Clouds in a Changing Climate

Sandrine Bony[1] & Bjorn Stevens[2]

1 : LMD/IPSL, Paris, France
2 : MPI, Hamburg, Germany

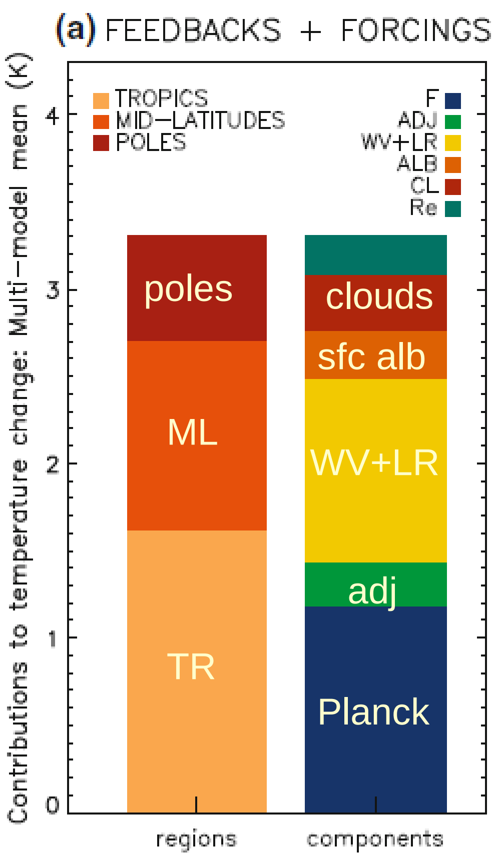
Lecture #2 : Cloud feedback processes

ÉCOLE DE PHYSIQUE
des HOUCHES

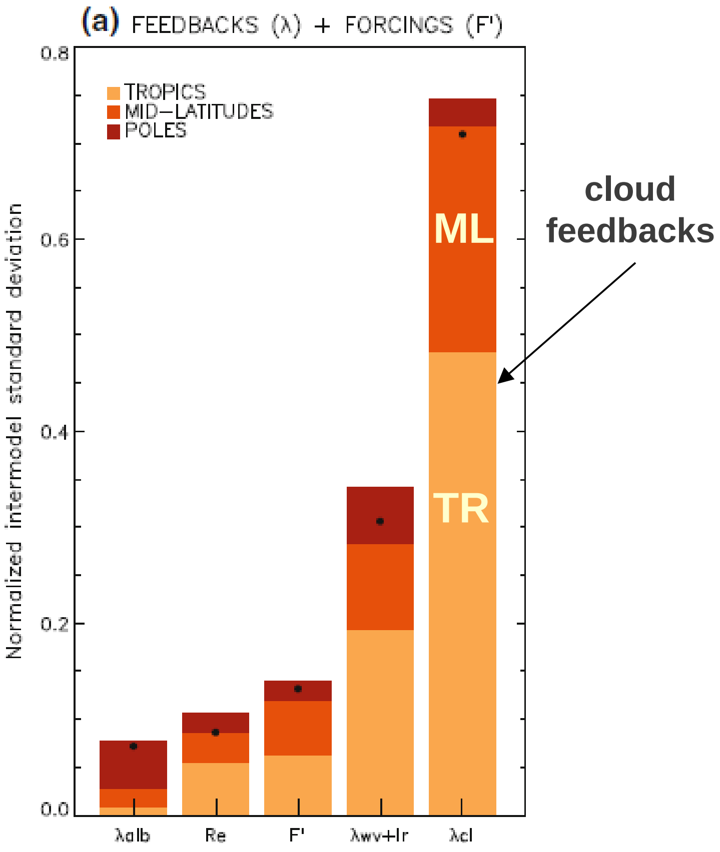
EUCLIPSE « Clouds in Climate » Summerschool
Les Houches, France, Jun 25 – Jul 5 2013

Cloud feedbacks constitute the primary source of uncertainty for climate sensitivity estimates

Multi-Model Mean



Inter-model spread



Vial et al., Clim. Dyn., 2013

Cloud feedbacks & climate change

- Have we made any progress in 30 years ?
- Depends on our metrics for progress...
- At the time of the Charney Report : only a vague idea as to why cloudiness should change with either increasing CO_2 or surface temperatures.
- This lecture :

  - Some progress in our ability to articulate and understand cloud feedbacks in terms of a variety of physical processes and mechanisms

  - Highlight some open issues

But first :

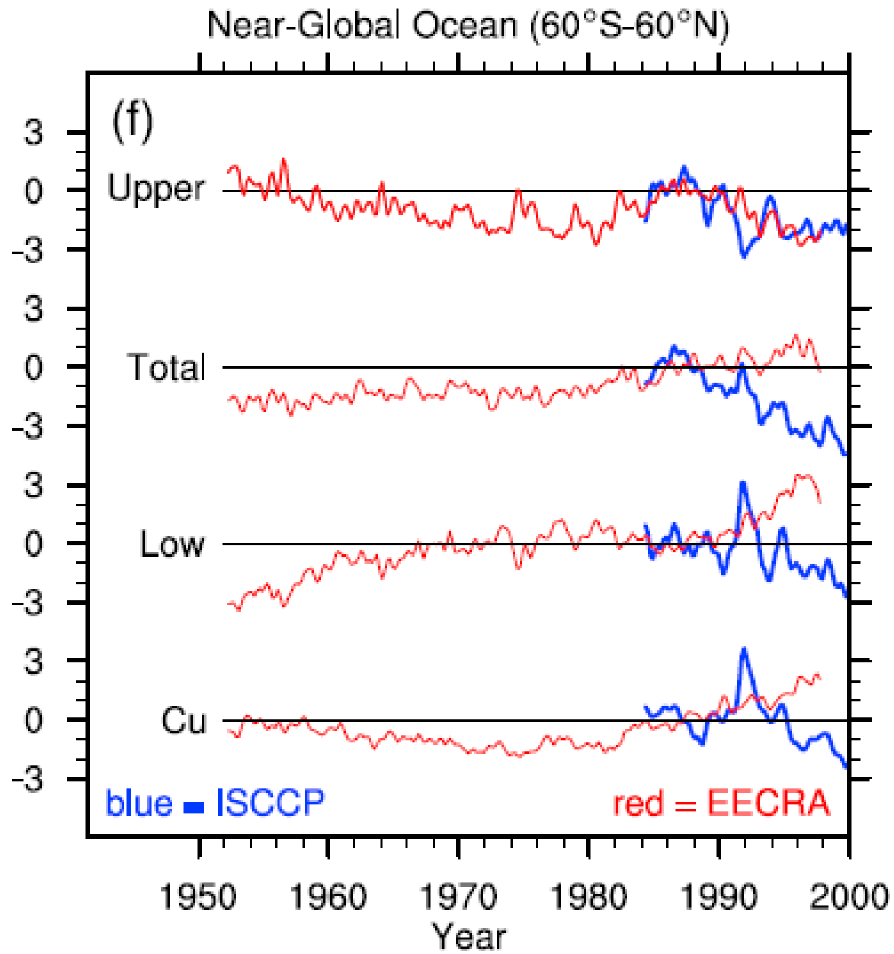
Could we assess cloud feedbacks directly from observations ?

Could we assess cloud feedbacks from observations ?

Multi decadal-scale variations

EECRA = in-situ obs

ISCCP = satellite obs



Upper-level cloudiness

Total cloudiness

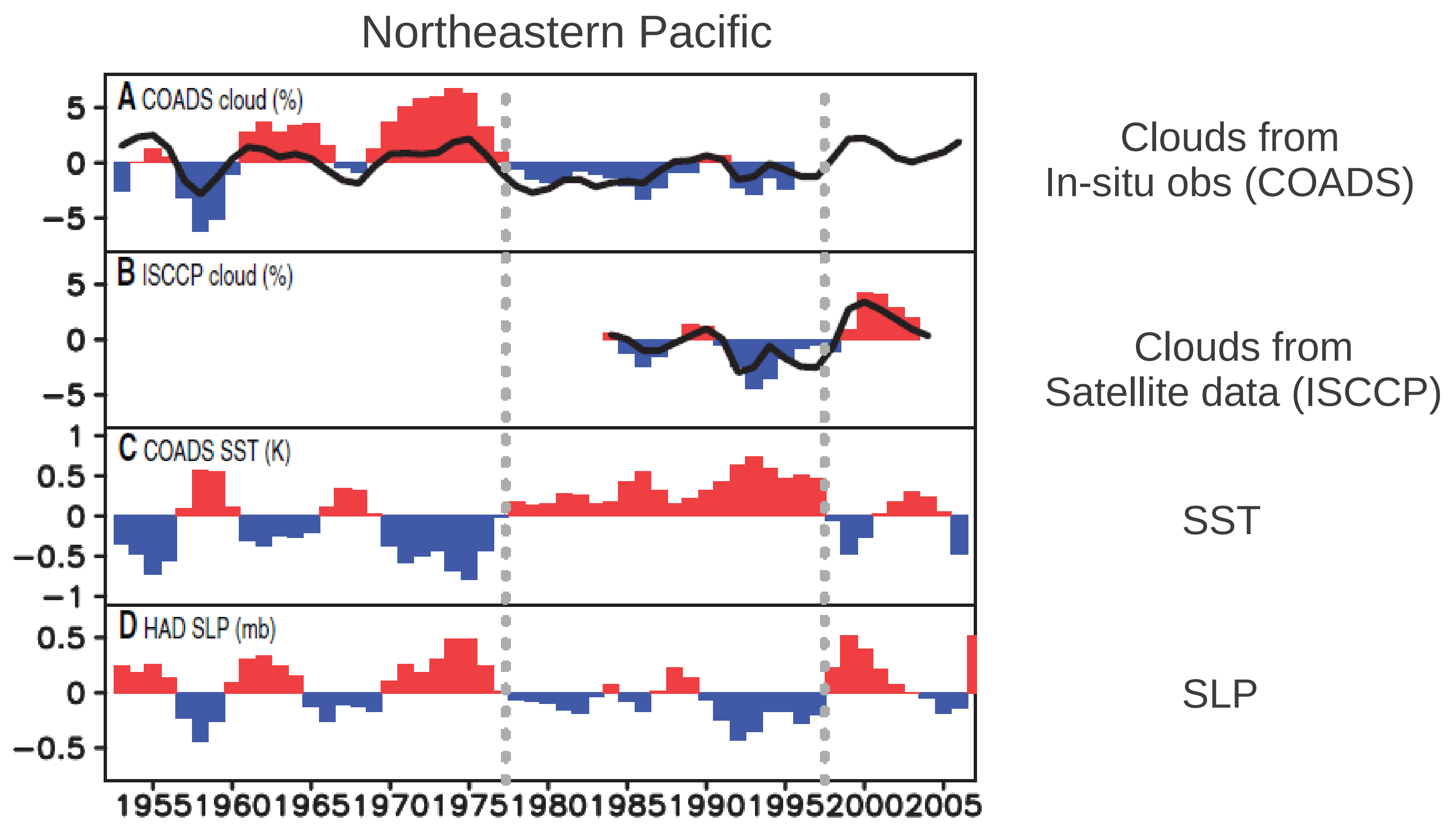
Low-level cloudiness

- Discrepancies between in-situ and satellite observational records
- Natural variability vs anthropogenically-forced changes ??

Norris, JGR, 2005

Could we assess cloud feedbacks from observations ?

Multi decadal-scale variations



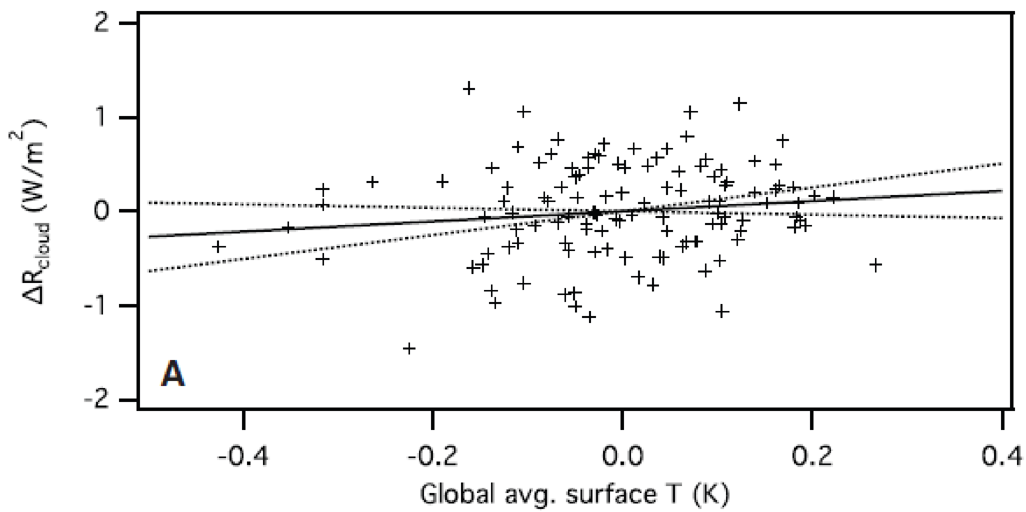
- Decadal variations in cloudiness and SST
- Suggest a positive low-cloud feedback over the Northeastern Pacific
- How much is decadal variability an analogue of long-term climate change ?

