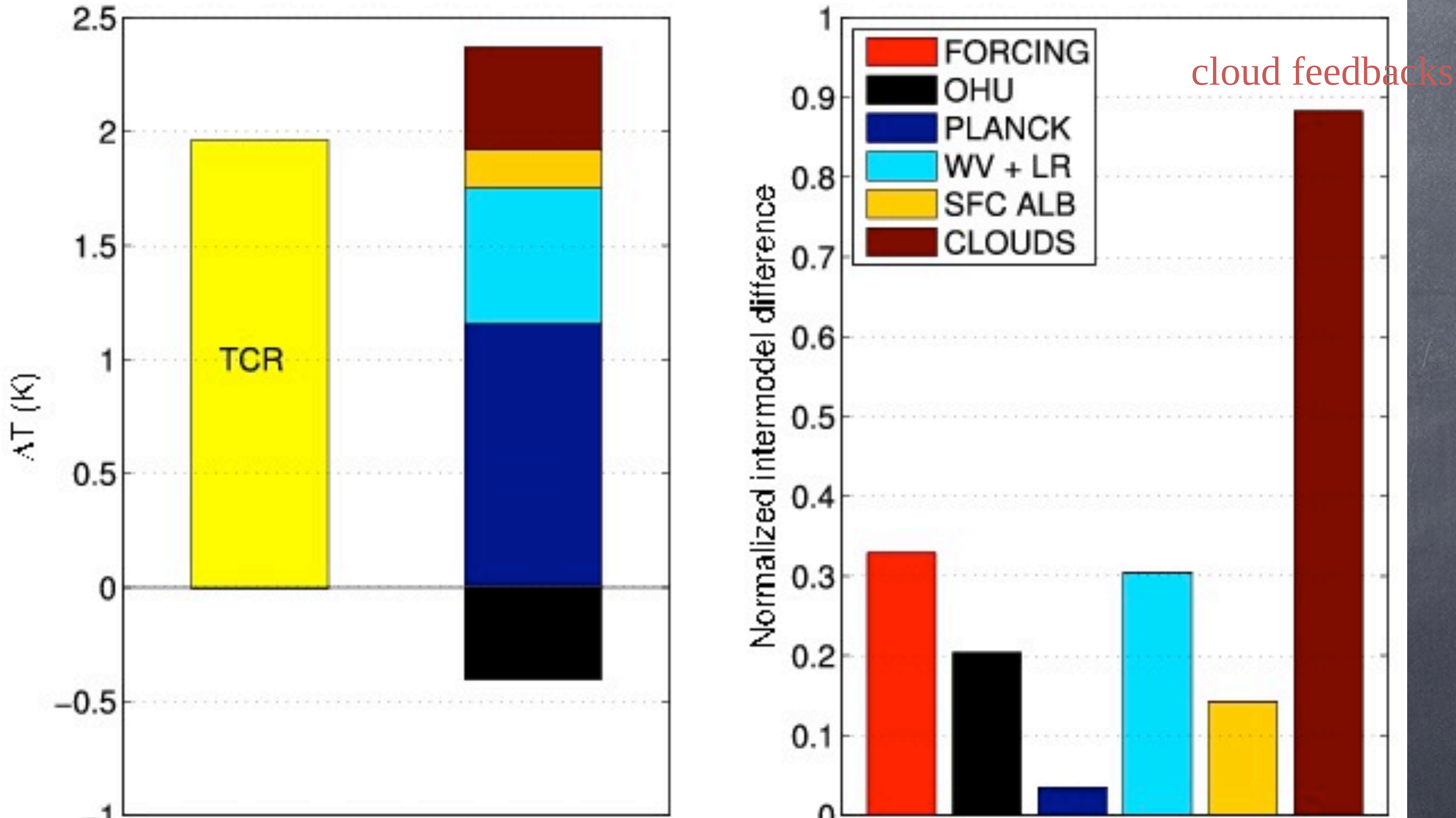


[IPCC 2007, Chapter 8]

Spread in climate sensitivity and TCR : a concern for many aspects of climate change research (assessment of climate extremes and impacts, the design of mitigation scenarios, etc)

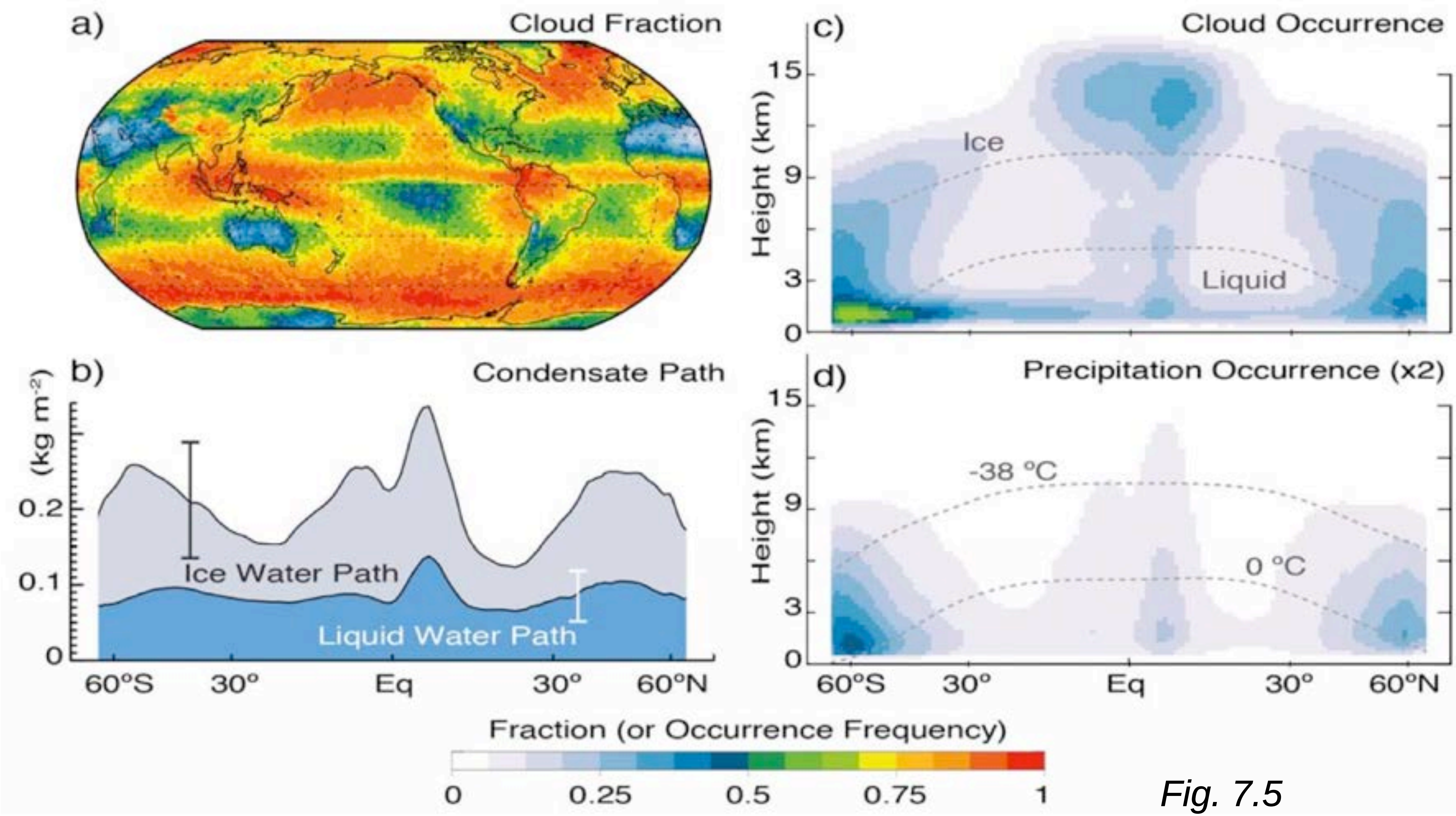
Origin of the spread : radiative forcing ? climate feedbacks ? ocean heat uptake ?

Decomposition of the Transient Climate Response (TCR) simulated by CMIP3/AR4 OAGCMs :



multi-model mean ***inter-model differences (standard deviation)***

(Dufresne & Bony, J. Climate, 2008)



a)
Cloud Fraction
c)
Cloud Occurrence
Height (km)
15
9
3
0
Ice
Liquid
b)
Condensate Path
(kg m-2)
0.2
0.1
0
Ice Water Path
Liquid Water Path
60°S
30°
Eq
30°
60°N
d)
Precipitation Occurrence (x2)
Height (km)
-38 °C
0 °C
Fraction (or Occurrence Frequency)
0
0.25
0.5
0.75
1

Fig. 7.5

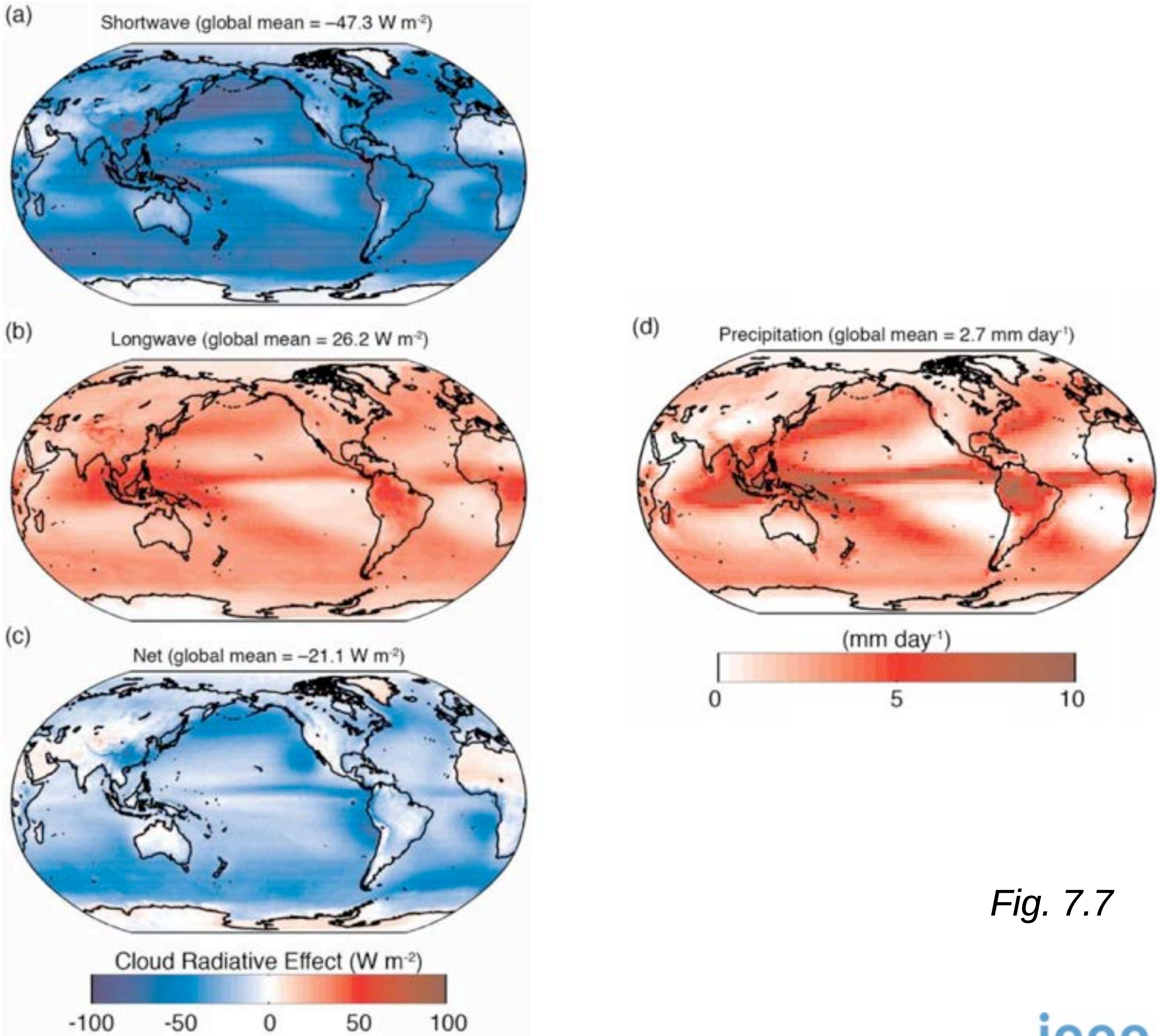

(a)
Shortwave (global mean = −47.3 W m-2)
(b)
Longwave (global mean = 26.2 W m-2)
(c)
Net (global mean = −21.1 W m-2)
Cloud Radiative Effect (W m-2)
-100 -50 0 50 100
(d)
Precipitation (global mean = 2.7 mm day-1)
(mm day-1)
0 5 10