Clement et al., Science, 2009

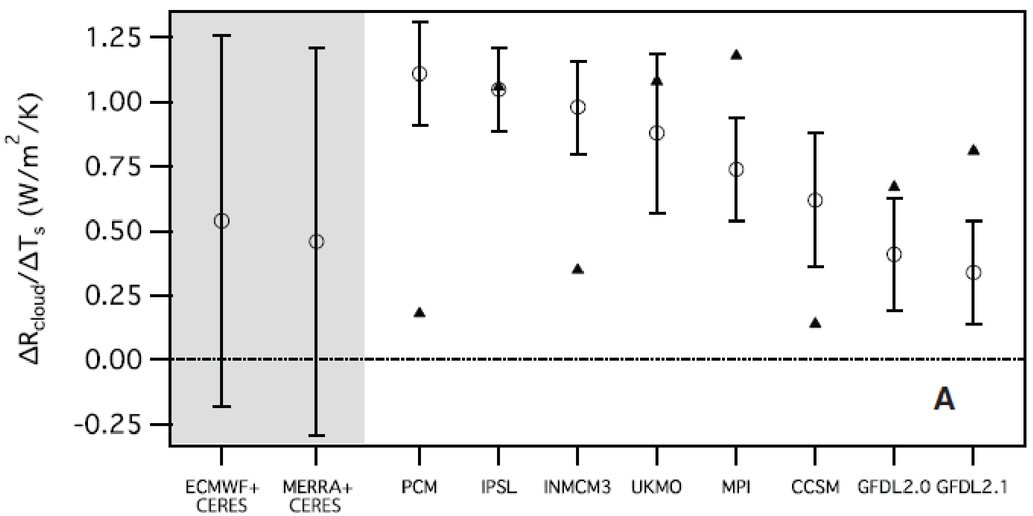
Could we assess cloud feedbacks from observations ?

ENSO variations (2000-2010)

CERES rad fluxes and SST data



Short-term cloud feedback



- Likely a positive cloud feedback...but a lot of uncertainty

- No correlation in the models between short-term and long-term cloud feedbacks

Dessler, Science, 2010

Could we assess cloud feedbacks from observations ?

Direct determination of cloud feedbacks from observations difficult...

- Uncertainties in long-term observational records
- Are observed climate variations an analogue of long-term climate changes ?

What are the alternatives ?

What are the alternatives ?

Observations can be used to :

- learn about clouds-controlling factors
- test hypotheses
- test processes at work in model cloud feedbacks

What are the alternatives ?

Observations can be used to :

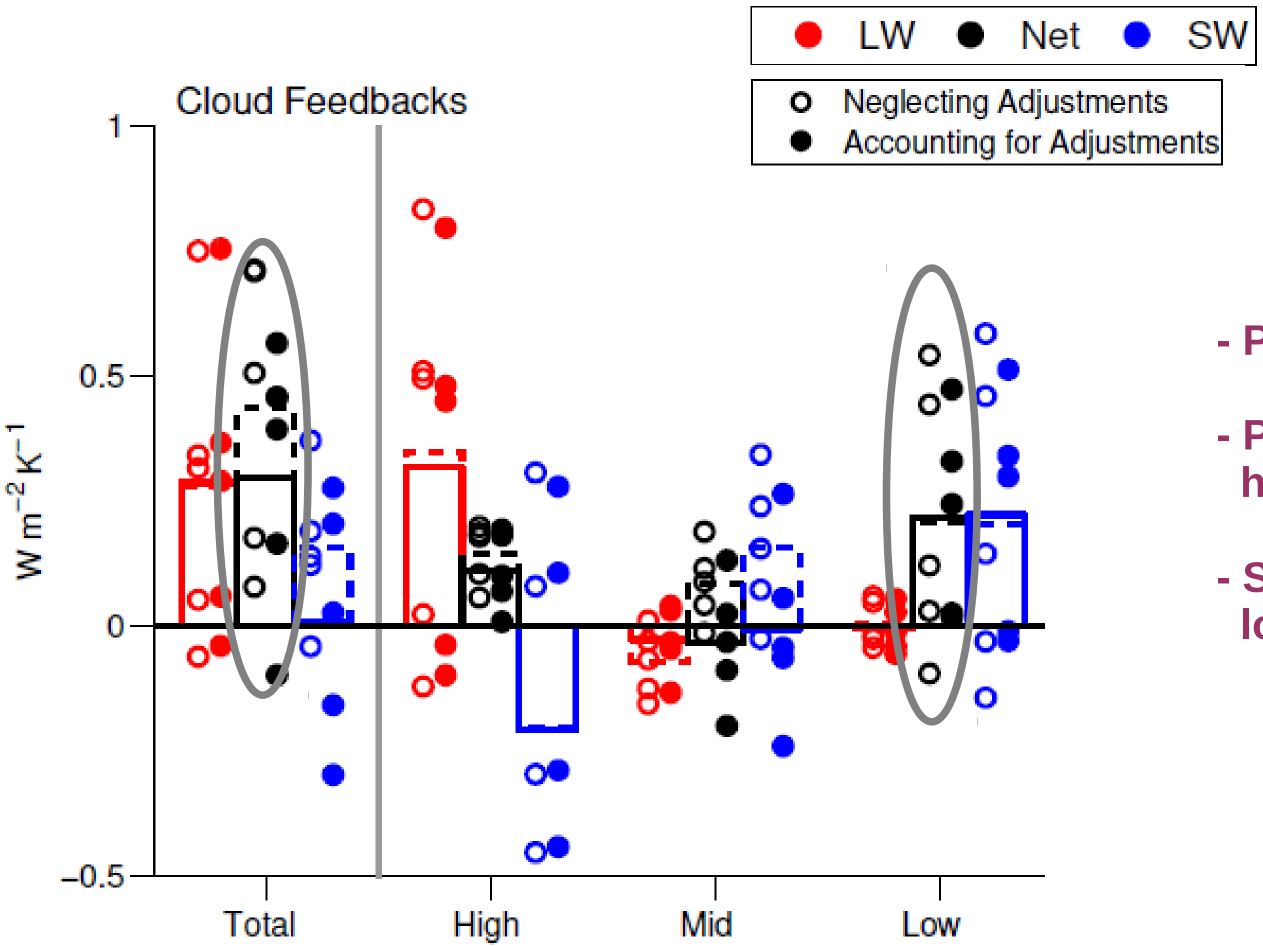
- learn about clouds-controlling factors
- test hypotheses
- test processes at work in model cloud feedbacks

Models, although imperfect, can be used to :

- challenge our ability to understand how clouds might change in a warming climate
- generate ideas (e.g. when trying to understand inter-model differences)
- help identify robust processes or mechanisms
  that should be then tested using observations or process models
  ...and maybe suggest new pieces for our « puzzle of understanding »

NB : some processes might be missing in all models

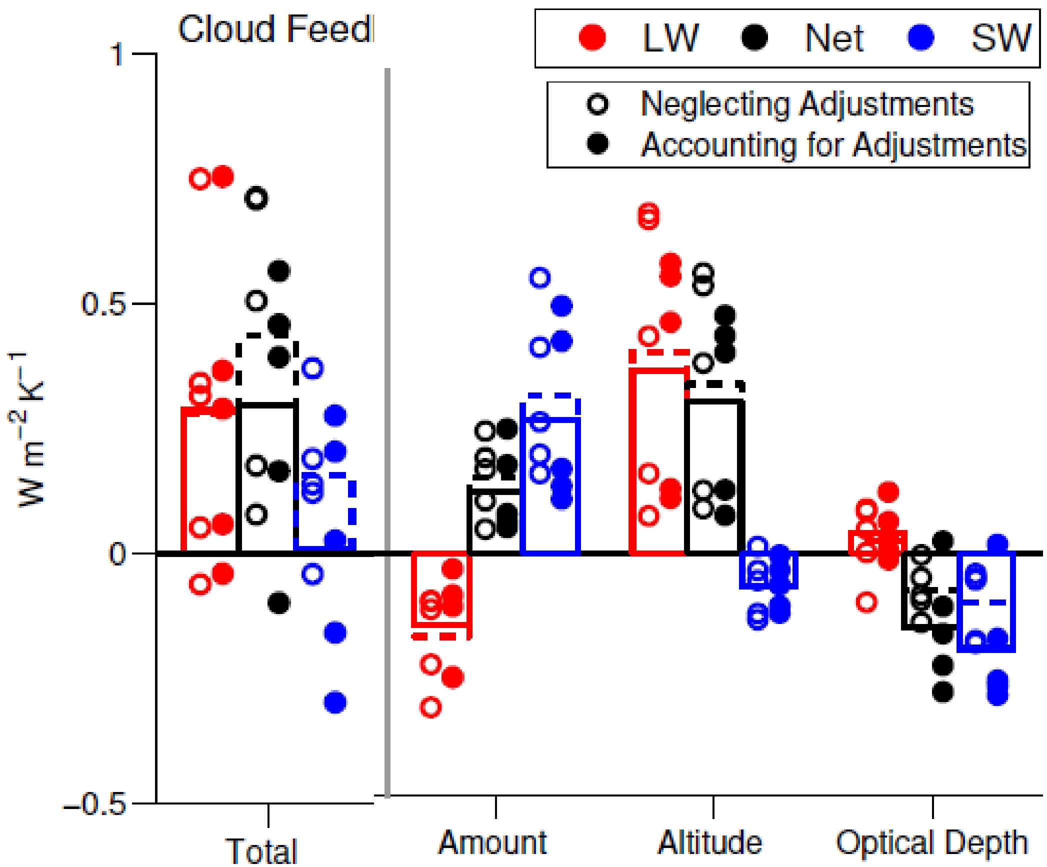
CMIP5 Cloud Feedbacks



- Positive cloud feedback
- Primarily arises from low-level and high-level cloud feedbacks
- Spread primarily arises from low-level cloud feedbacks

Zelinka et al., J. Climate, 2013

CMIP5 Cloud Feedbacks



In a warmer climate :

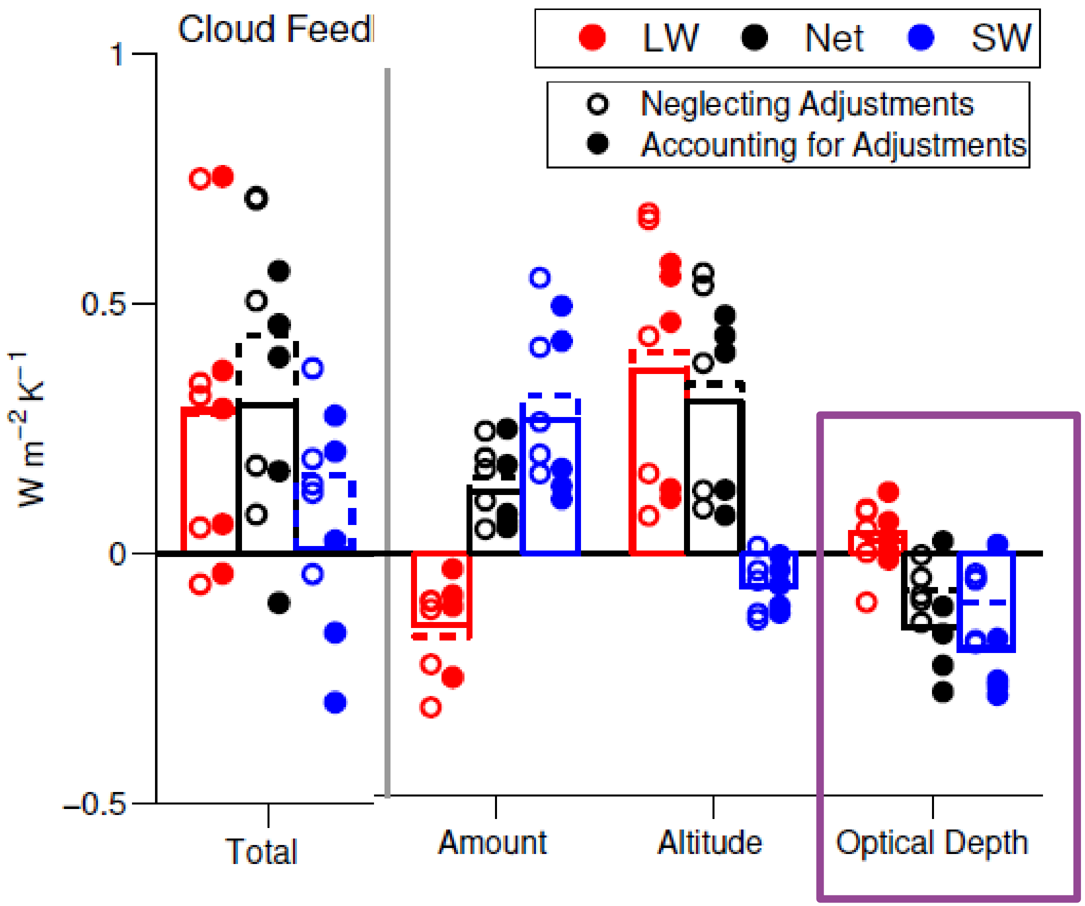
Fewer clouds
(positive feebdack)

Higher clouds
(positive feedback)

Optically thicker clouds
(negative feedback)

Zelinka et al., J. Climate, 2013

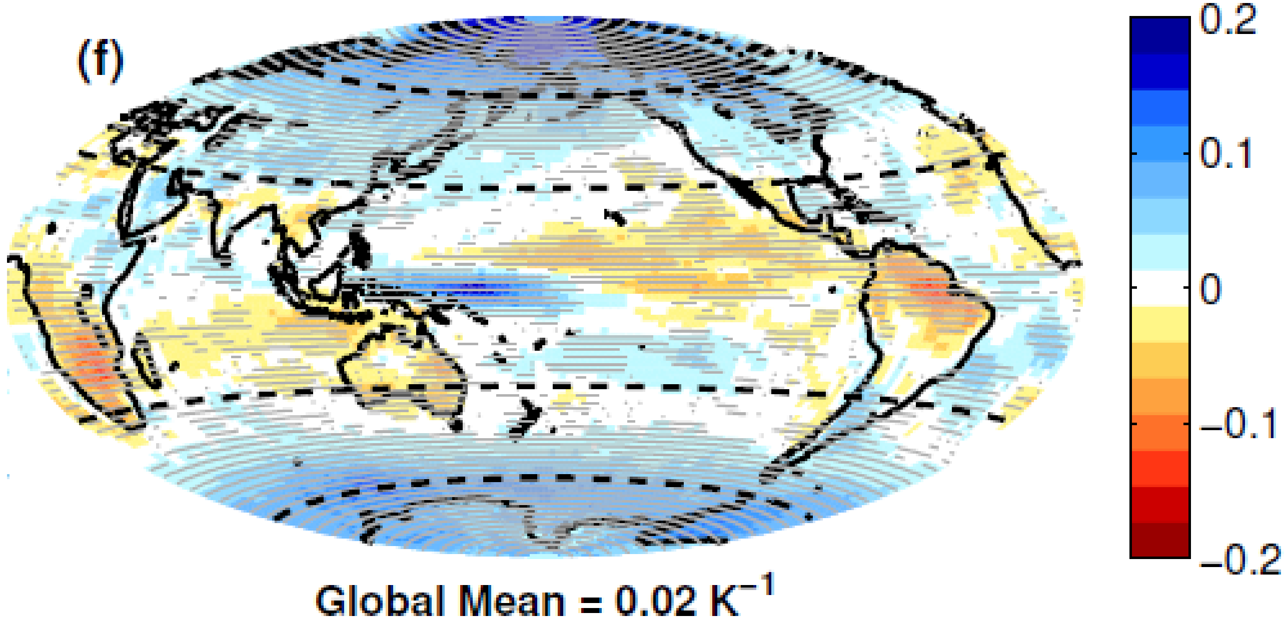
CMIP5 Cloud Feedbacks



Negative cloud feedback associated with increased cloud optical depth

Zelinka et al., J. Climate, 2013

Change in Cloud Optical Depth



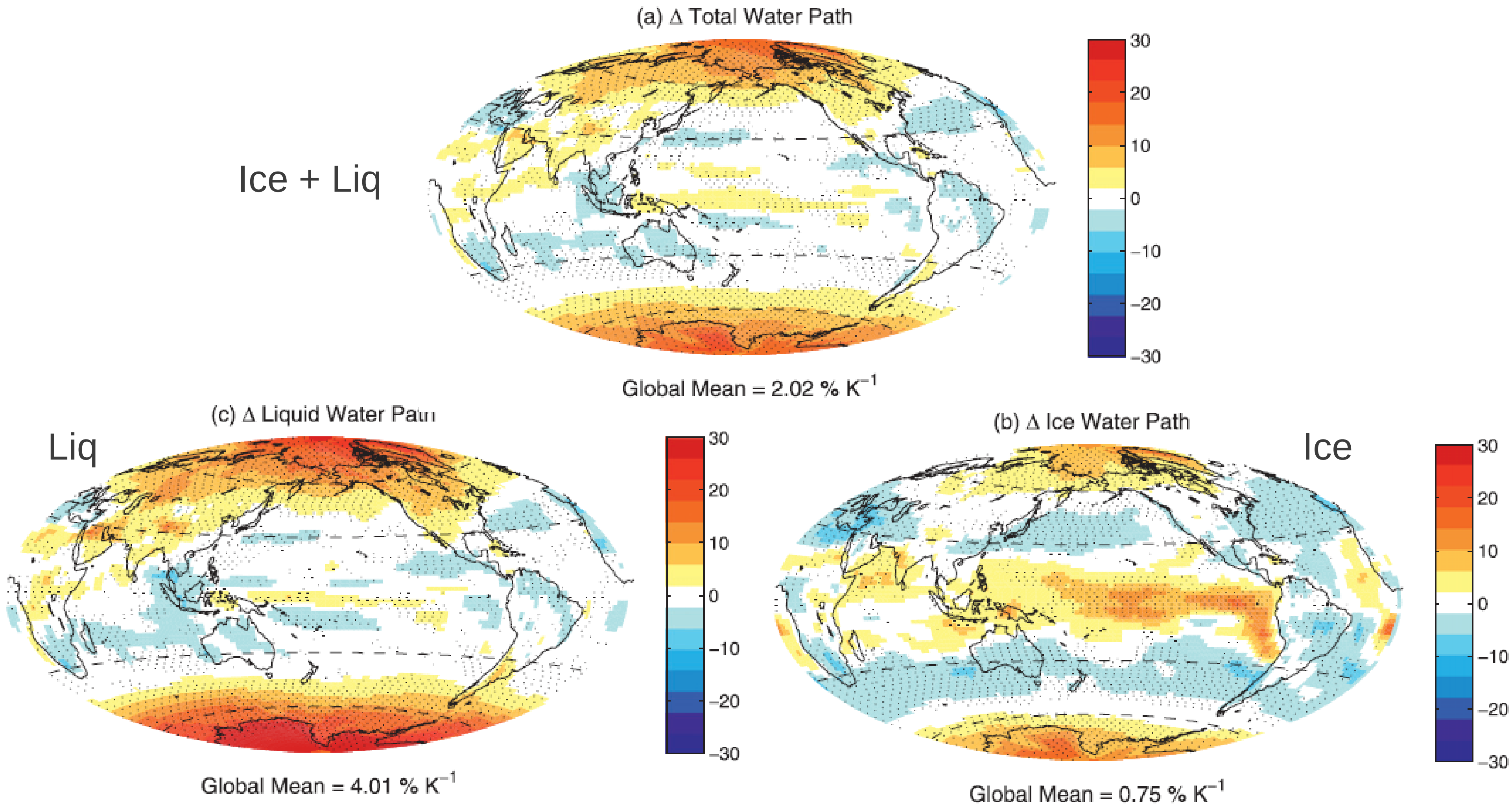
- Robust increase in cloud optical depth at latitudes poleward of about 40 deg.

- Negative cloud optical depth feedback arises mostly from the extratropics.

- High-latitude cloud optical thickness response likely related to changes in the phase and/or total water content of clouds.

Zelinka et al., J. Climate, 2013

Change in Cloud Water Path



Robust increase in total water path at high latitudes dominated by changes in the liquid phase

Zelinka et al., J. Climate, 2012b

How do we expect clouds to change with temperature ?

- It is only in the 80s that clear ideas of why and how cloudiness might depend on surface temperature began to emerge (e.g. Paltridge 1980).

  cf Rieck et al. (JAS, 2012) for an historical perspective

- An area of progress over the last decades....

Thermodynamical arguments

- In observations, total water contents of liquid and ice clouds tend to increase with temperature (Feigelson 1978, Somerville and Remer 1984)

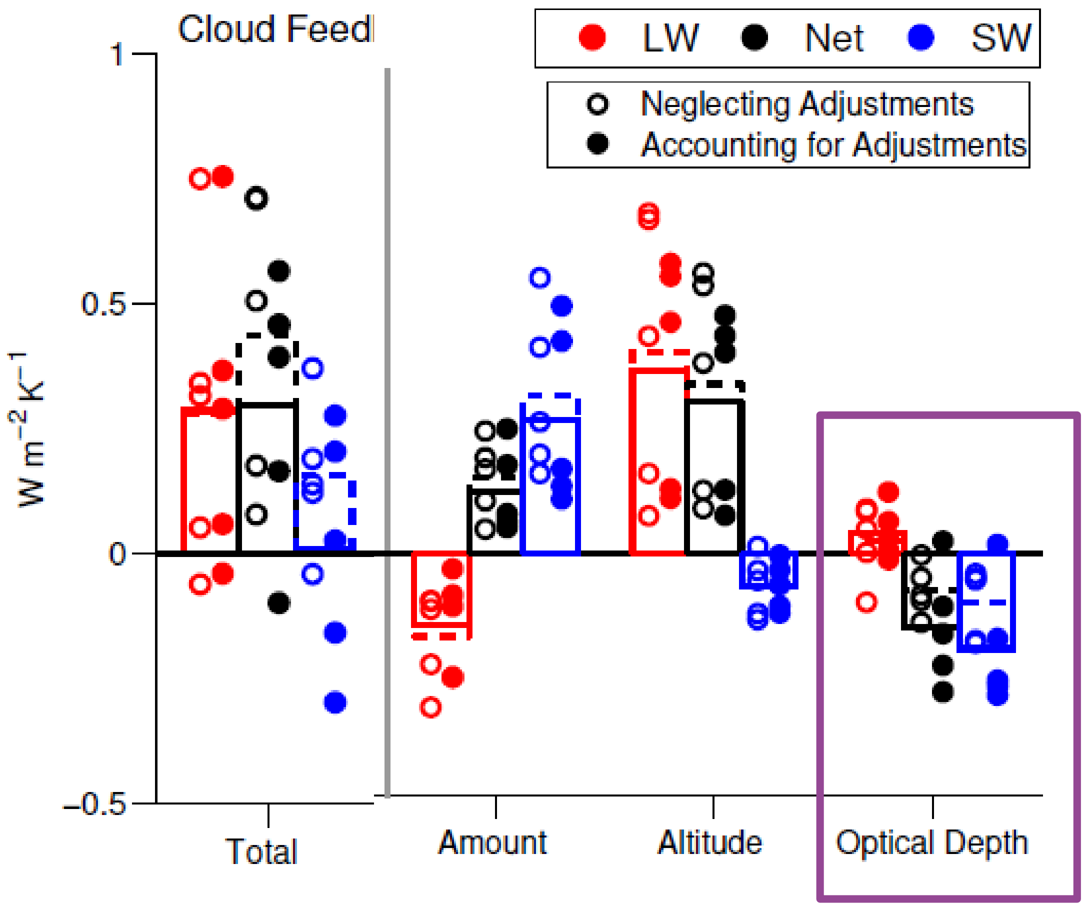
- The change in cloud liquid water with temperature depends on the change of the slope of the moist adiabat with respect to temperature (Betts and Harshvardan 1987)

$$f = \frac{1}{l}\left(\frac{\partial l}{\partial T}\right)_{p_1, p_2} = \frac{1}{\Gamma_W}\frac{\partial \Gamma_W}{\partial T}$$ with $\Gamma_W = -\langle(\partial\theta/\partial p)_{\theta_{ES}}\rangle$ (slope moist adiabat)

... and this rate of change in the mid and high latitudes is about twice that in the tropics

- **In a warmer climate, clouds should thus consist of more liquid water, and be brighter (negative feedback)**