Fig. 7.7

◆ = positive feedback contribution

◆ = ambiguous feedback contribution

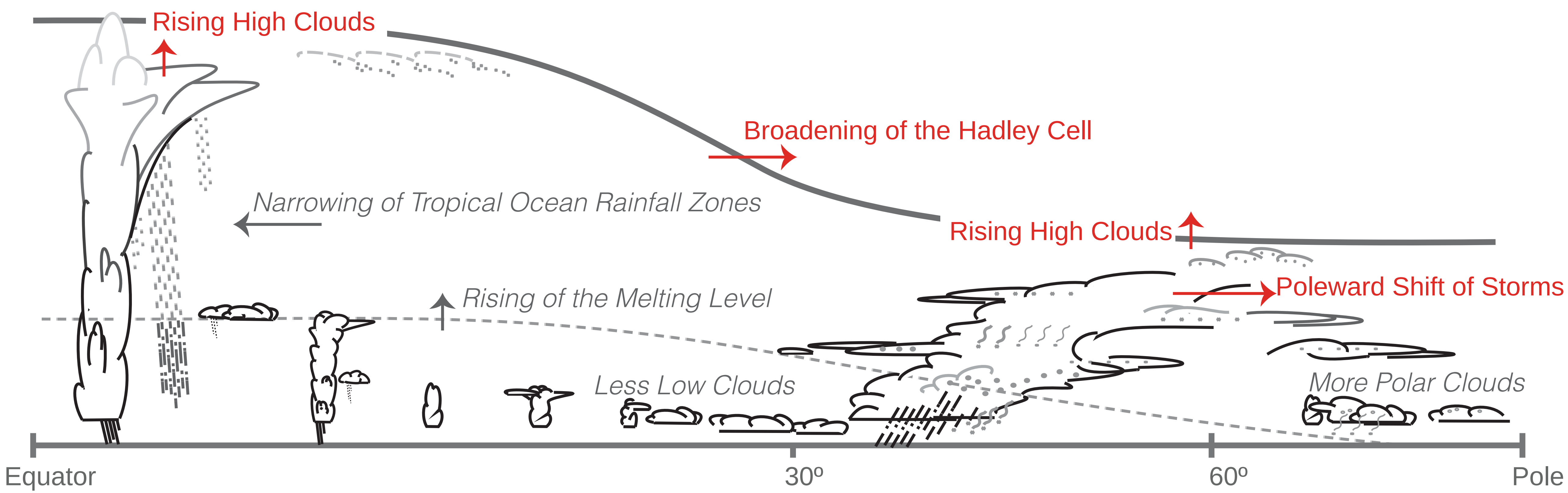
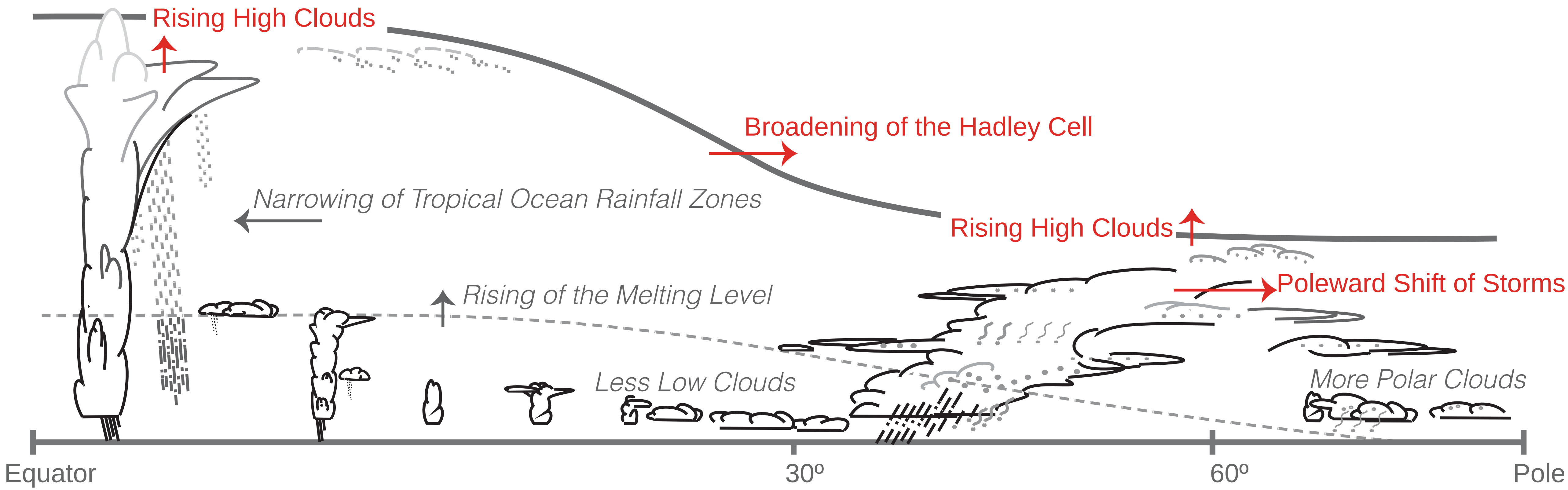


Fig. 7.11

◆ = positive feedback contribution

◆ = ambiguous feedback contribution

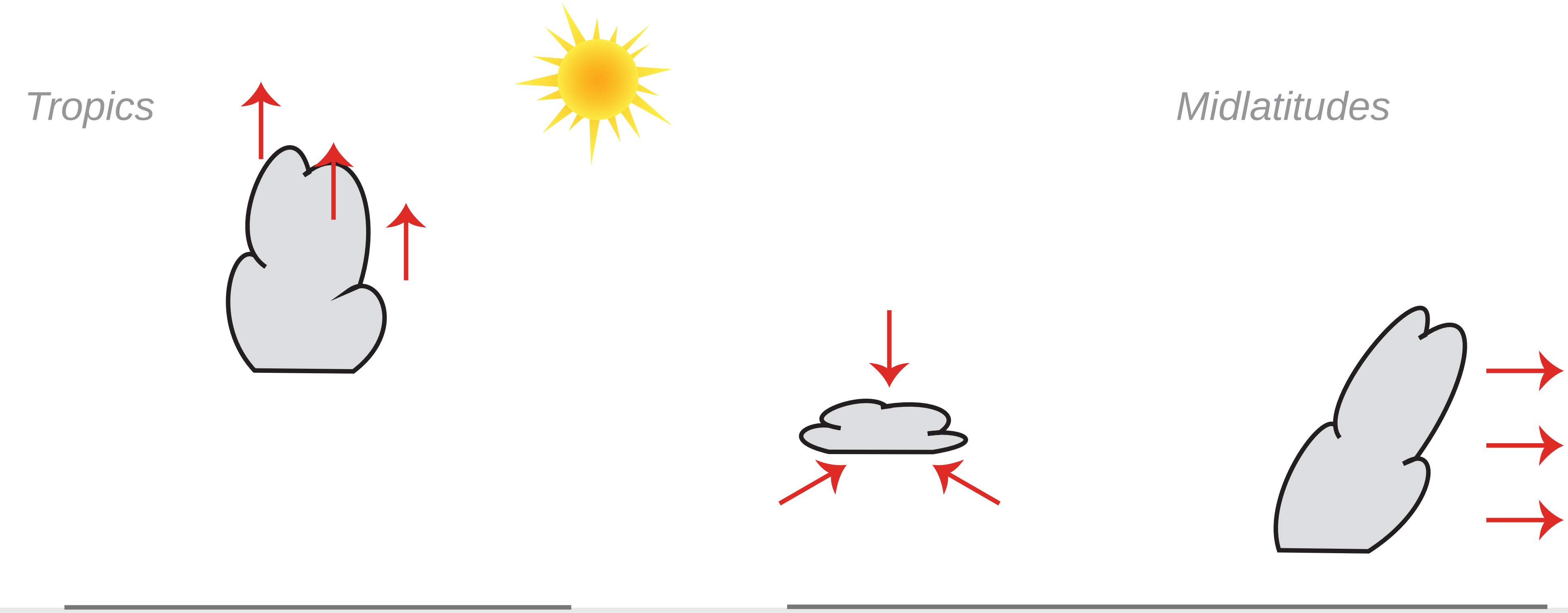


What could be missing?

- low cloud feedback remains highly variable in models
- cirrus cloud amount/thickness feedback might also be possible

Fig. 7.11

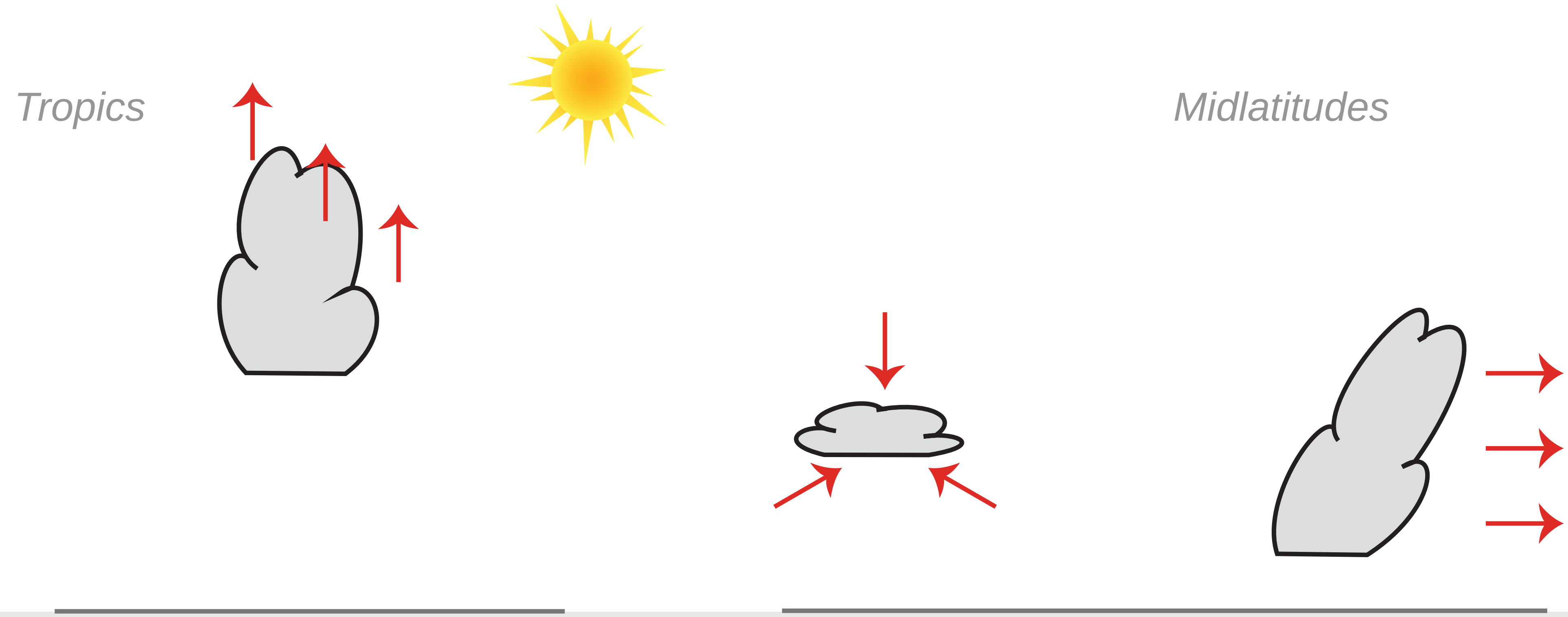
Greenhouse Warming



Cloud Response	High clouds rise as troposphere deepens, increasing difference between cloud top and surface temperature.	Reduction in mid- and low-level cloudiness (left). Shift of cloudy storm tracks poleward into regions with less sunlight (right).
Feedback Mechanism	High clouds more effectively trap infrared radiation, increasing surface warming.	Less sunlight reflected by clouds back to space, increasing surface warming.

DRAFT Fig. FAQ 7.1

Greenhouse Warming



	Tropics	Midlatitudes
Cloud Response	High clouds rise as troposphere deepens, increasing difference between cloud top and surface temperature.	Reduction in mid- and low-level cloudiness (left). Shift of cloudy storm tracks poleward into regions with less sunlight (right).
Feedback Mechanism	High clouds more effectively trap infrared radiation, increasing surface warming.	Less sunlight reflected by clouds back to space, increasing surface warming.

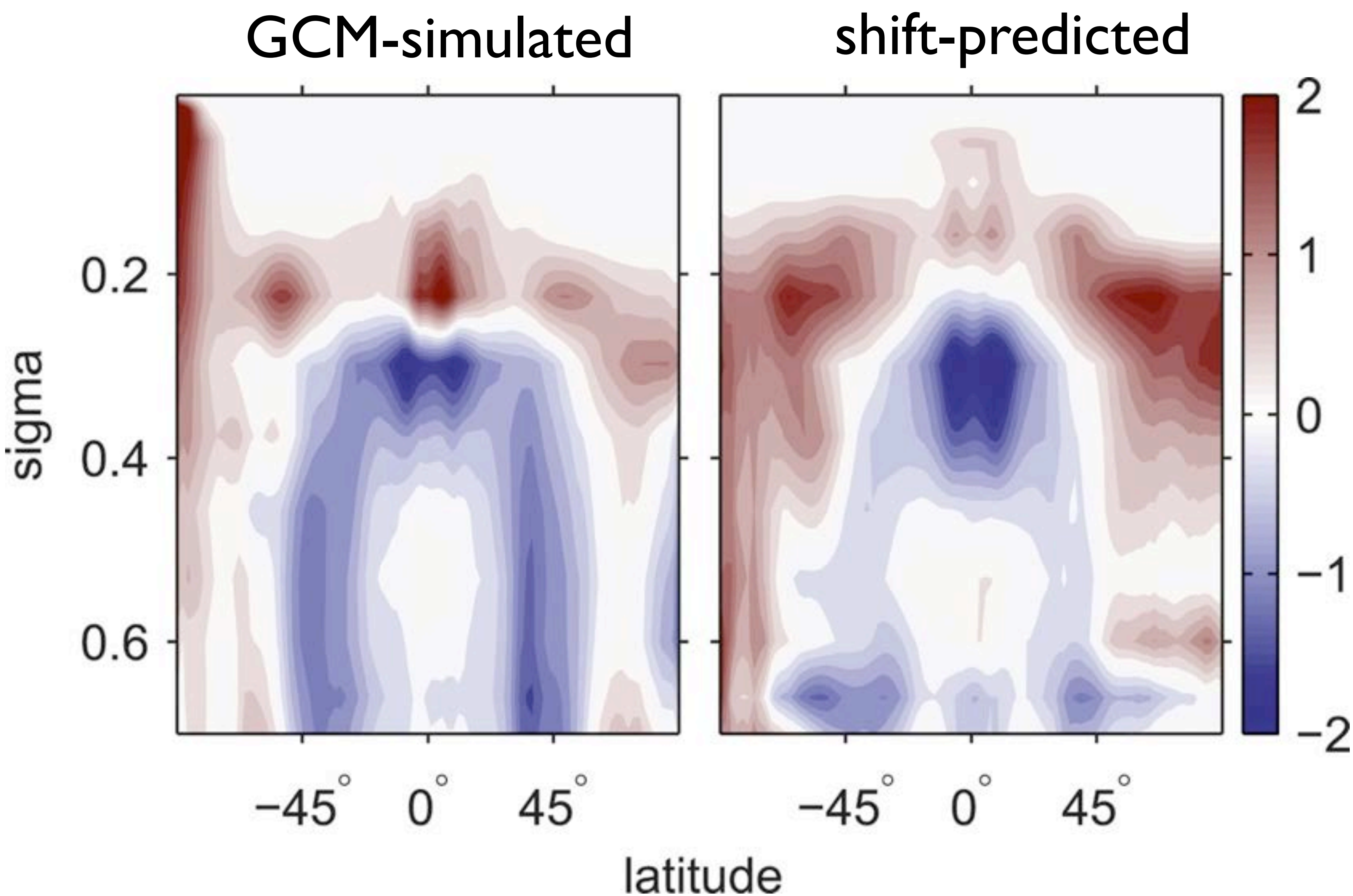
These mechanisms are tied to large-scale circulation changes that are robust and relatively well understood.

DRAFT Fig. FAQ 7.1

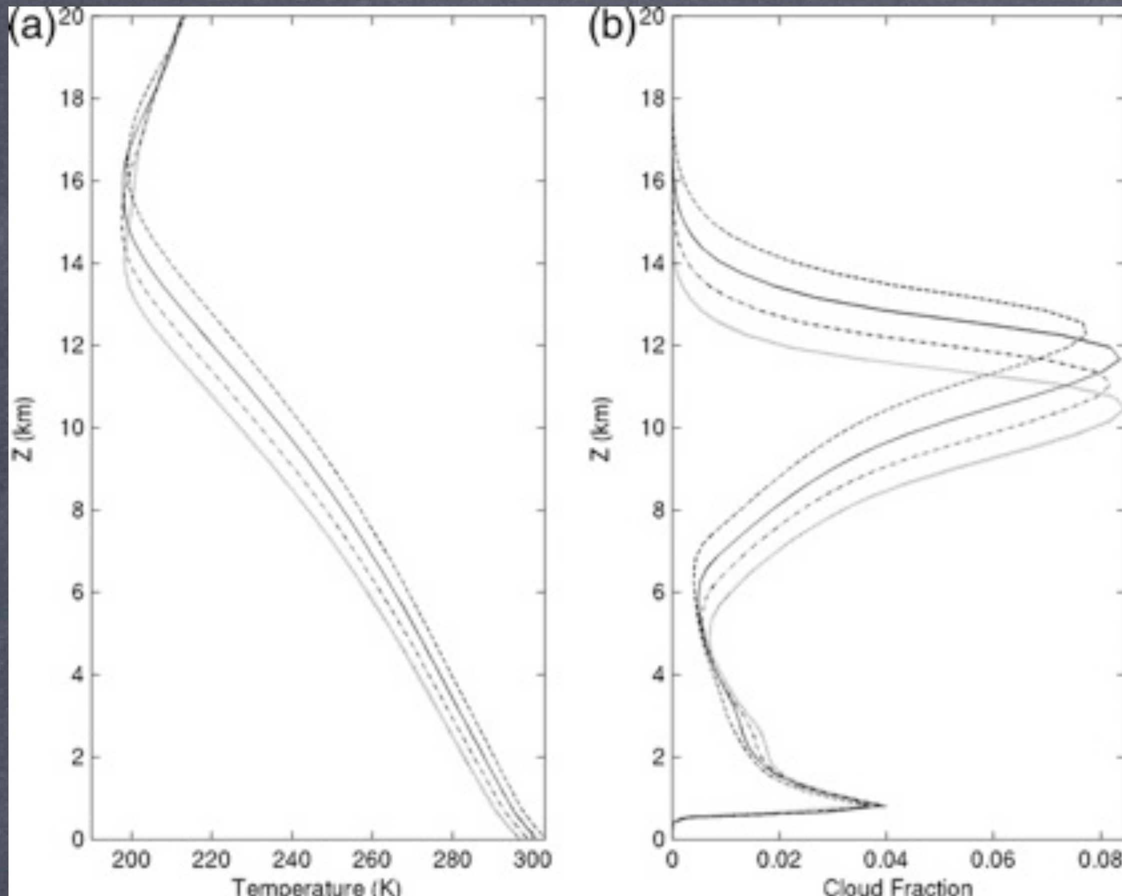
Robust features

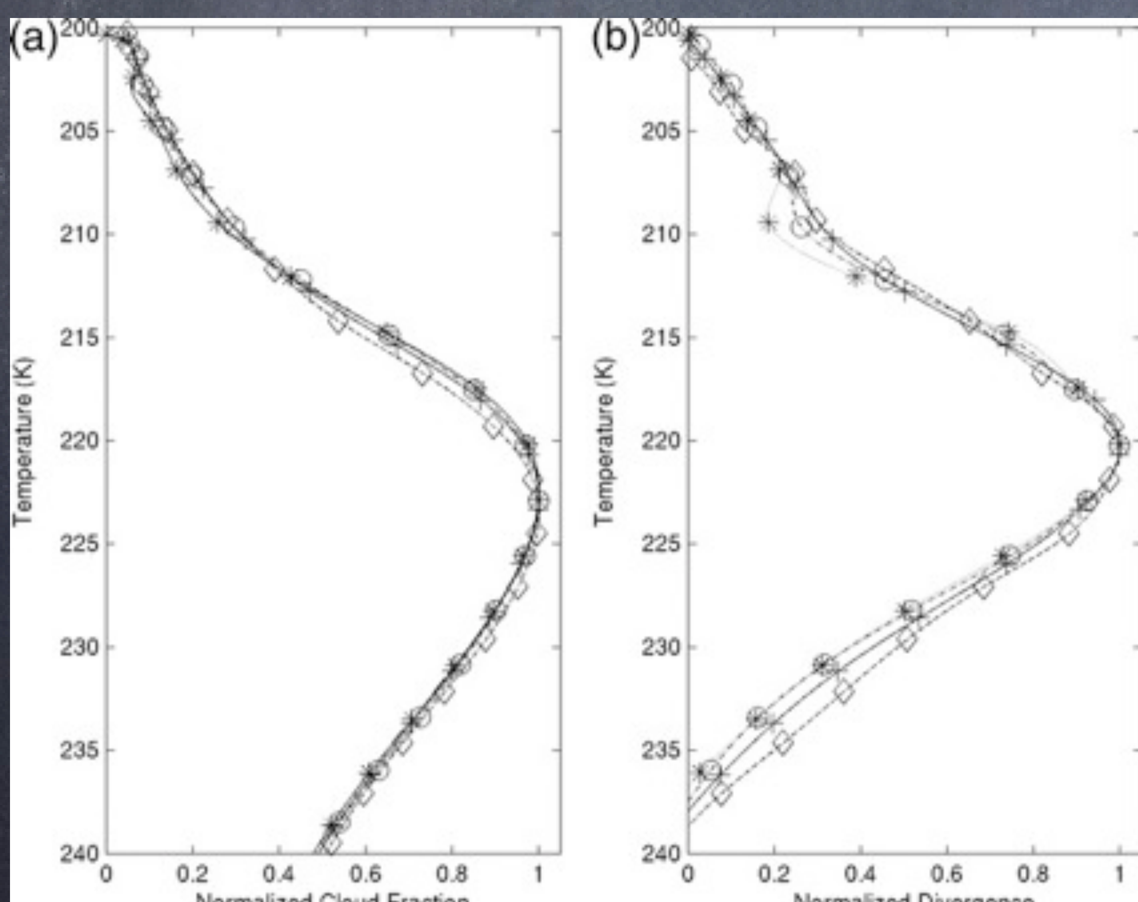
- Rise in elevation of deep clouds as explained by "Fixed Anvil Temperature" hypothesis (Hartmann and Larson 2002; Zelinka and Hartmann 2009). Positive feedback ~0.4 W $m^{-2}K^{-1}$.
- Poleward shift of clouds along with storm tracks and tropical edge appears to cause strong positive feedback but hard to quantify (Bender et al. 2012)
- Most models also lose low clouds, especially in the subtropics, and have less cloud cover globally on average (Zelinka et al. 2011) also a positive feedback.