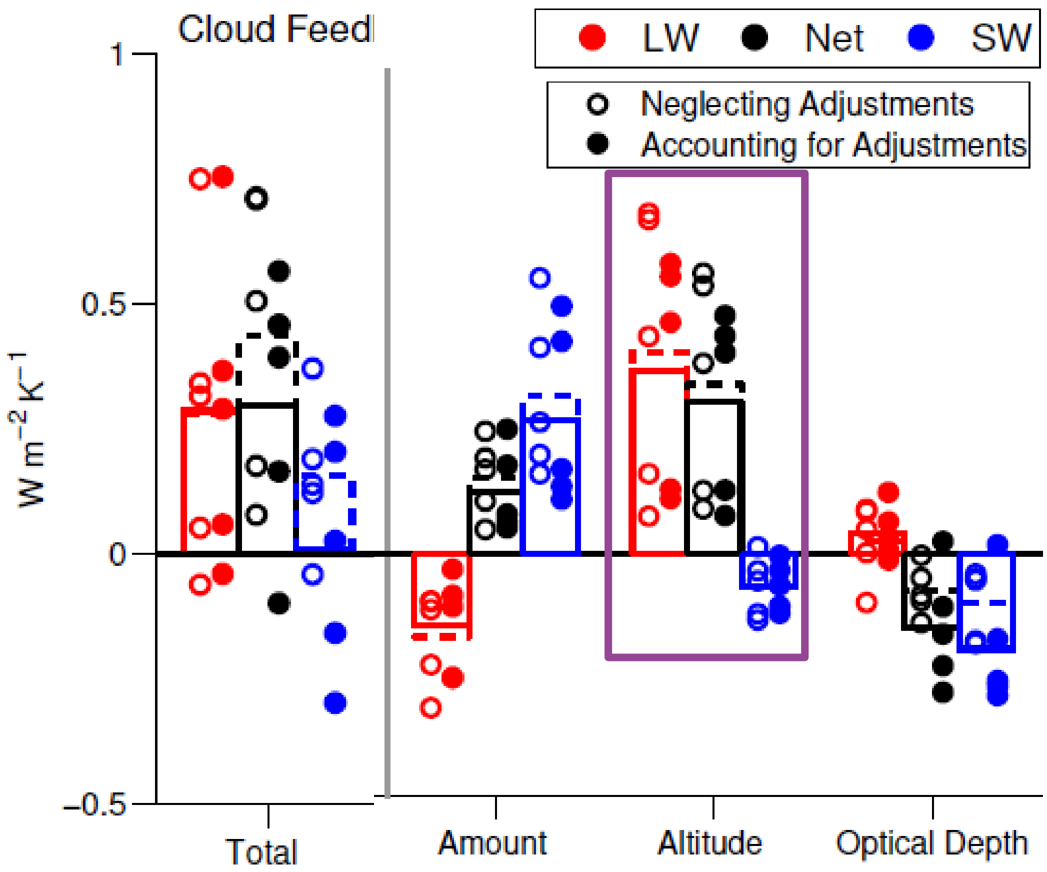
CMIP5 Cloud Feedbacks



Need to also consider
dynamical influences,
e.g. :
phase changes
poleward shift of the storm tracks
change in storms frequency/intensity
(cf Gunilla's lecture)

Zelinka et al., J. Climate, 2013

CMIP5 Cloud Feedbacks



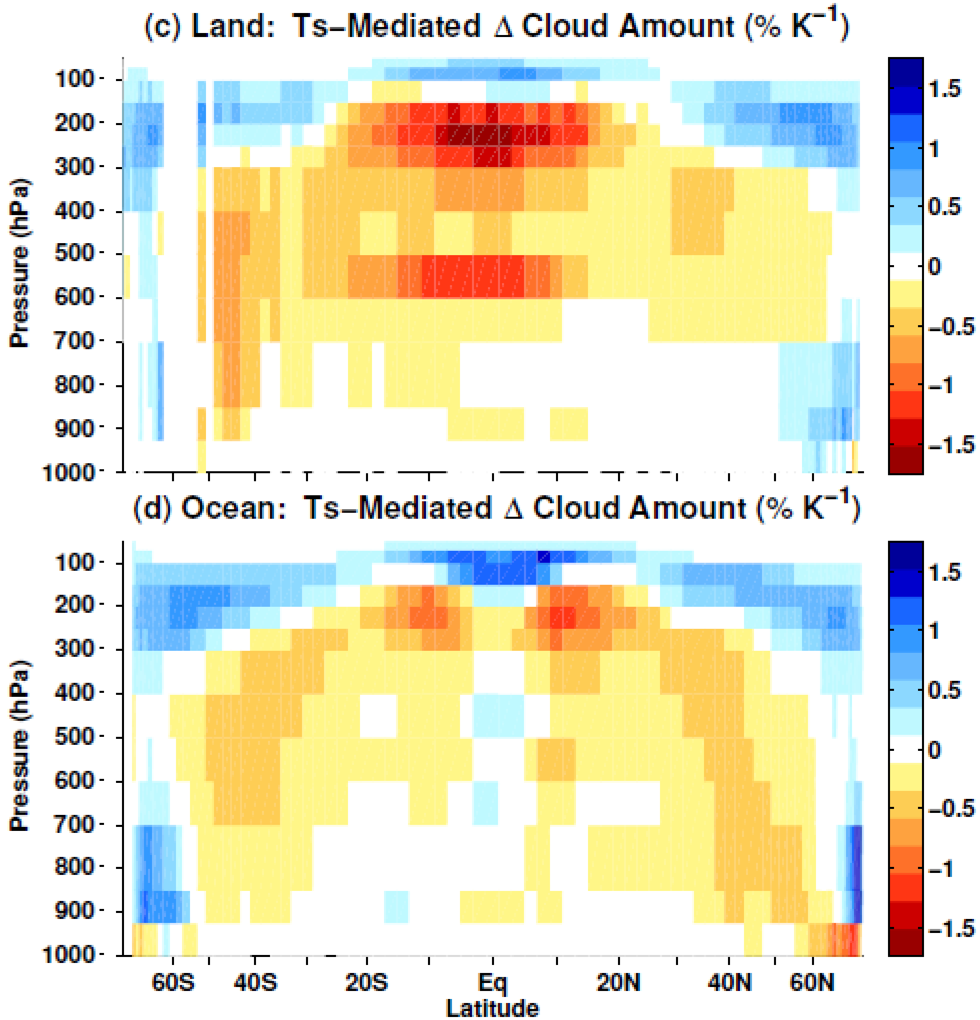
Positive cloud feedback associated with higher clouds

Zelinka et al., J. Climate, 2013

In a warmer climate, climate models robustly predict a rise of upper-level clouds

land

ocean

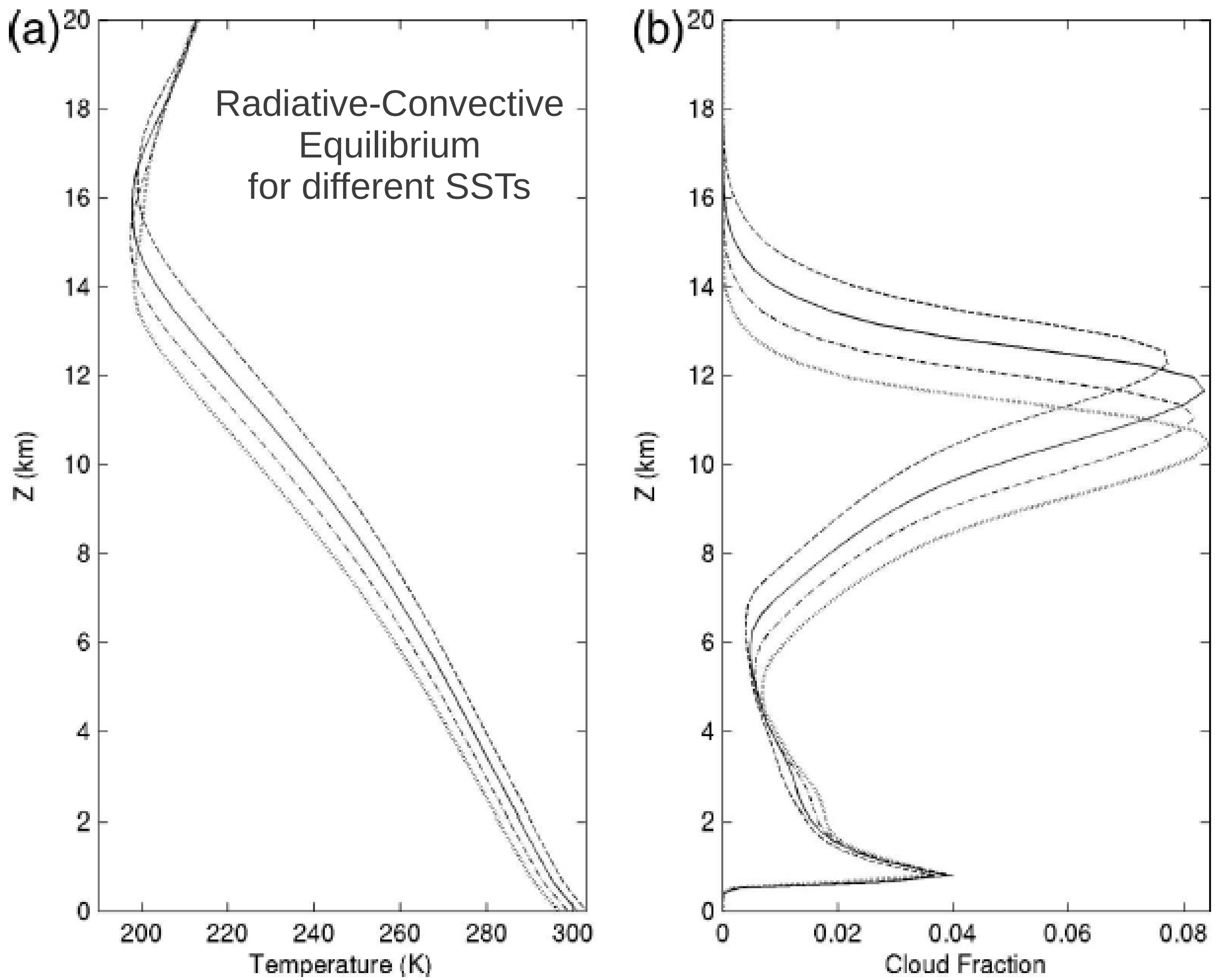


Zelinka et al., J. Climate, 2013

Cloud Resolving Models as well

Temperature   Cloud fraction

Height



SST increases

Kuang and Hartmann, J. Climate, 2007
also Tompkins and Craig 1998

How much does it contribute to the LW cloud feedback ?

Depends on the change in cloud top temperature relative to the surface temperature change....

A Radiative-Convective Model Study of the CO_2 Climate Problem

T. Augustsson

George Washington University, NASA-Langley Research Center, Hampton, Va. 23665

V. Ramanathan

National Center for Atmospheric Research,[1] Boulder, Colo. 80307

(Manuscript received 26 May 1976, in revised form 14 December 1976)

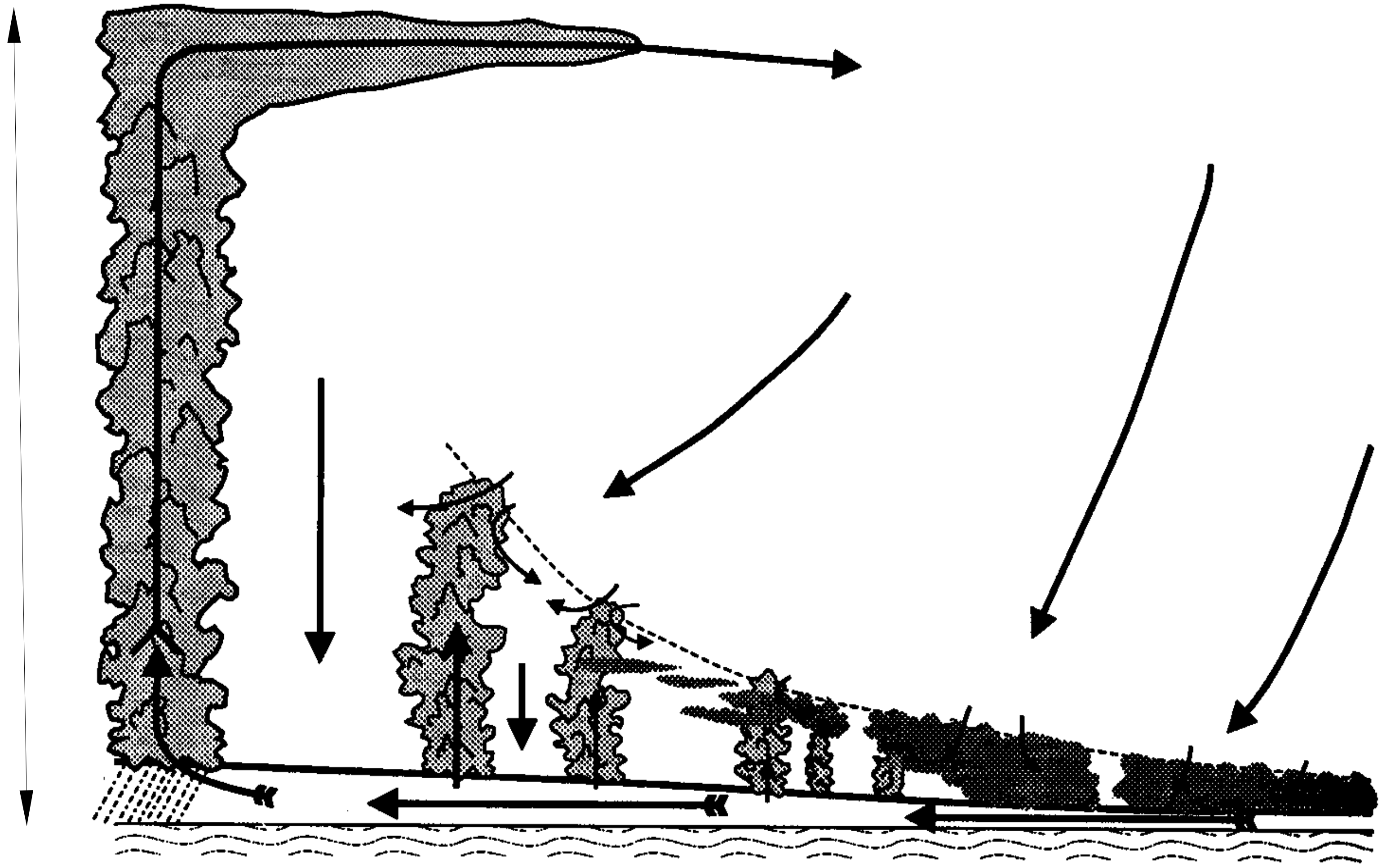
No.	Experiment description	Increase in T_s (K)	dF/dT_s (W m^{-2} K^{-1})	
1.	Constant CTA model $\Omega=1$.	1.98	2.24	Fixed cloud-top altitude
2.	Constant CTT model $\Omega=1$.	3.2	1.38	Fixed cloud-top temperature