Warming-induced cloud amount changes

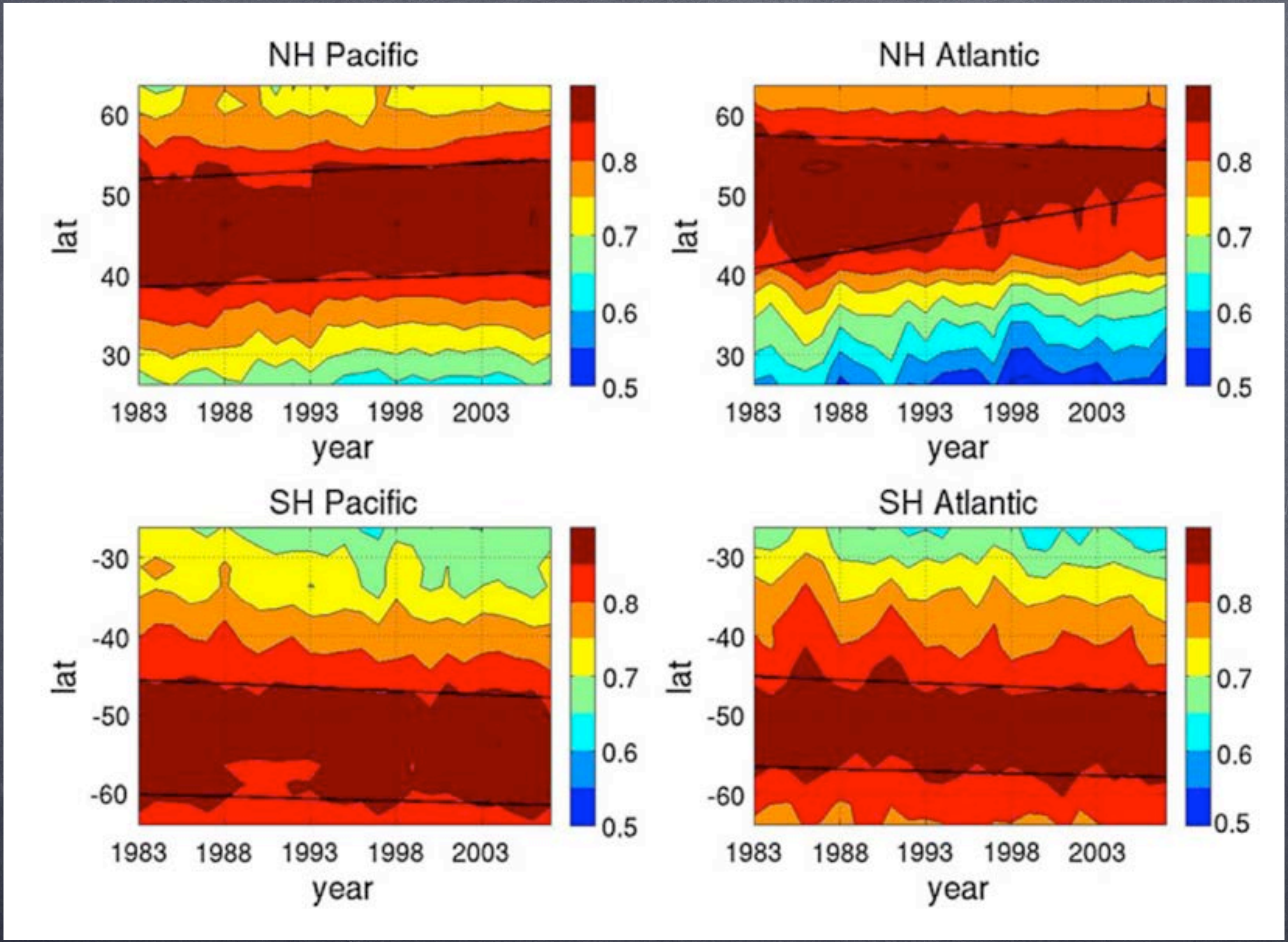


Similar upward shift occurs in all fields *(T, q, u, v)*
(Singh and O'Gorman 2012)

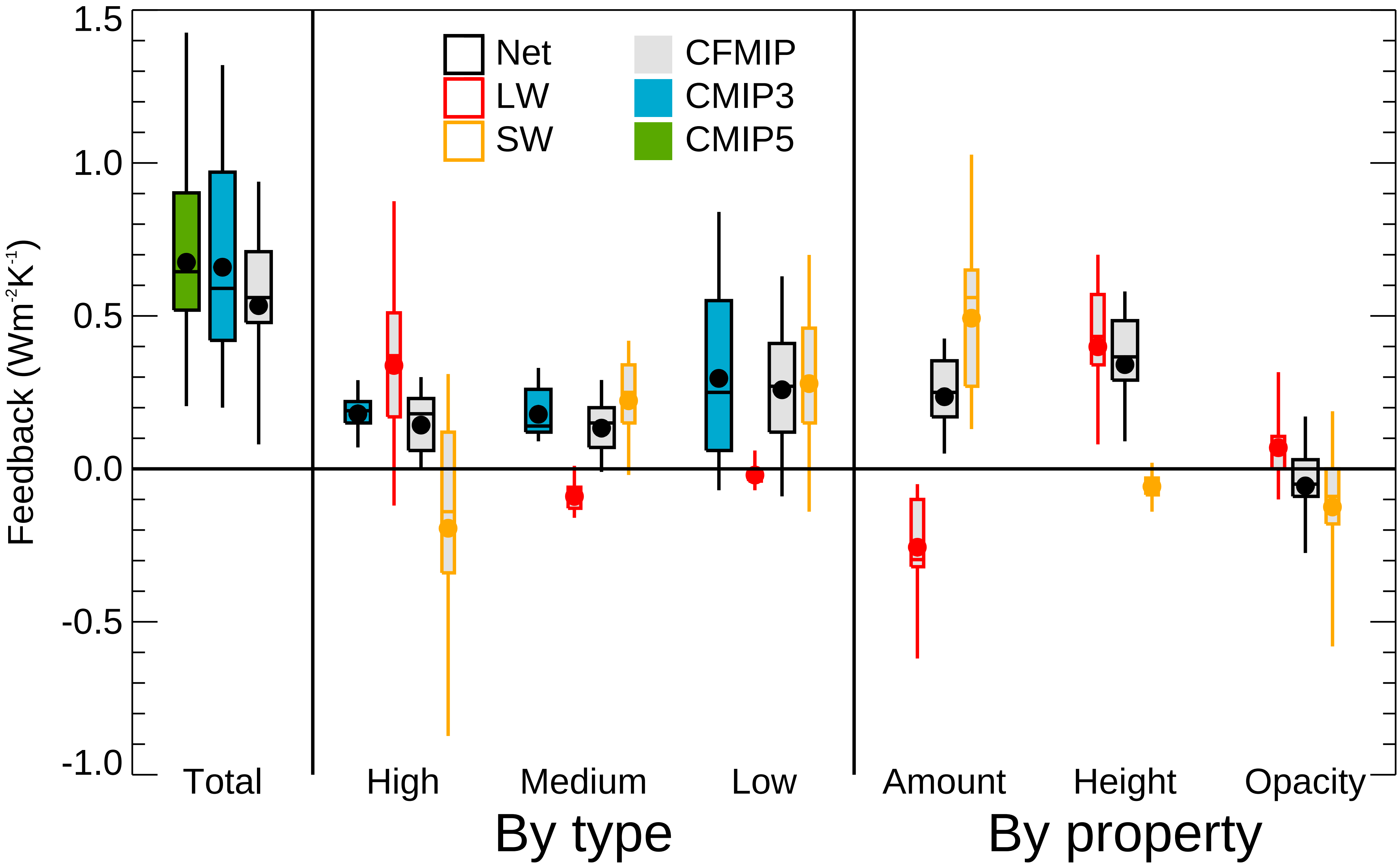




- FAT/PHAT mechanism: clouds always peak around 220K regardless of climate, due to radiation+circulation constraint
- Explicit cloud-resolving simulations of radiative-convective equilibrium (e.g., Kuang and Hartmann 2007) confirm FAT. Also consistent with observations (e.g., Eitzen et al. 2009, 2011)
- Means clouds exert a **stronger greenhouse effect** as climate warms. Physics analogous to those of the water vapour feedback.



Clouds moving poleward in both hemispheres (Bender et al. 2012)

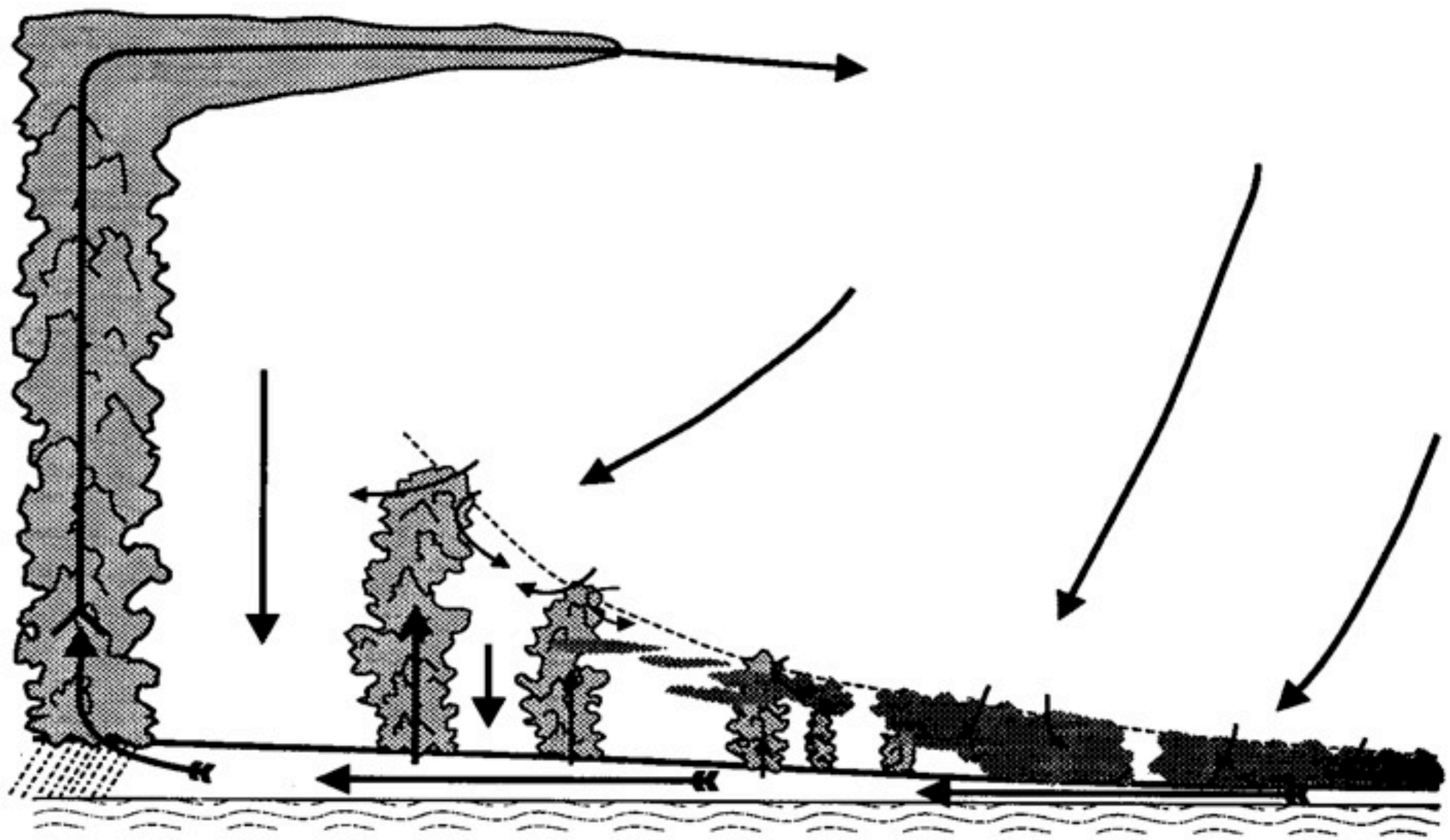


Data from Zelinka et al. (2012,2013); Soden and Vecchi (2011); Held and Soden (2008)

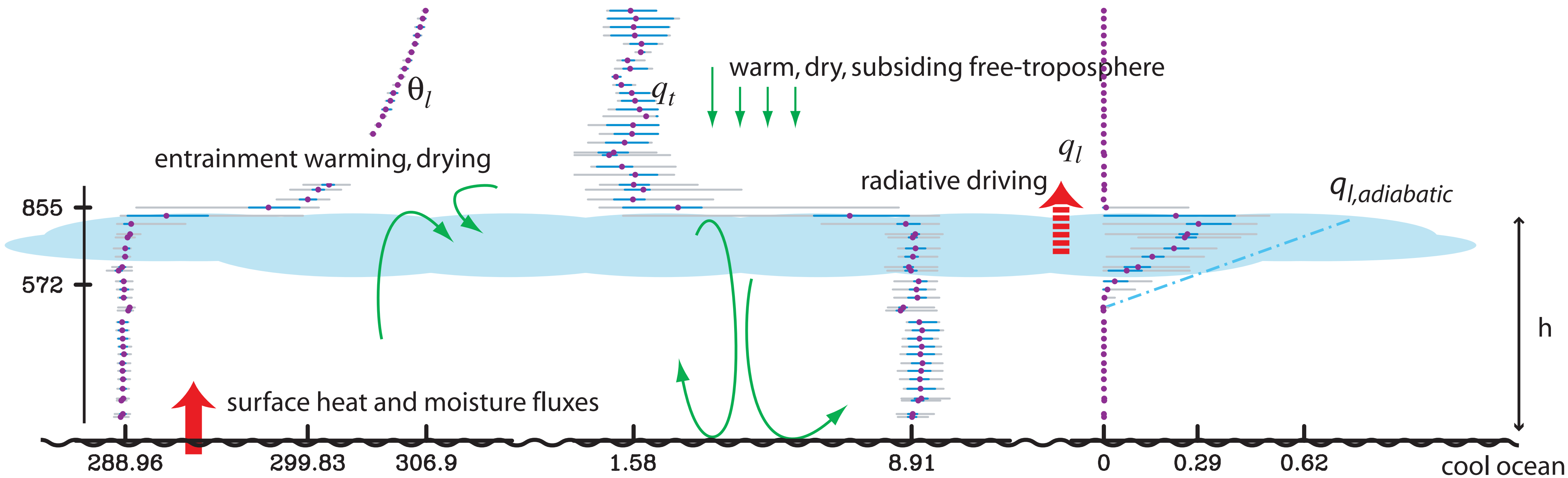
Note: CFMIP = Cloud Feedback Model Intercomparison Project

Summary 2013

- There are robust, positive cloud feedback mechanisms seen in GCMs and confirmed in observations and/or process models.
- There are non-robust changes in low clouds; that happen to add more positive feedback in most GCMs, but we don’t know why.
- Divergent low cloud responses are the main reason GCMs have different climate sensitivities (especially in CMIP3).