There are no clear-cut theoretical justifications for choosing any one of the models shown in Table 2 as a more representative model for the real world. The results only indicate the large uncertainty in the model results introduced by the assumptions made in radiative-convective model

Augustsson & Ramanathan, JAS, 1976

What controls the high-level cloud top altitude / temperature ?

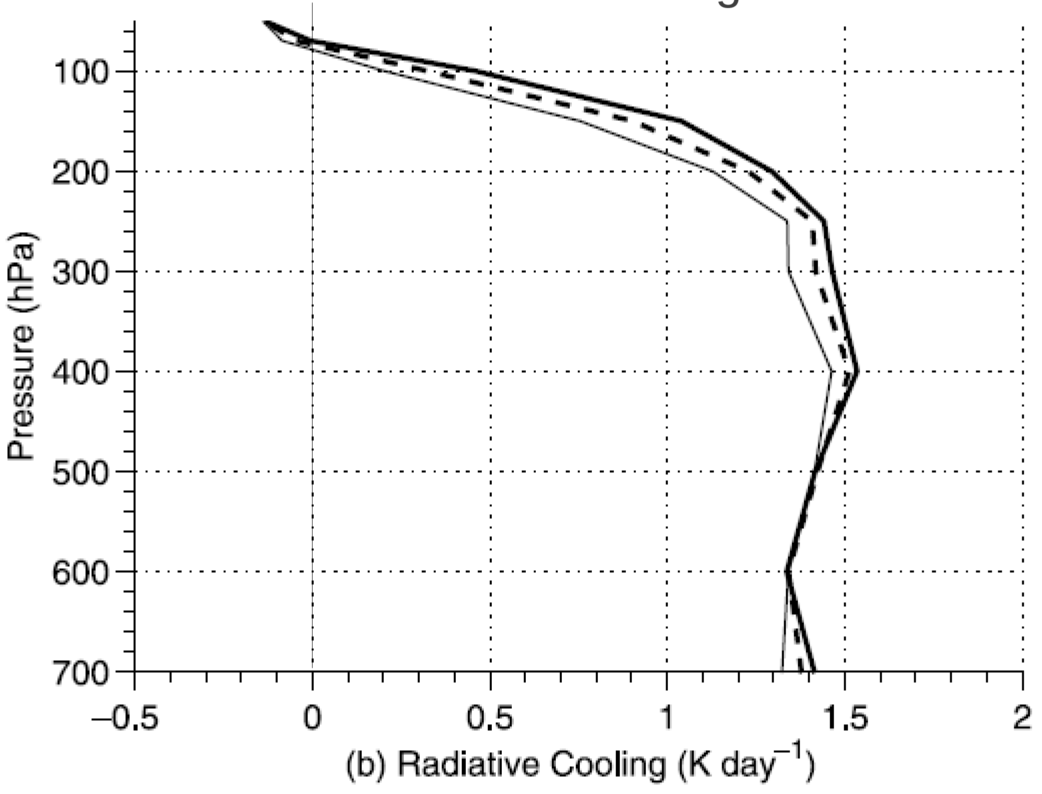
- **High-level cloud top closely related to the depth of the convection layer**



What controls the high-level cloud top altitude / temperature ?

- In radiative-convective equilibrium, **the depth of the convection layer is determined by the depth of the atmospheric layer destabilized by radiation**

Radiative cooling rate

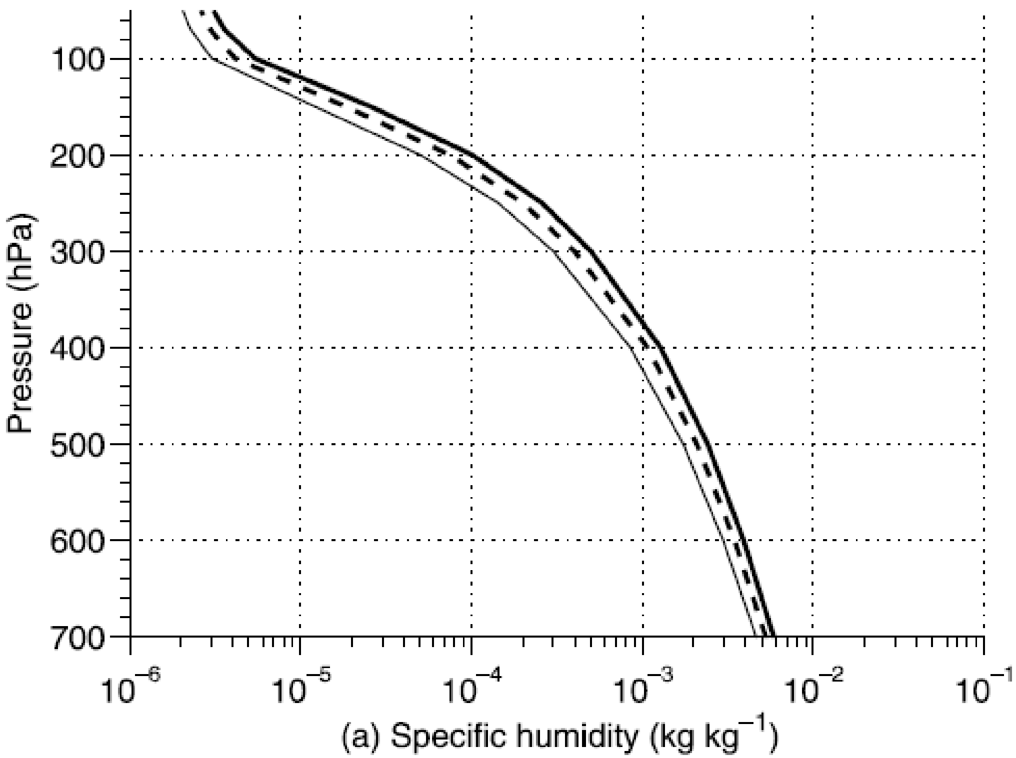


What controls the high-level cloud top altitude / temperature ?

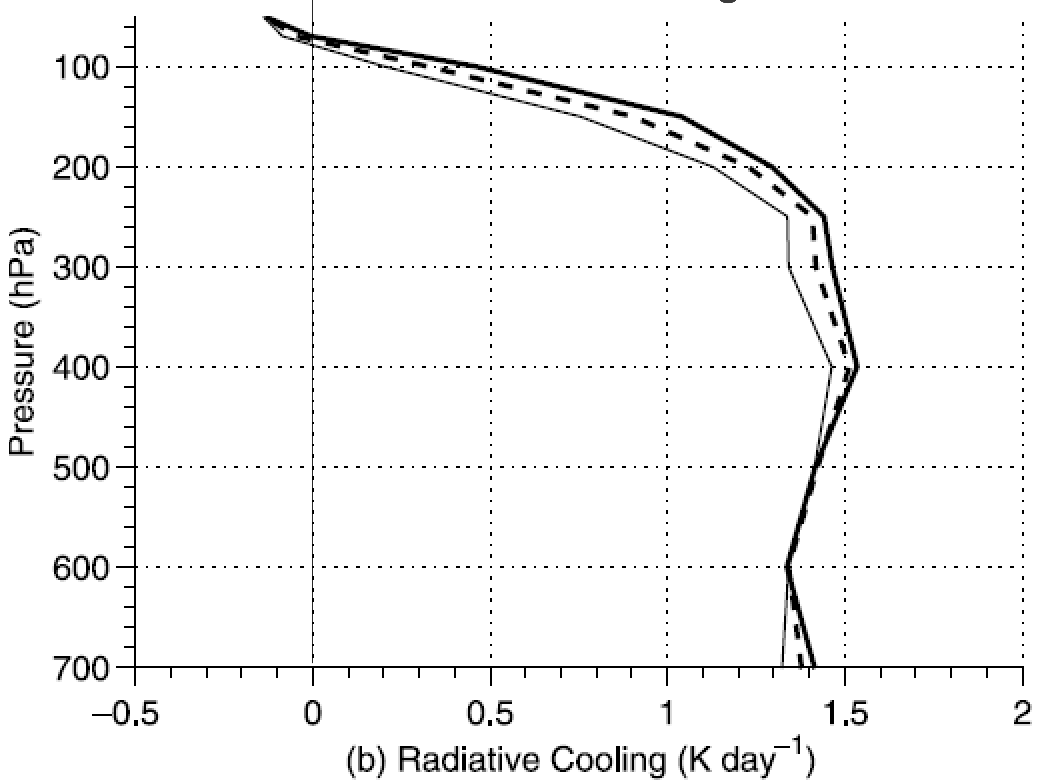
- In radiative-convective equilibrium, **the depth of the convection layer is determined by the depth of the atmospheric layer destabilized by radiation**

- **The rate of radiative cooling strongly depends on water**

Specific humidity



Radiative cooling rate

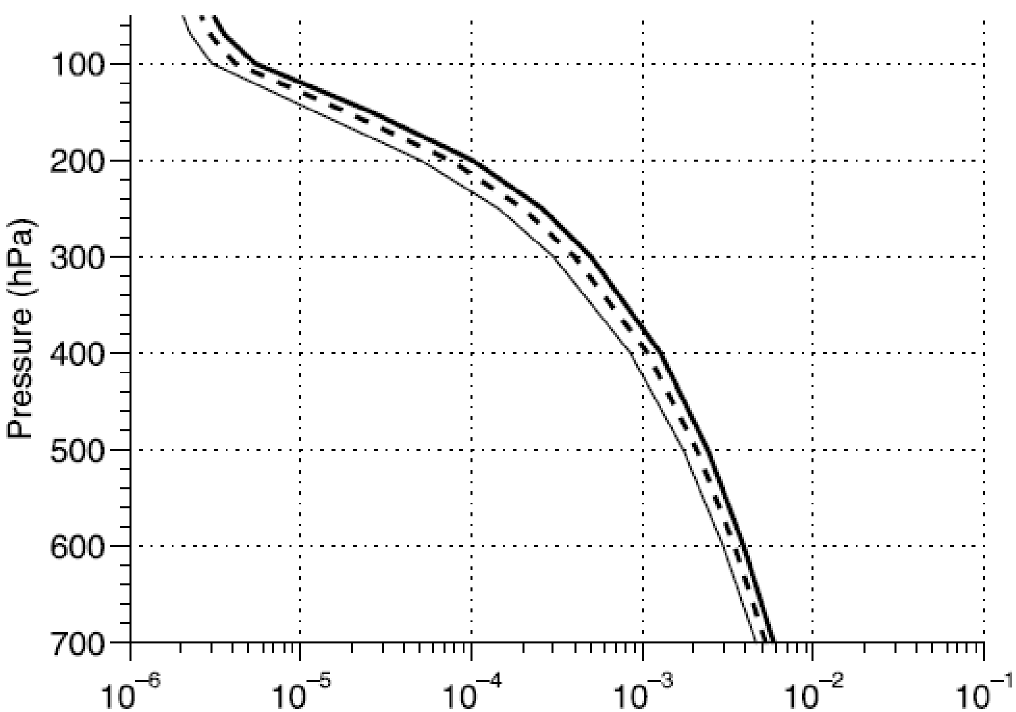


What controls the high-level cloud top altitude / temperature ?