Shallow / nonprecipitating convection



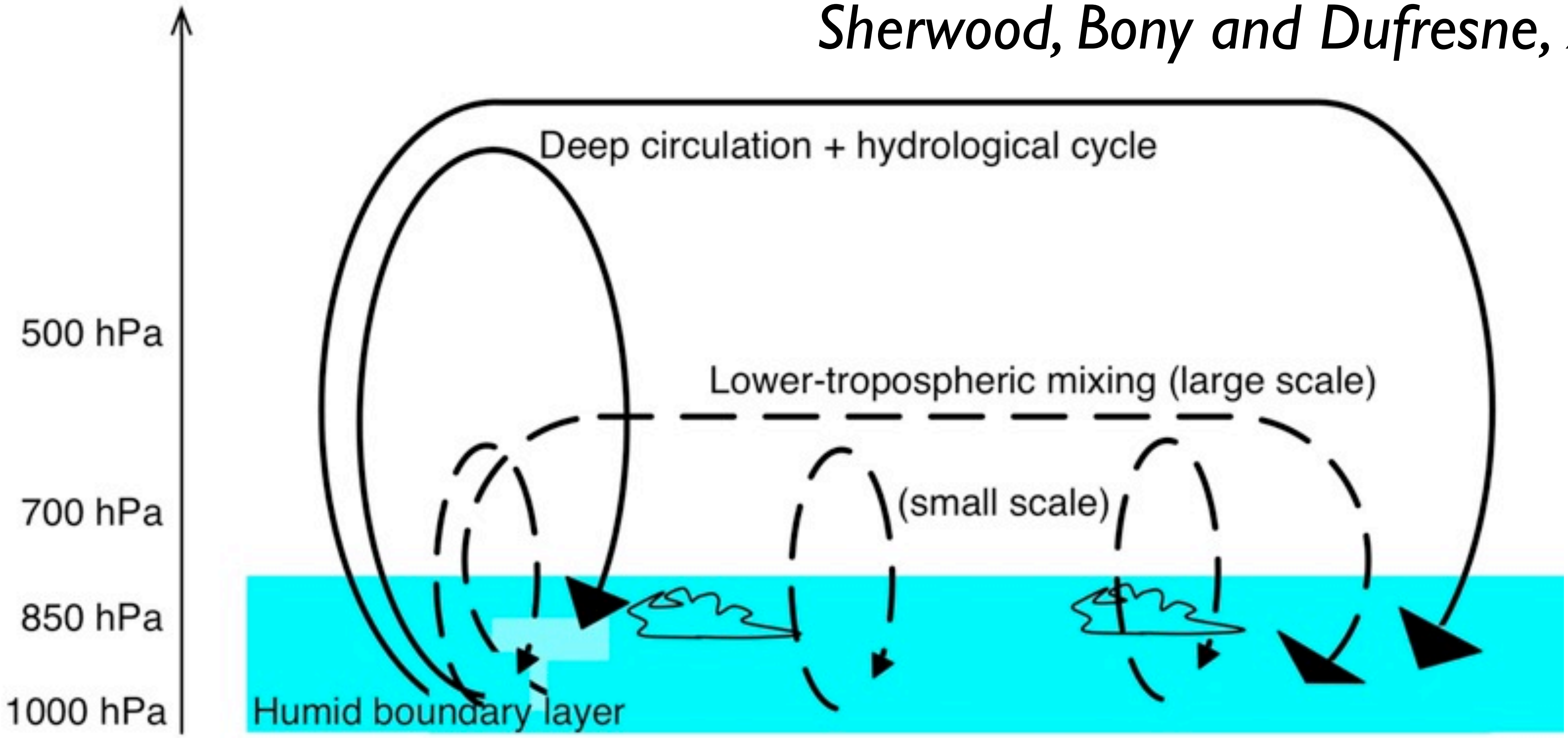
Stevens 2005

q_t = total water
q_l = liquid water
θ_l = θ w/liquid evaporated

- *Empirically*: inversion strength correlates with low-cloud amount, in regions of subsidence → focus on $\Delta\theta$. But this really does not explain GCM spread (and there is a lot of low cloud in ascent regions).
- *Physically*: low cloud amount very sensitive to q_l.

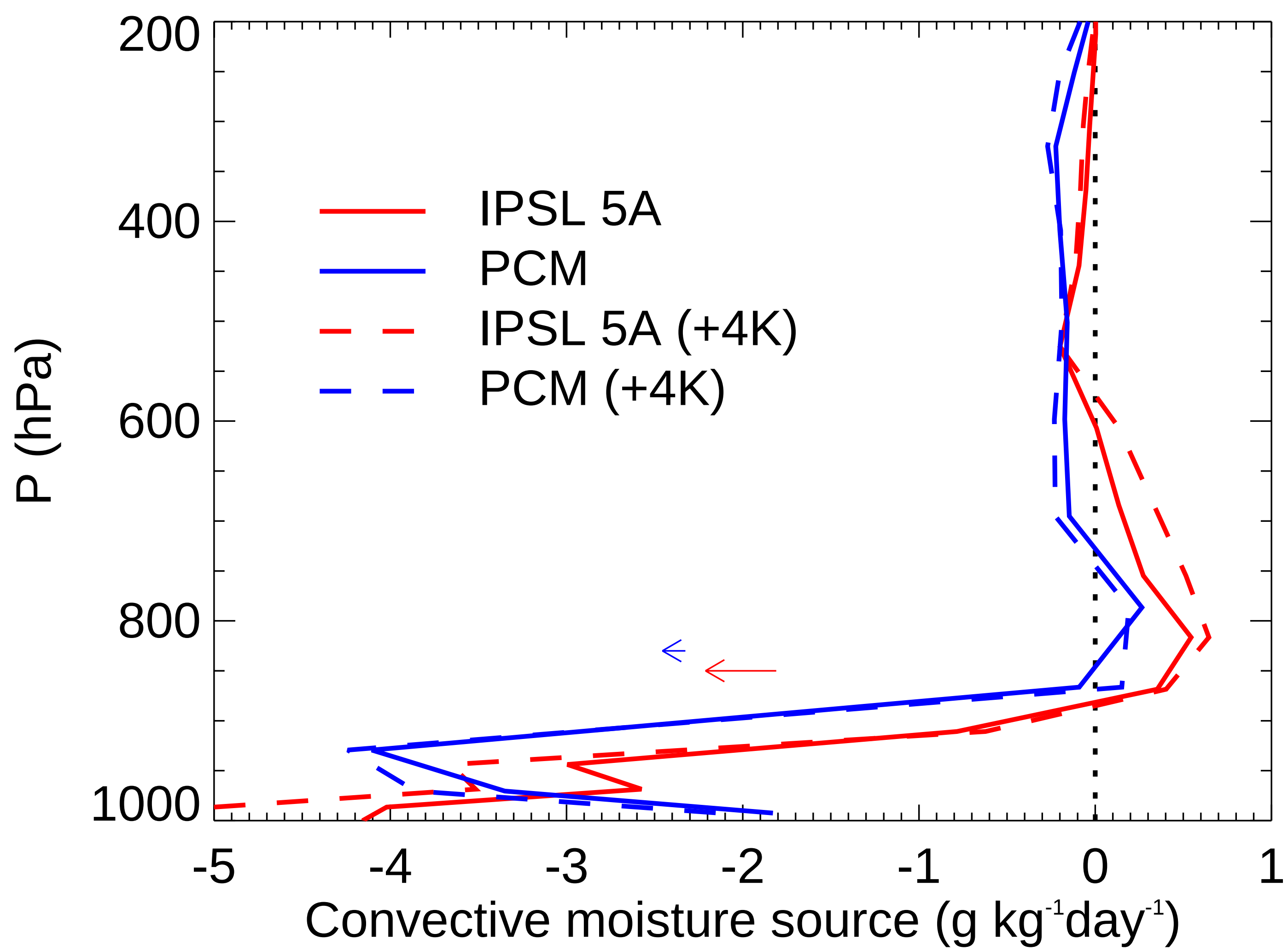
"Lower-Tropospheric mixing" vs. deep overturning

Sherwood, Bony and Dufresne, 2014.



- In warmer climate, water vapour increases 6%/K or more.
- Deep circulation coupled tightly to radiation, slows down to compensate for the increased H_2O density.
- LT-mixing is not coupled; variations can affect mean relative humidity (Sherwood and Meyer 2006). What happens to it?

1. Small-scale component

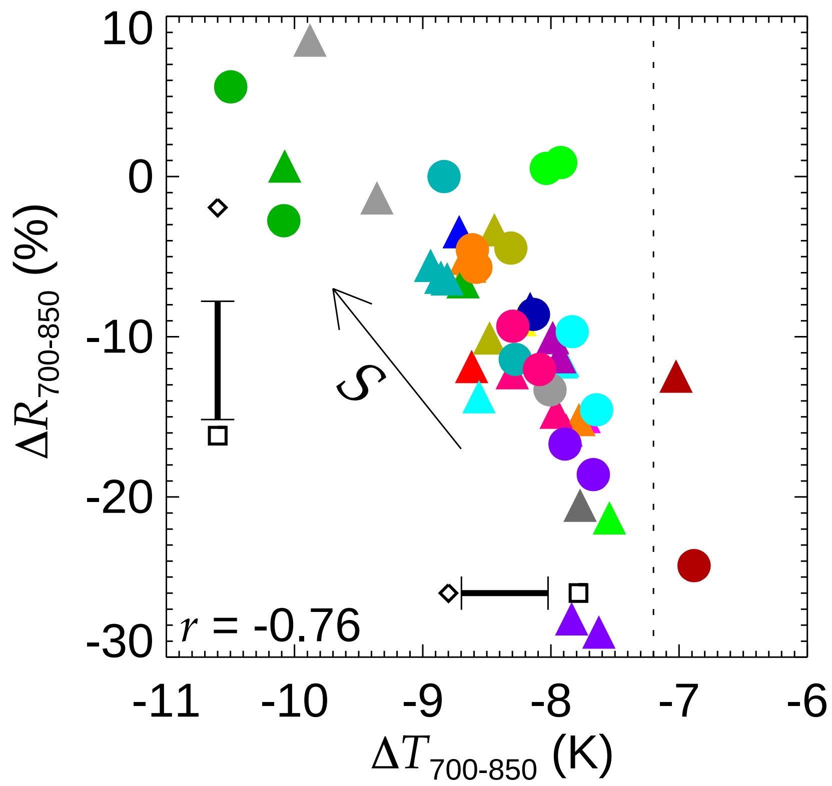


IPSL ECS = 4.3 °C

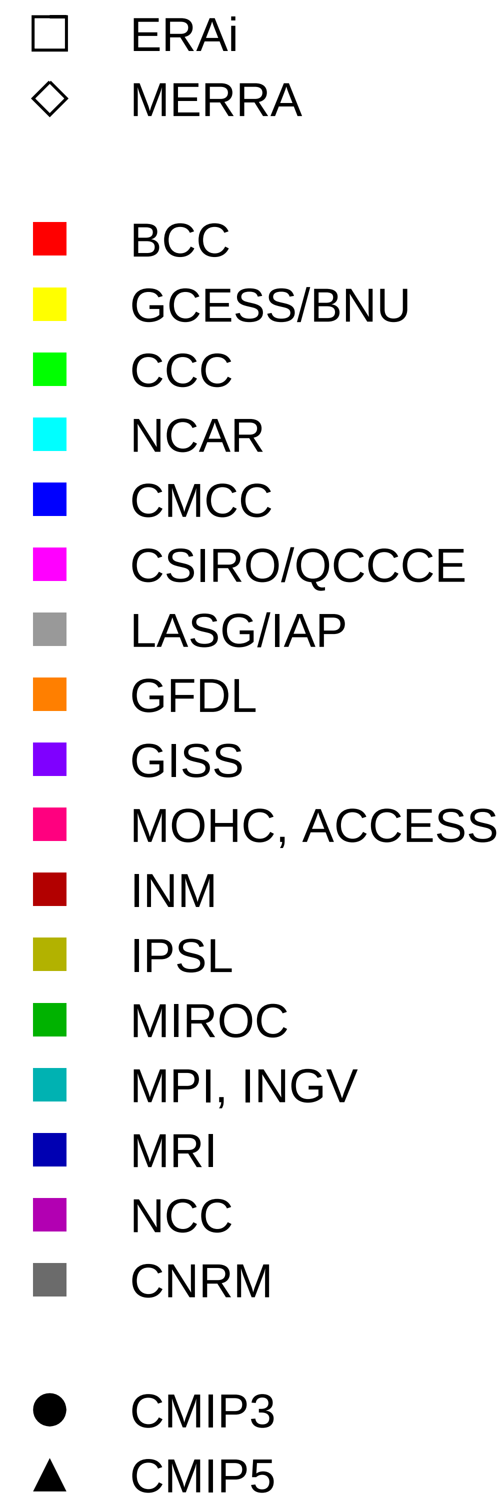
PCM ECS = 2.1 °C

Parameterized convective transport out of PBL increases by ~6%/K in IPSL, <2%/K in PCM.

Small-scale lower-trop mixing index



$$S \equiv \frac{\Delta R}{100\%} - \frac{\Delta T}{9\mathrm{K}}$$



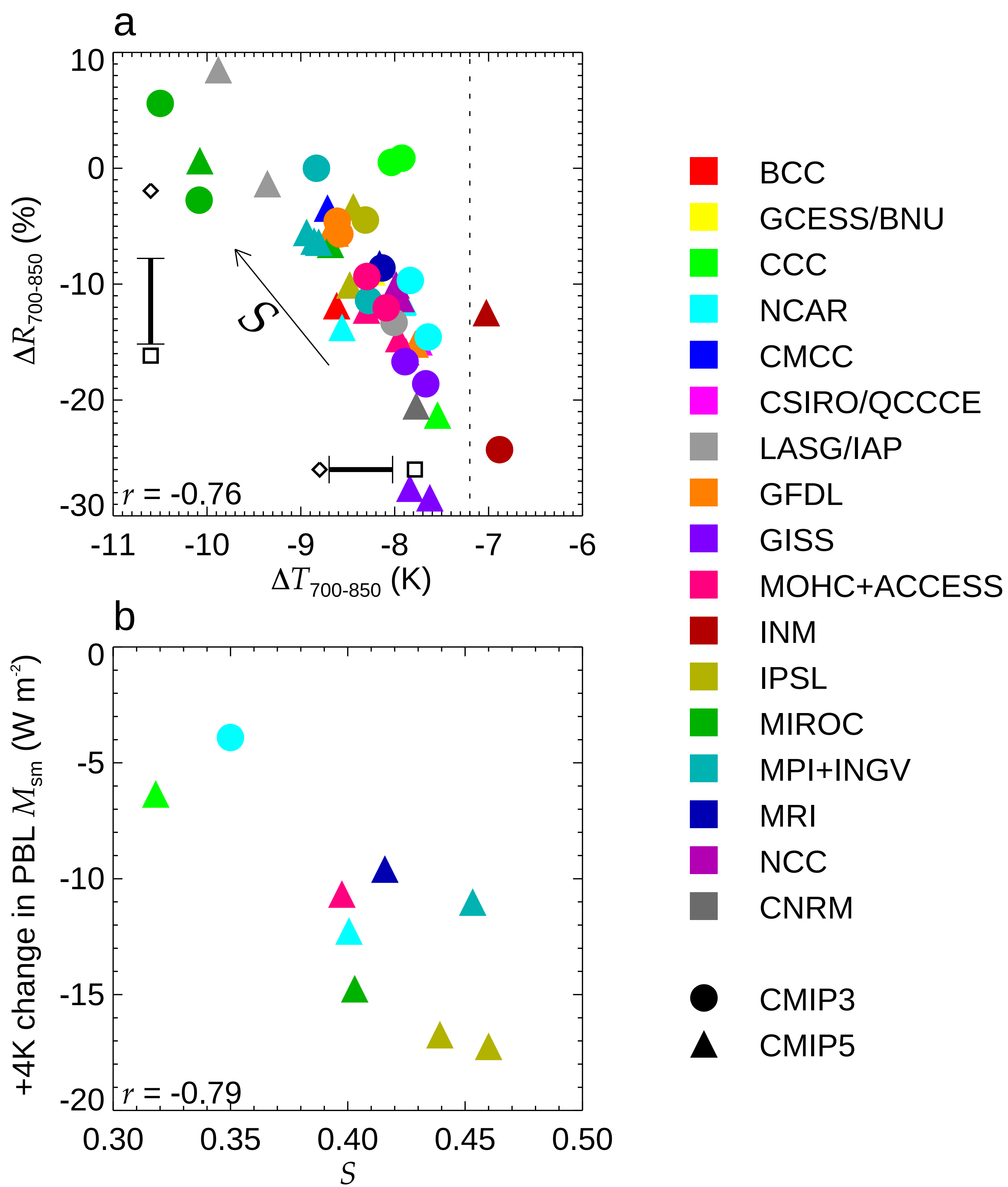
ΔR: Relative humidity at 700 minus that at 850
ΔT: Same, for temperature

Averaged over lowest quartile of ω at 500 hPa (roughly, the Indo-Pacific warm pool ascent region)

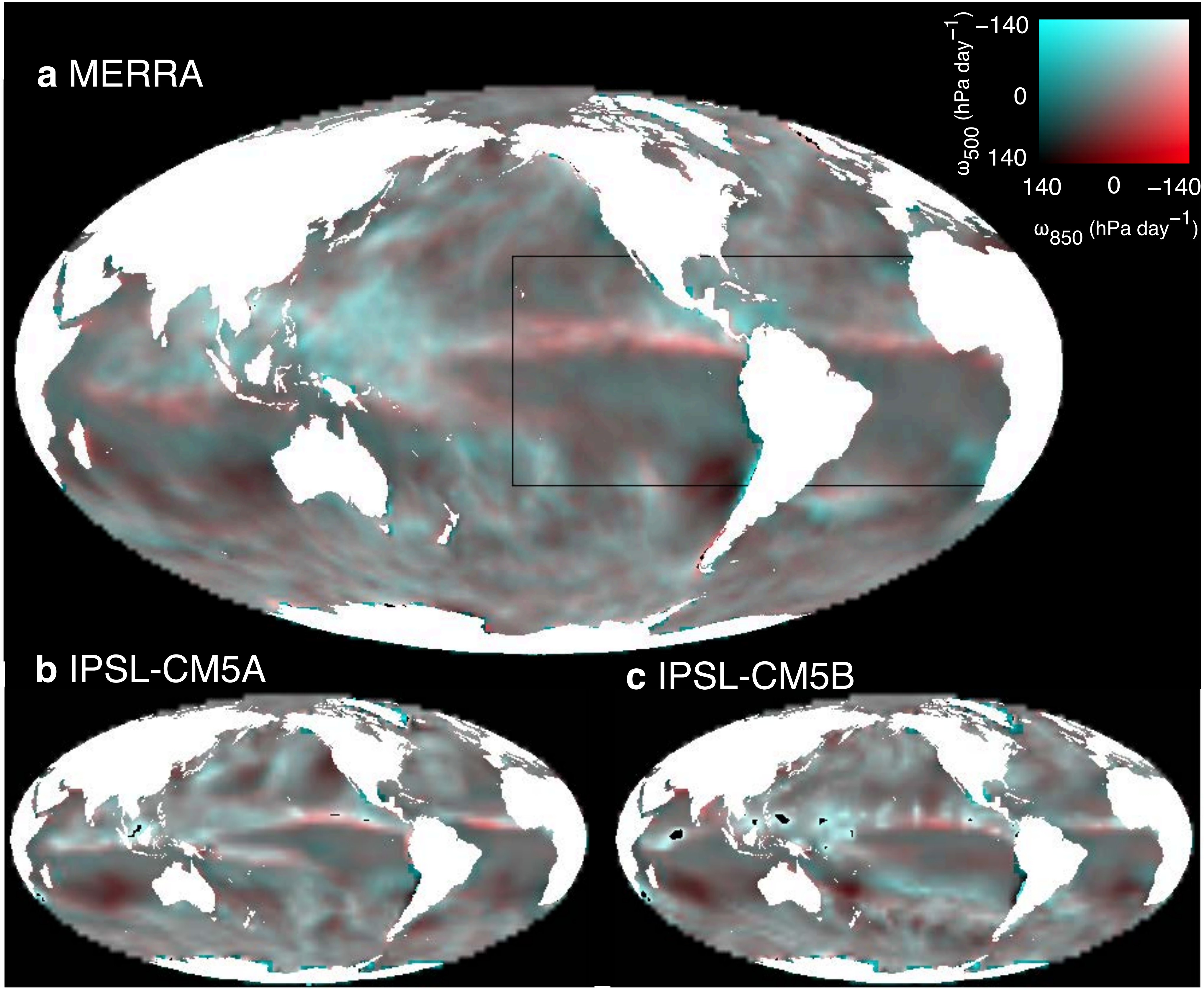
Strong small-scale LT-mixing brings each air property at 700 hPa closer to that in the PBL (high correlation between ΔR and ΔT!)

...characterise LT-mixing with index S.