- Because water vapor pressure decreases as temperature decreases, **at some altitude water molecules become so scarce that their contribution to radiative cooling becomes negligible.**

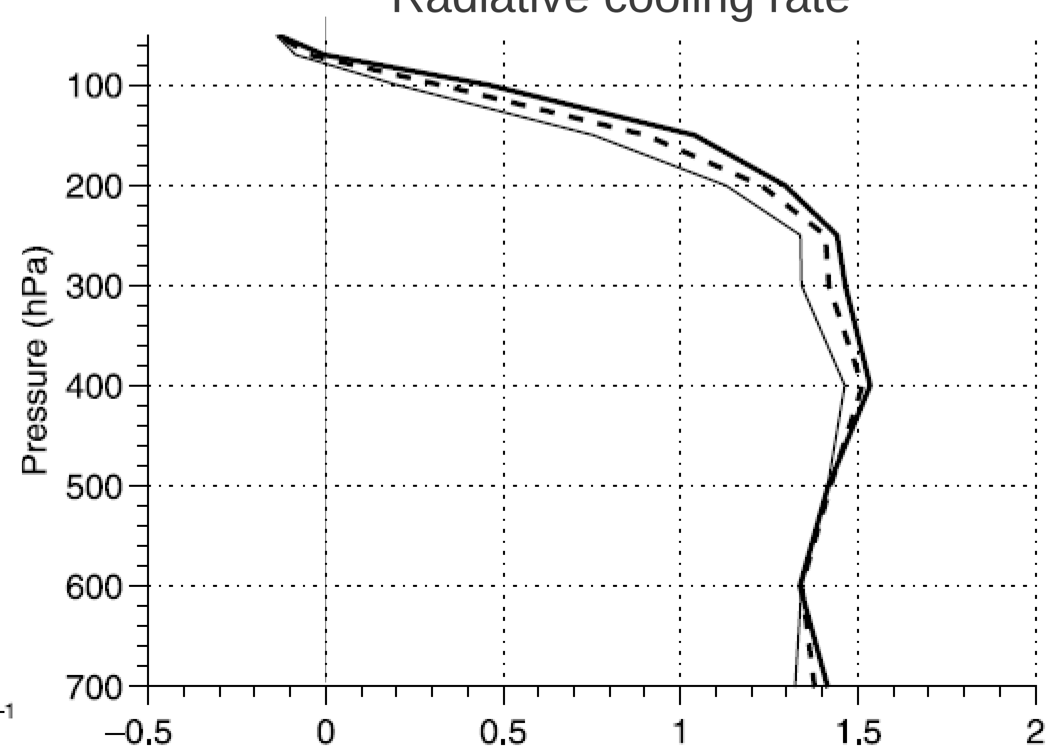
- This defines the upper limit of the radiatively driven convection layer

Specific humidity



(a) Specific humidity (kg kg^{-1})

Radiative cooling rate



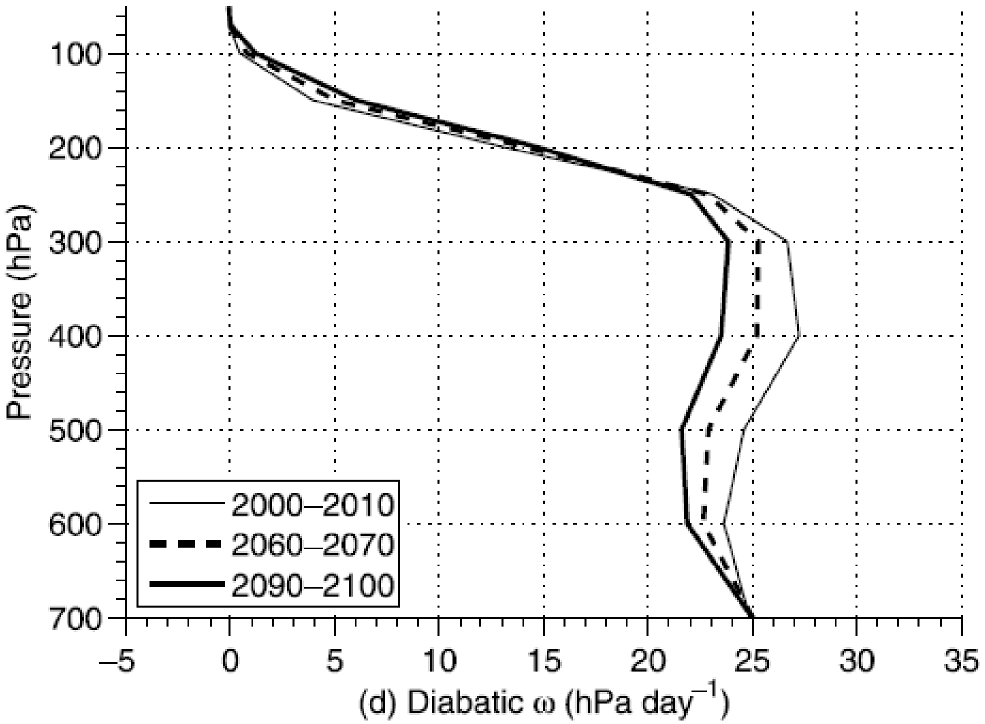
(b) Radiative Cooling (K day^{-1})

What controls the high-level cloud top altitude / temperature ?

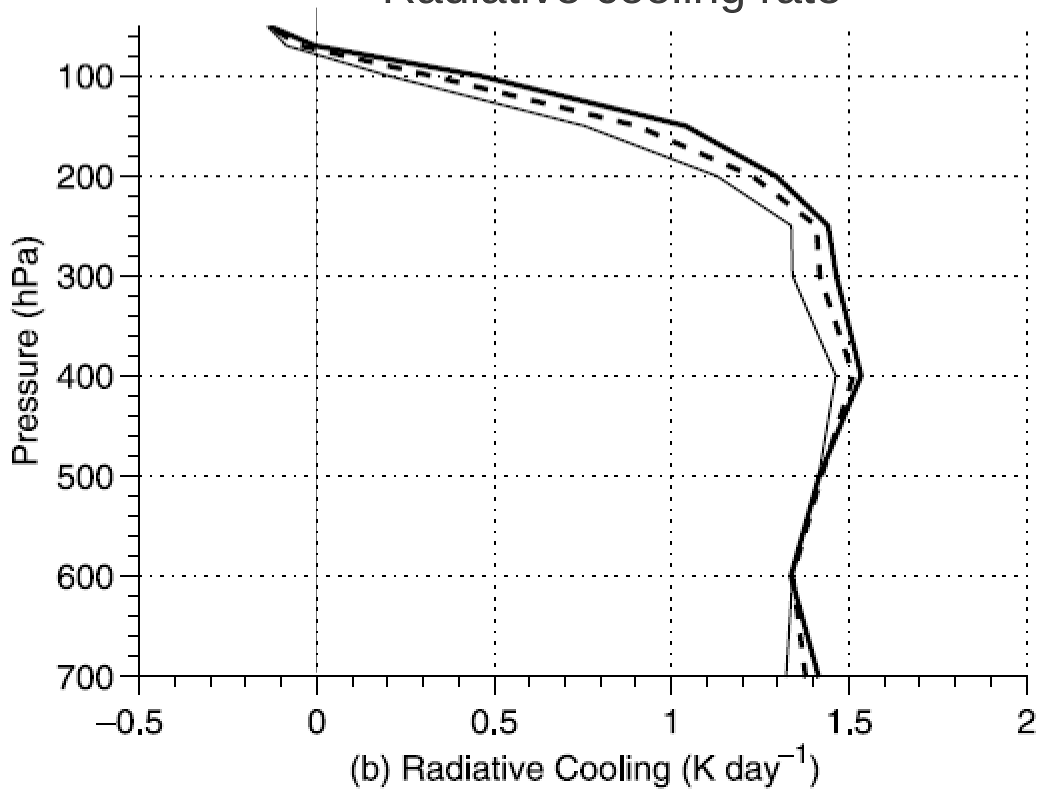
- In clear skies, **the radiative cooling is balanced by adiabatic heating through subsidence** :

$$\omega = \frac{Q_R}{\sigma}$$ where σ is the static stability.

Subsidence (in clear skies)



Radiative cooling rate



What controls the high-level cloud top altitude / temperature ?

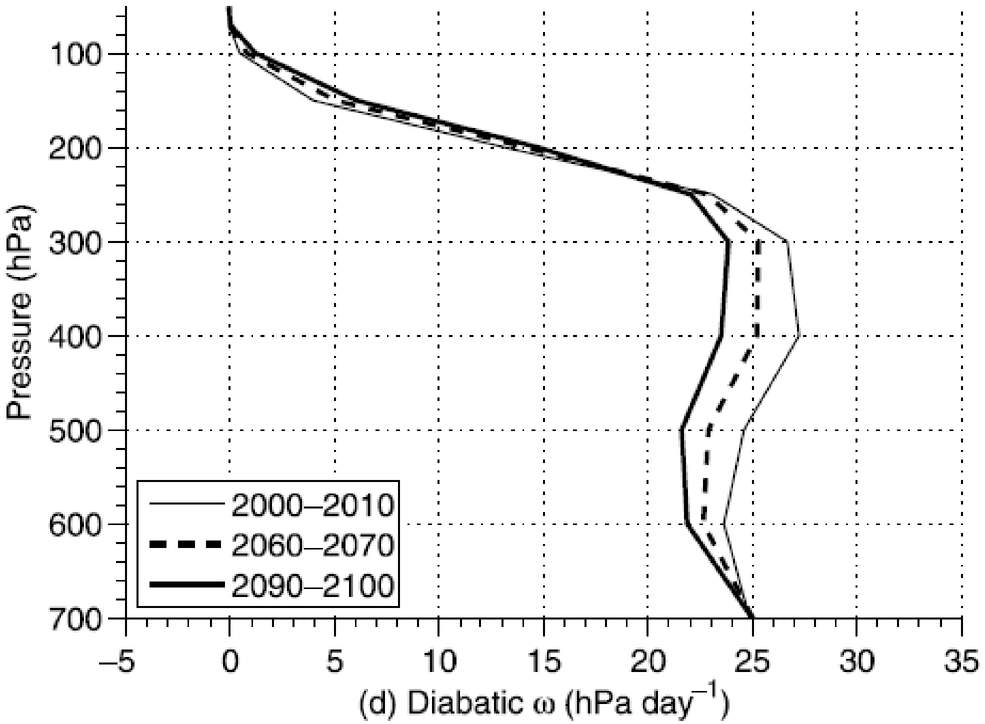
- In clear skies, **the radiative cooling is balanced by adiabatic heating through subsidence** :

$$\omega = \frac{Q_R}{\sigma}$$ where σ is the static stability.

- The strong decline of radiative cooling with altitude must thus be accompanied by a **strong convergence of mass at that level :**

$$-\nabla_H \cdot \mathbf{U} = \frac{\partial \omega}{\partial p}$$

Subsidence (in clear skies)