With warming, convective drying of PBL increases more in models with higher S



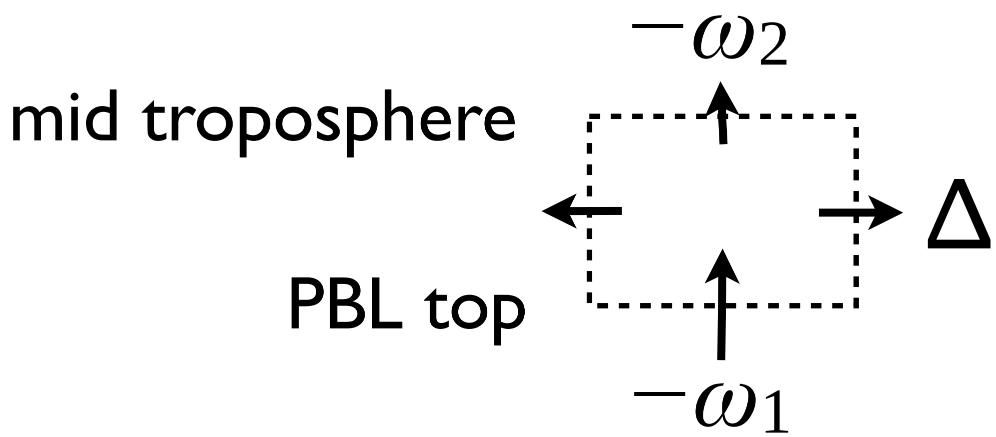
2. Large-scale component



IPSL-5A ECS = 4.3 °C

IPSL-5B ECS = 2.6 °C

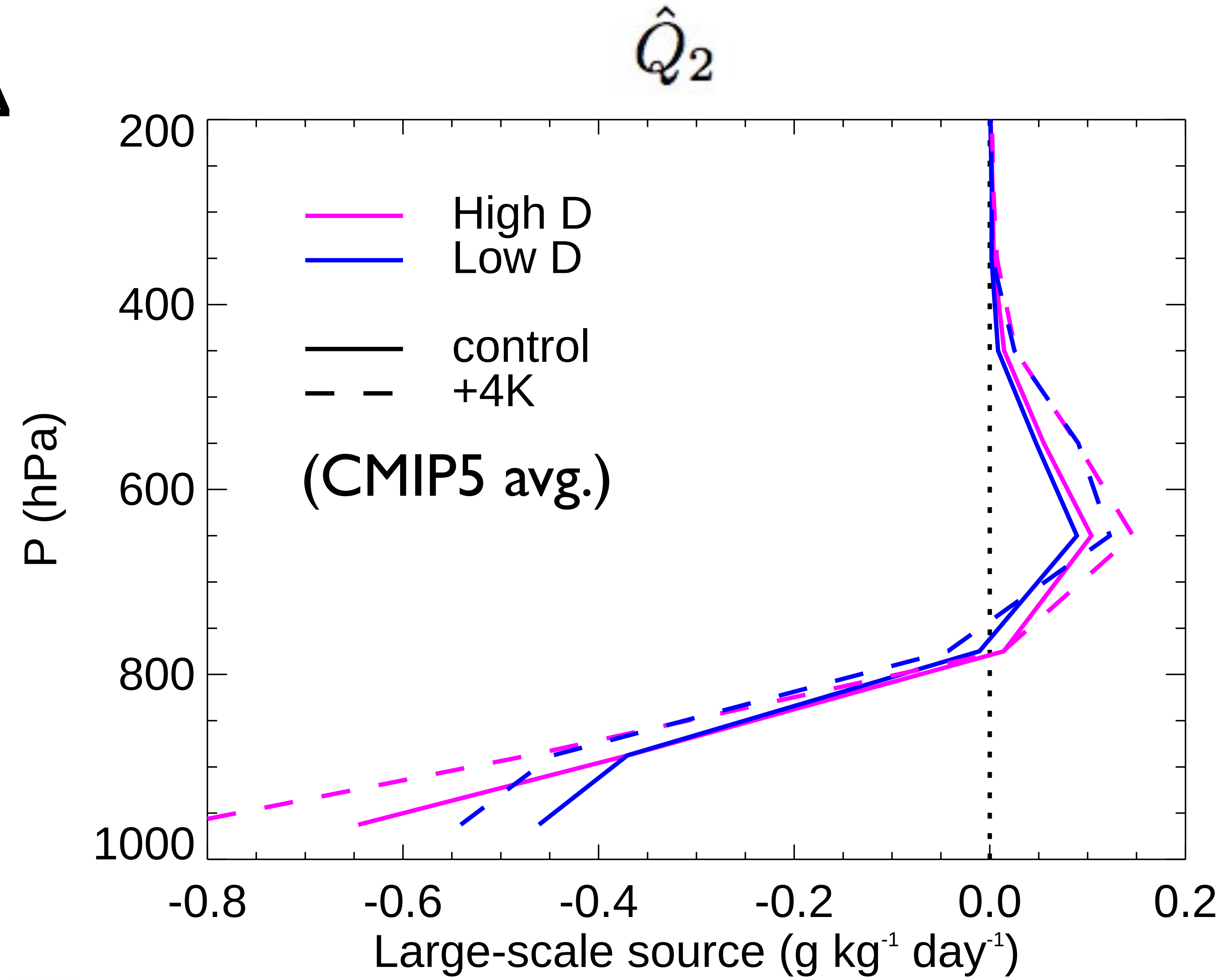
Large-scale LT-mixing moisture transport and index



ω_1 = avg. at 850, 700 hPa

ω_2 = avg. at 600, 500, 400 hPa

$$\Delta = \omega_2 - \omega_1$$



$$D \equiv \frac{\langle \Delta\, H(\Delta)\, H(-\omega_1) \rangle}{\langle -\omega_2\, H(-\omega_2) \rangle}$$

Ratio of LT-mixing to deep overturning.

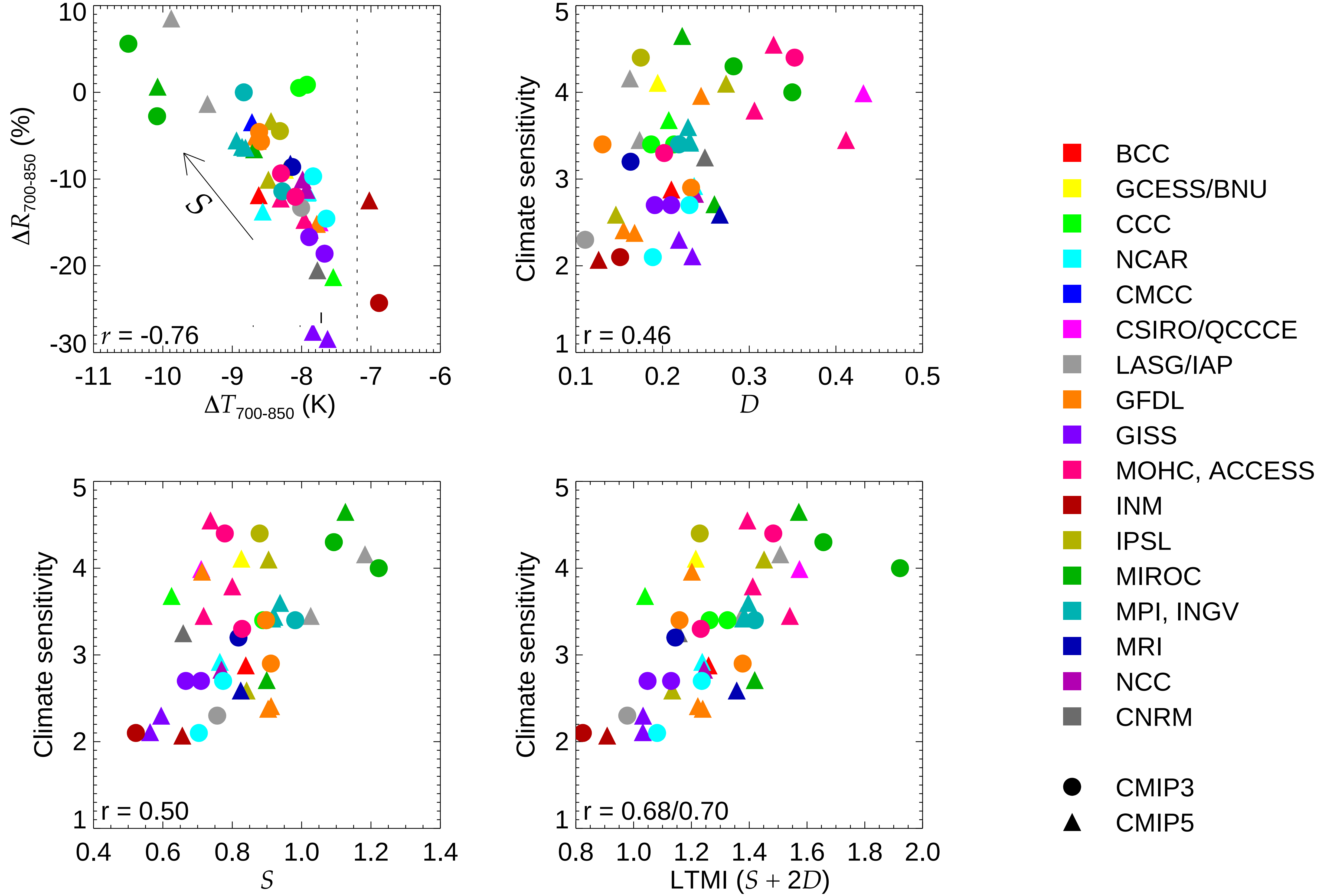
Our index for large-scale LT-mixing

$$\hat{Q}_2 = -\langle q \frac{d\omega}{dp} H(\Delta)\, H(-\omega_1) \rangle$$

Moisture source due to LT-mixing.

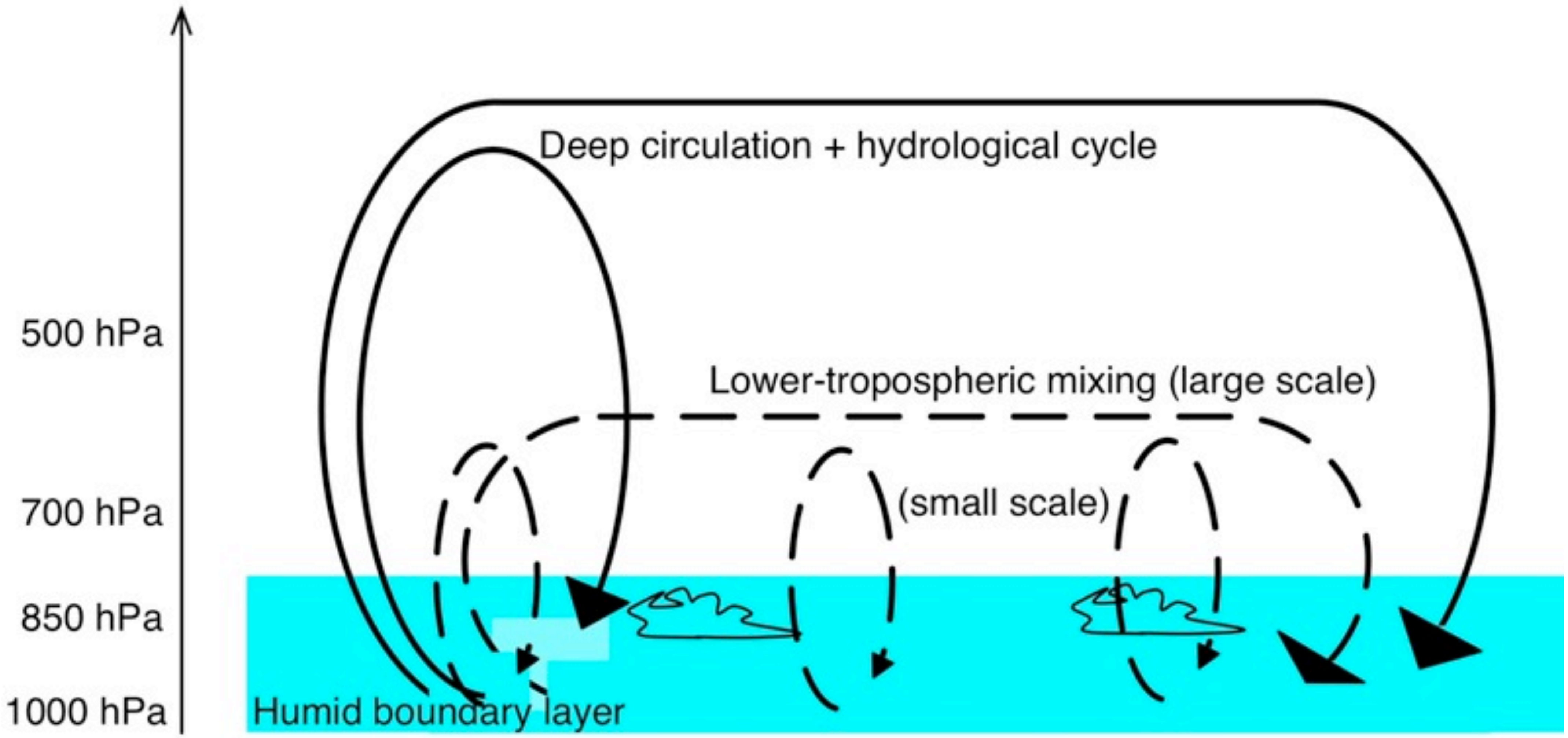
Increases at ~6%/K.