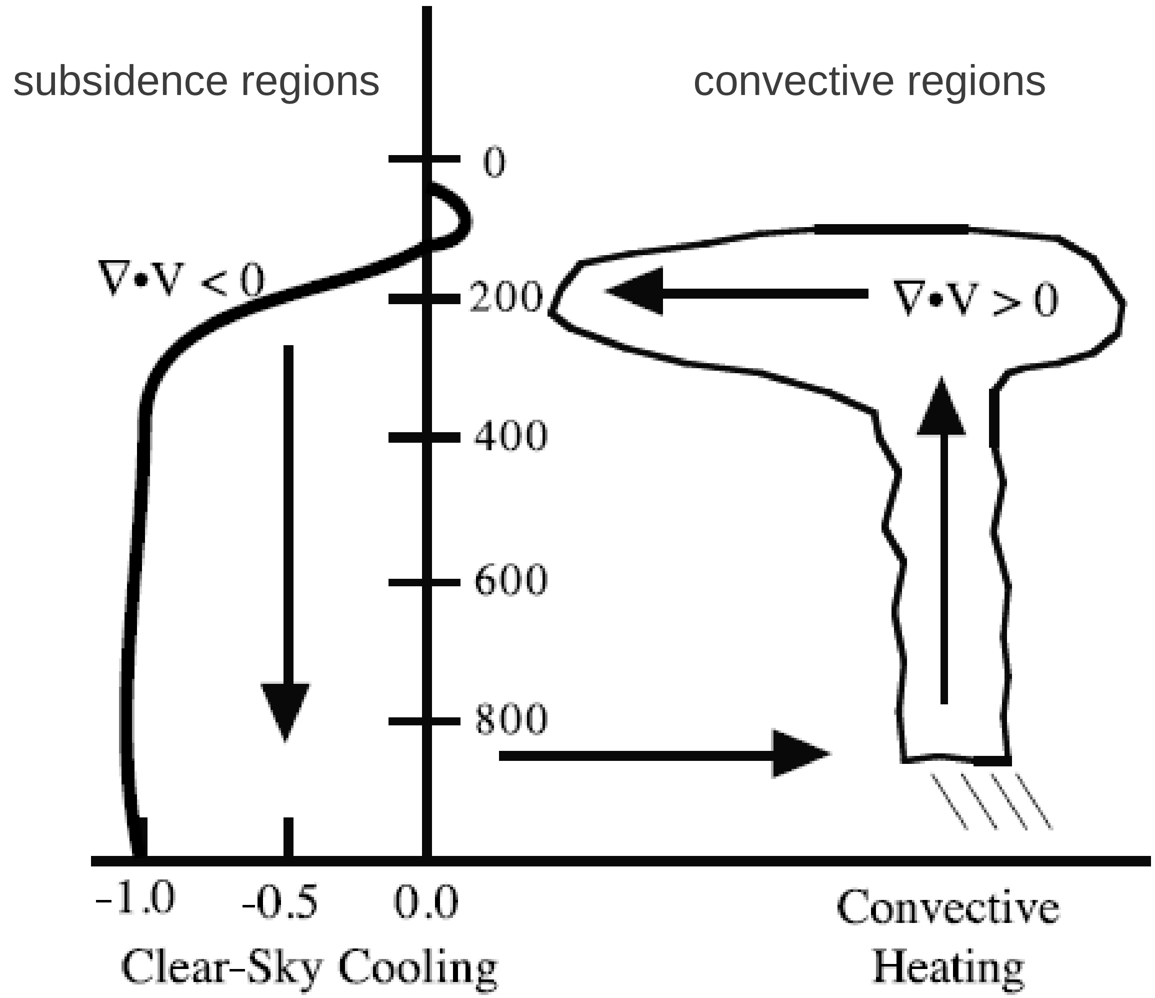


- The strong convergence of mass in subsidence regions of the tropics is **balanced by a strong divergence of mass from the convective regions.**

- The divergence of mass is associated with the frequent **occurrence of convective anvil clouds at this level**

Hartmann and Larson, GRL, 2002
Zelinka and Hartmann, JGR, 2010

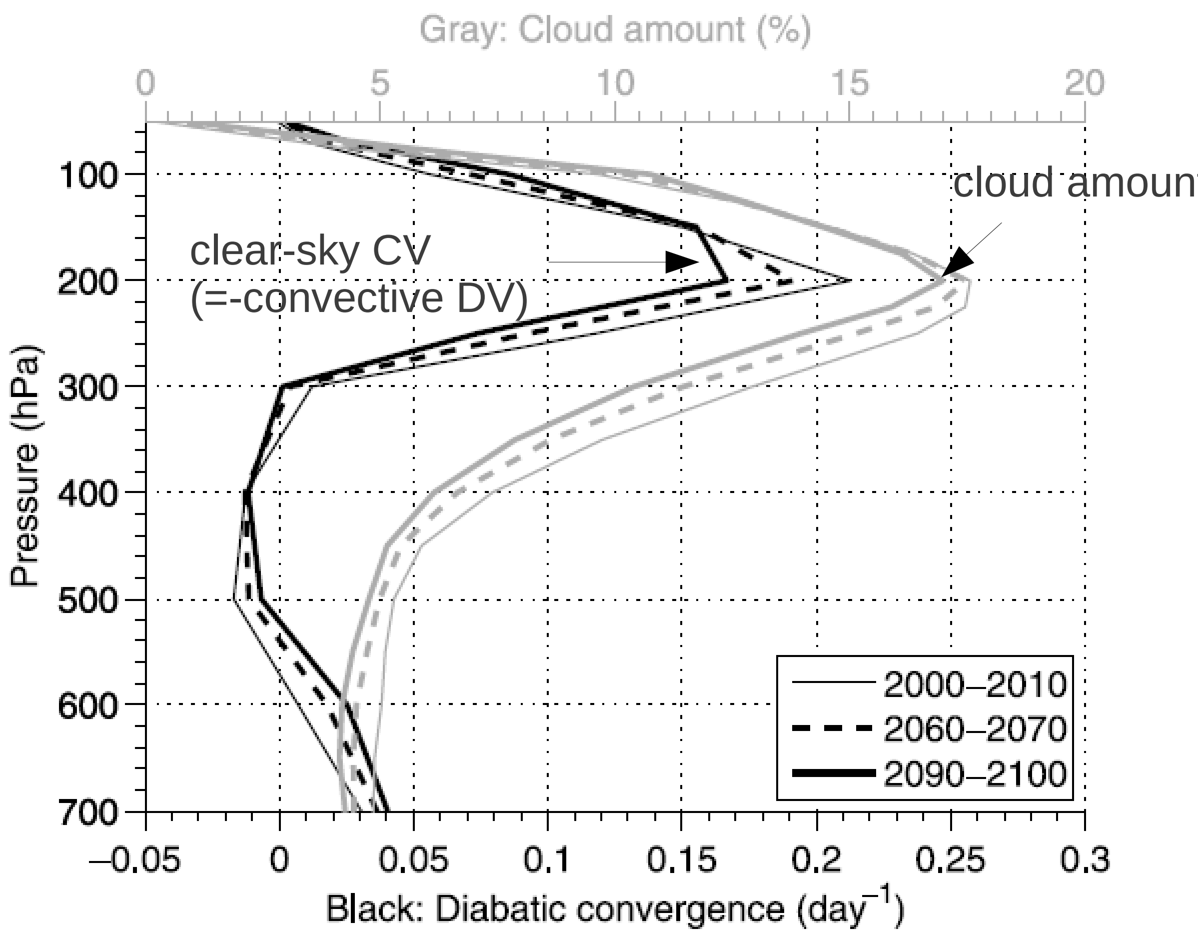
What controls the high-level cloud top altitude / temperature ?



Hartmann and Larson, GRL, 2002

What controls the high-level cloud top altitude / temperature ?

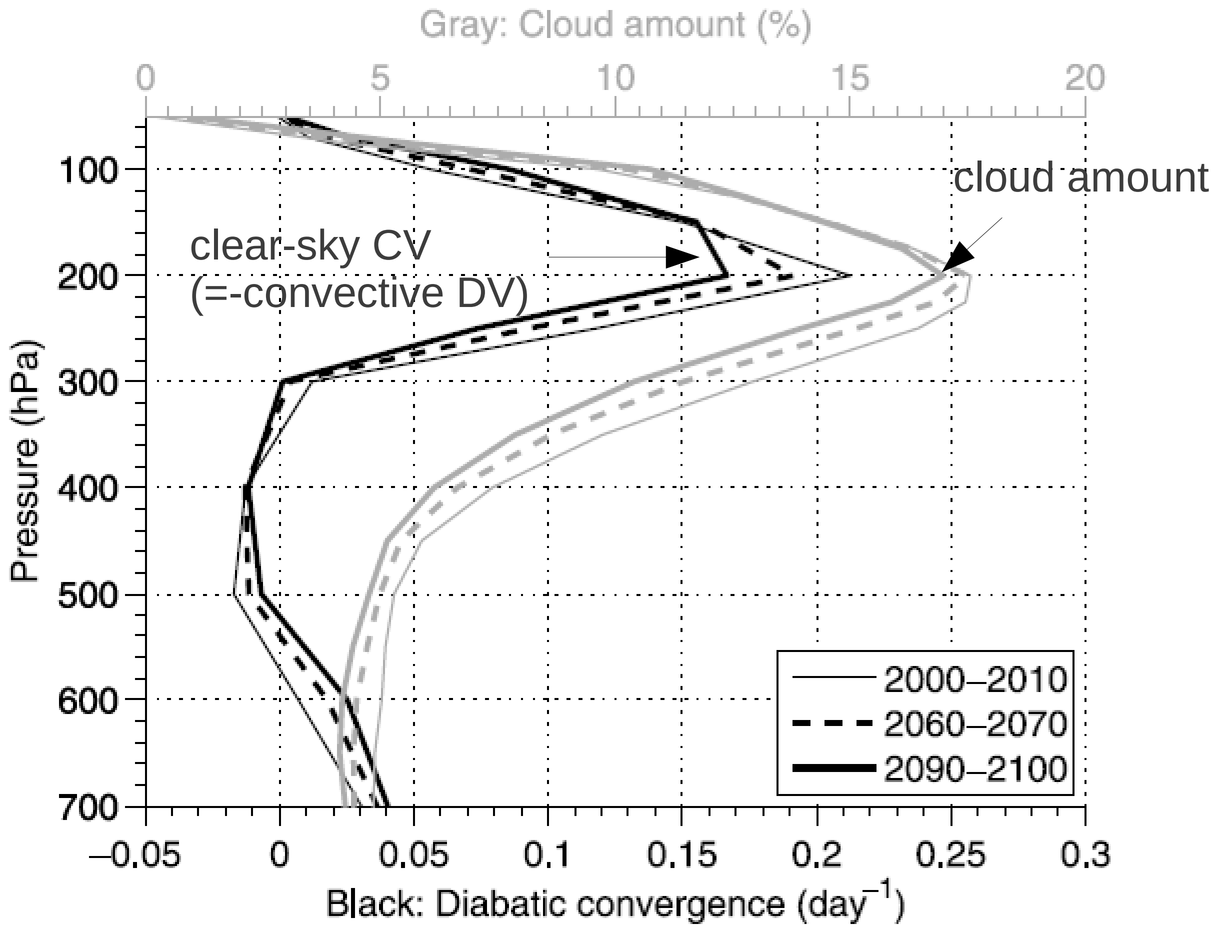
The cloud amount is maximum at the same altitude as the maximum of clear-sky mass convergence (i.e. maximum convective detrainment implied at the same level)



Zelinka and Hartmann, JGR, 2010

What controls the high-level cloud top altitude / temperature ?

Suggests that the temperature at the detrainment level, and thus the emission temperature of tropical anvil clouds, remains roughly constant, including in climate change.

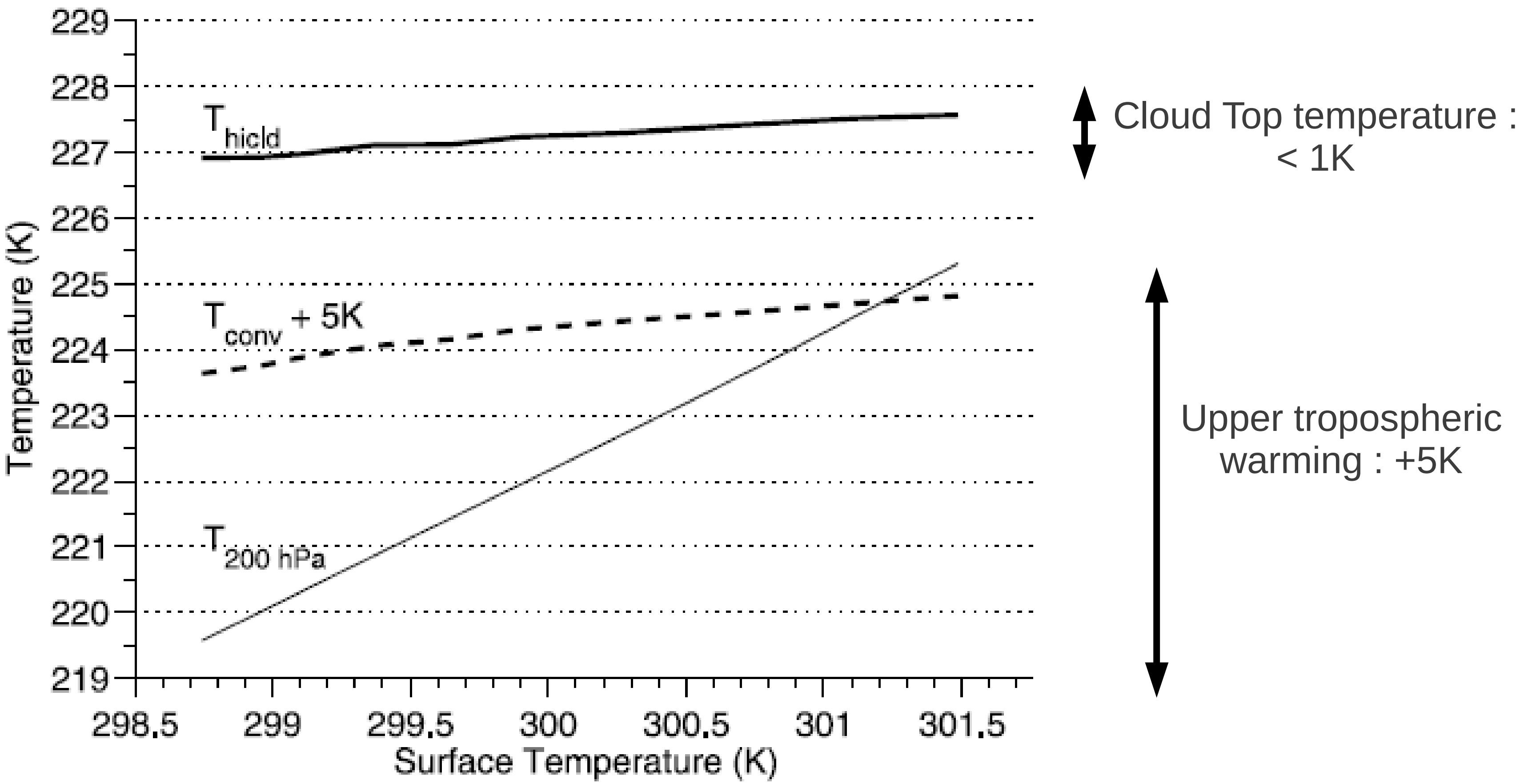


Zelinka and Hartmann, JGR, 2010

Indeed !