Results

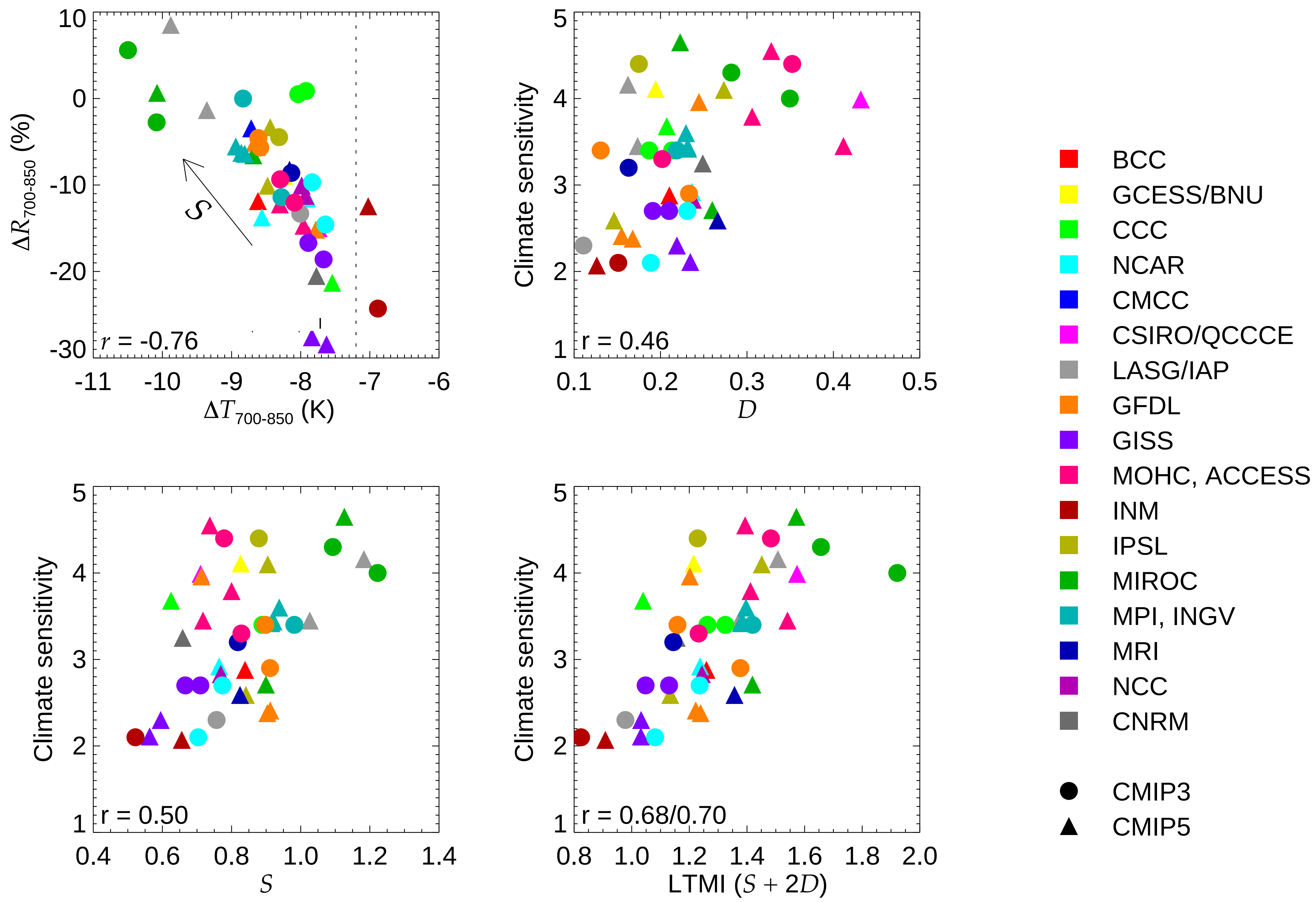


$\Delta R_{700\text{-}850}$ (%)
$\Delta T_{700\text{-}850}$ (K)
S
r = -0.76
Climate sensitivity
D
r = 0.46
S
r = 0.50
LTMI ($S + 2D$)
r = 0.68/0.70
BCC
GCESS/BNU
CCC
NCAR
CMCC
CSIRO/QCCCE
LASG/IAP
GFDL
GISS
MOHC, ACCESS
INM
IPSL
MIROC
MPI, INGV
MRI
NCC
CNRM
CMIP3
CMIP5

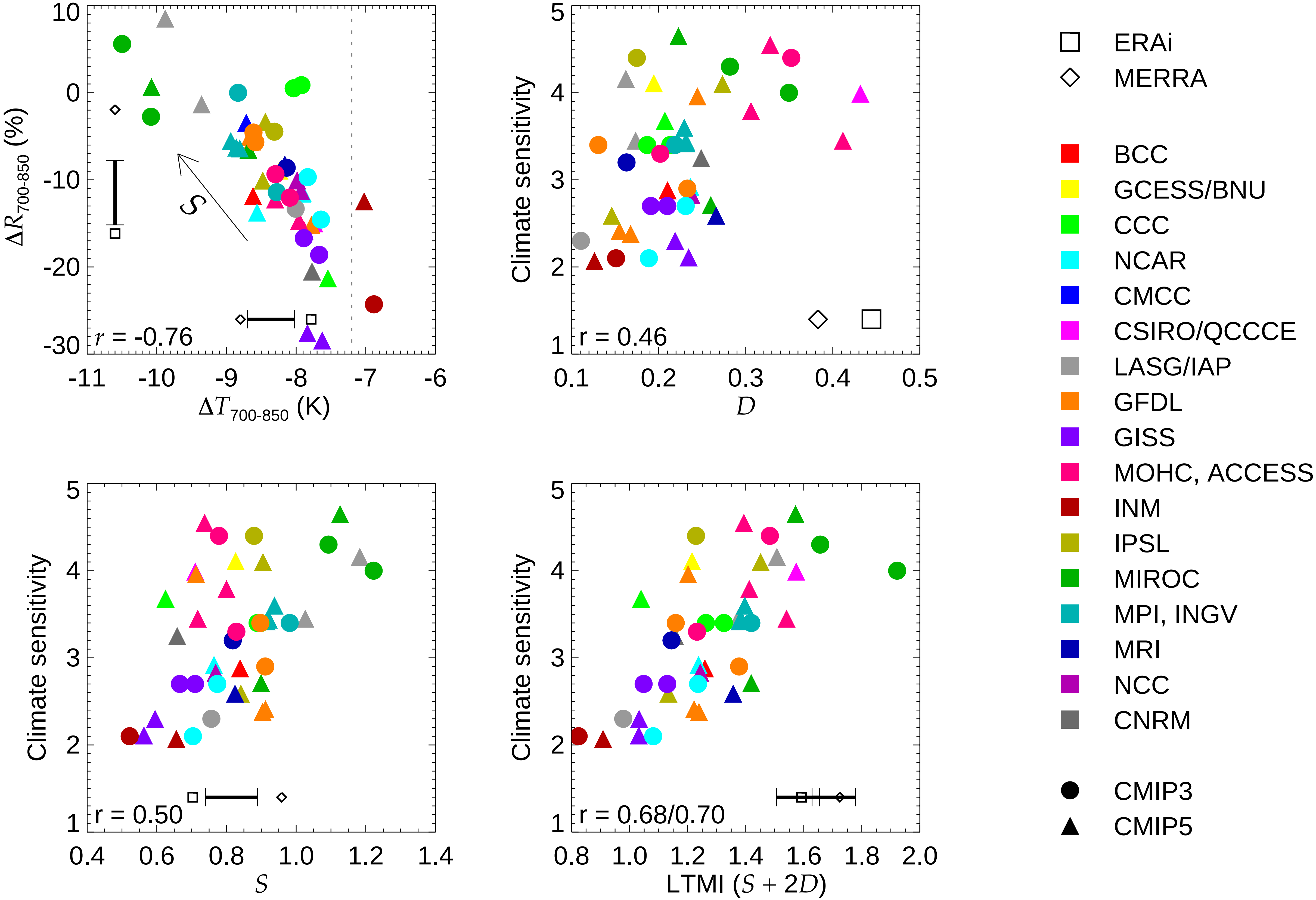
MILC (Mixing-Induced Low Cloud) feedback



- In warmer climate, water vapour transport by LT-mixing increases 6%/K or more, but surface evaporation increases by only 2%/K.
- Amount of LT-mixing varies by factor of ~4 among GCMs.
- Increased dehydration of PBL as climate warms, depending on amount of LT-mixing in the base state, causes loss of low cloud in most GCMs.



Sunday, 12 January 14



$\Delta R_{700\text{-}850}$ (%)
$\Delta T_{700\text{-}850}$ (K)
S
r = -0.76
Climate sensitivity
D
r = 0.46
S
r = 0.50
LTMI (S + 2D)
r = 0.68/0.70
ERAi
MERRA
BCC
GCESS/BNU
CCC
NCAR
CMCC
CSIRO/QCCCE
LASG/IAP
GFDL
GISS
MOHC, ACCESS
INM
IPSL
MIROC
MPI, INGV
MRI
NCC
CNRM
CMIP3
CMIP5

Conclusions

- Known cloud feedback mechanisms in GCMs arise from dynamical and thermodynamic controls on clouds
- New MILC mechanism
  - can explain half the variance in ECS among GCMs (and implies ECS > 3°C)
  - implies "remote control" of low-cloud properties by behaviour in deep convective regions
  - This requires new multiscale approaches

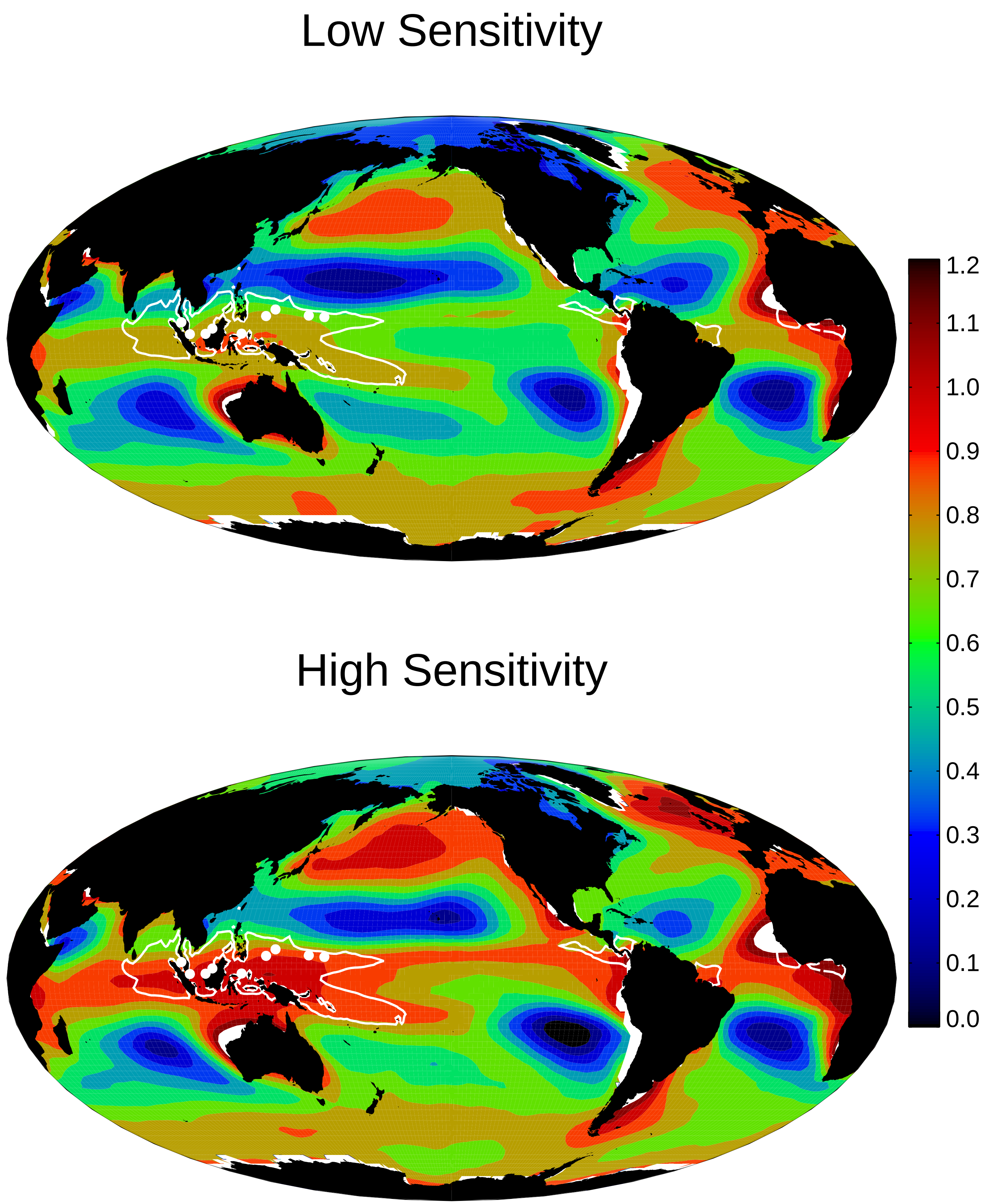
Remaining questions

- What controls strengh of lower-trop mixing?
- How does the warmer system reestablish water balance?
- What explains the rest of the ECS variance?
- Do clouds respond as faithfully to the dynamical/ thermodynamic controls in reality as in GCMs?
- If ECS>3°C, why isn't the world warming faster?
  - Other "dark feedbacks" that are negative?
  - Aerosols cooling more than we think?

Role for SPARC

- Dynamical and strat/TTL roles in cloud control
- Cirrus feedbacks remain a "wild card" that needs more attention - TTL again
- Traditional dynamical approaches need to incorporate condensational heating to be truly useful - a "grand challenge"

$$S \equiv \frac{\Delta R}{100\%} - \frac{\Delta T}{9\mathrm{K}}$$



Enhanced small-scale mixing is quasi-global