Fixed-Anvil Temperature (FAT) mechanism

In GCMs...

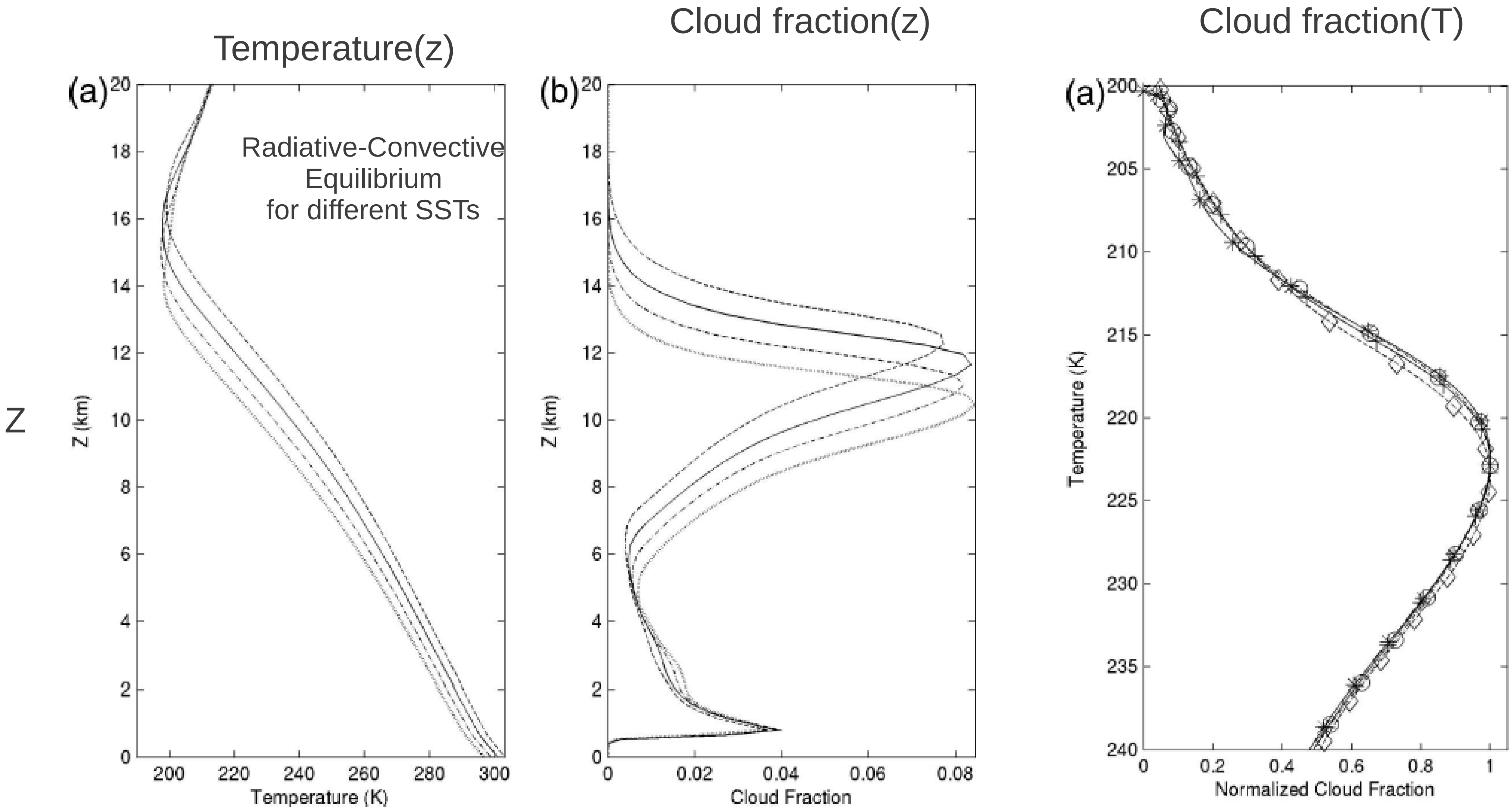


Hartmann and Larson, GRL, 2002
Zelinka and Hartmann, JGR, 2010

Indeed !

Fixed-Anvil Temperature (FAT) mechanism

In CRMs...



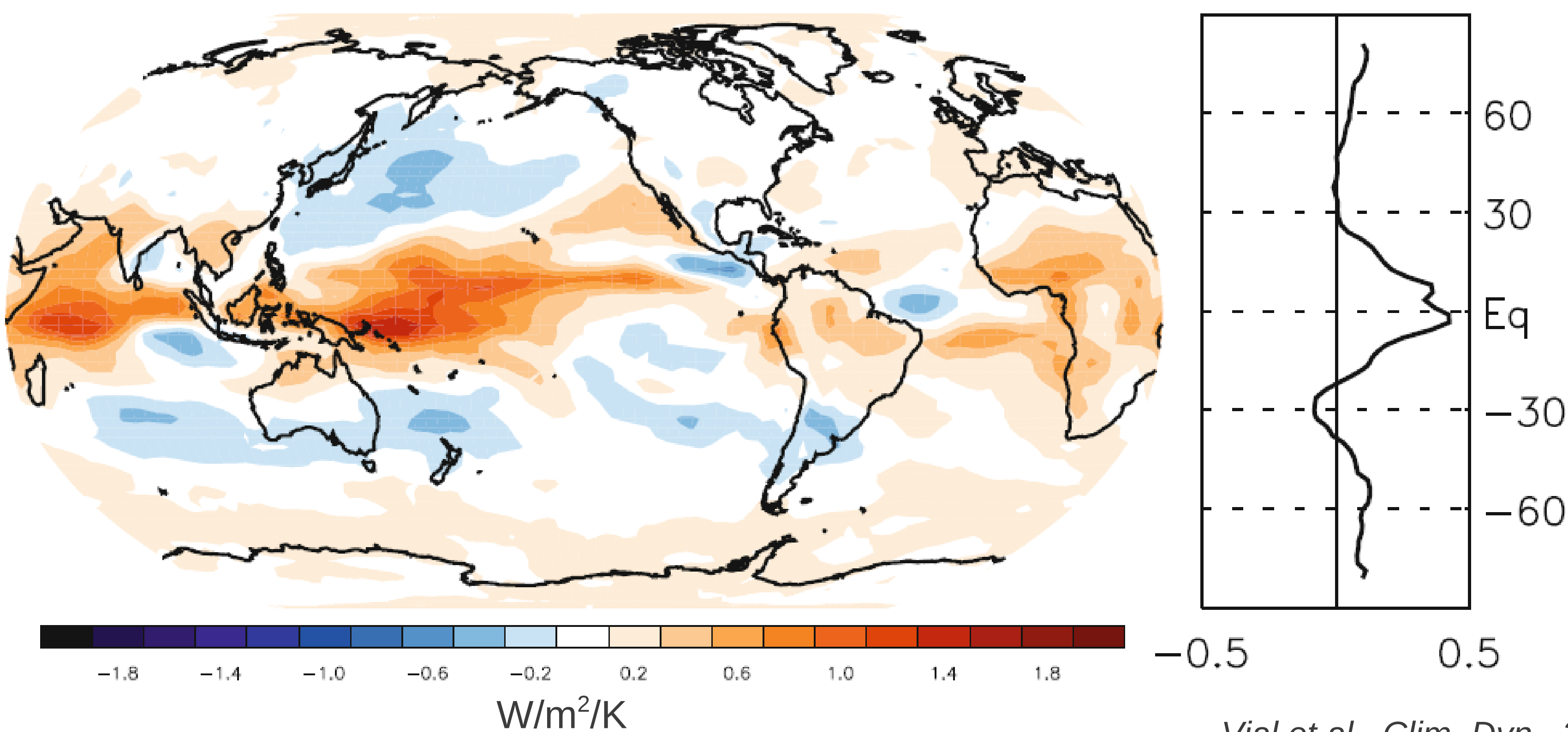
Kuang and Hartmann, J. Climate, 2007

Implications of FAT for cloud feedbacks ?

- Because cloud tops are not warming in step with surface and atmospheric temperatures, the tropics become less efficient at radiating away heat

- **Implies a positive LW cloud feedback**

CMIP5 LW cloud feedback



Vial et al., Clim. Dyn., 2013

Implications of FAT for cloud feedbacks ?

- Because cloud tops are not warming in step with surface and atmospheric temperatures, the tropics become less efficient at radiating away heat

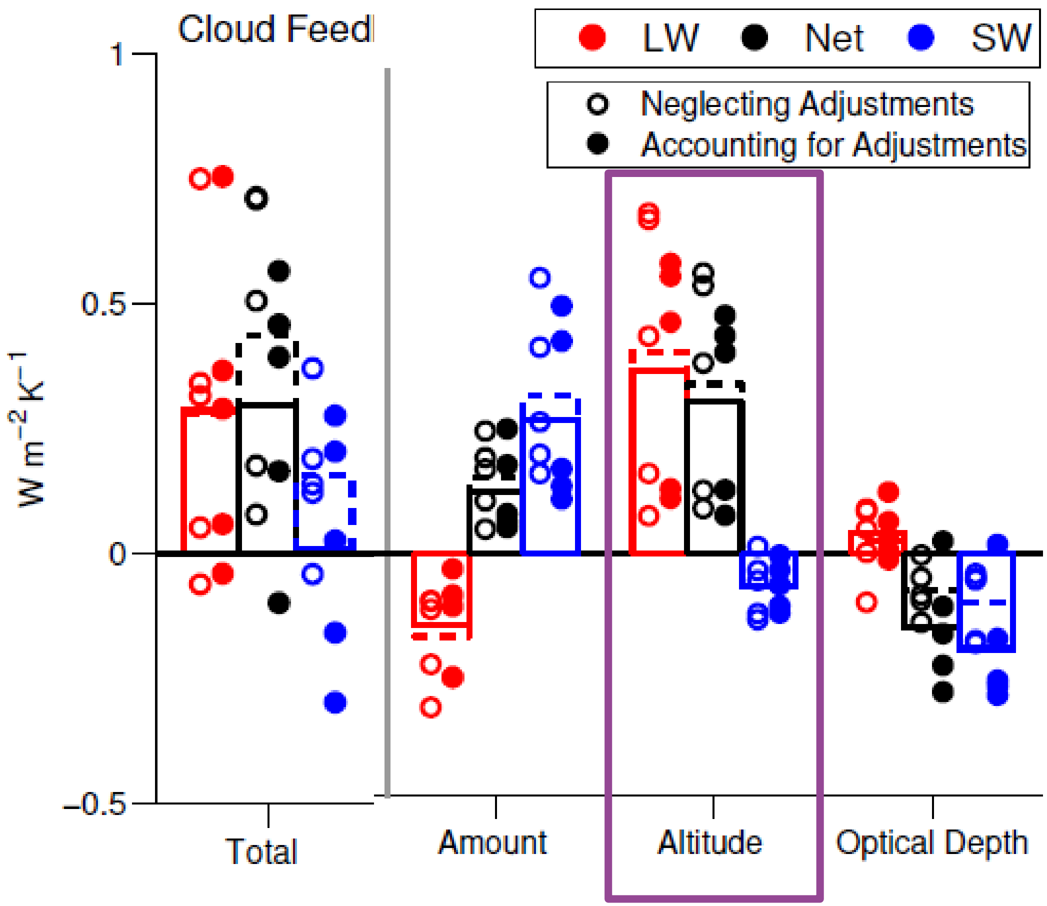
- **Implies a positive LW cloud feedback**

- Verified by GCMs, CRMs, and observations (Eitzen et al. 2009)
  + based on physical arguments

- **FAT thus constitutes a robust LW cloud feedback mechanism**

Hartmann and Larson, GRL, 2002
Zelinka and Hartmann, JGR, 2010

CMIP5 Cloud Feedbacks

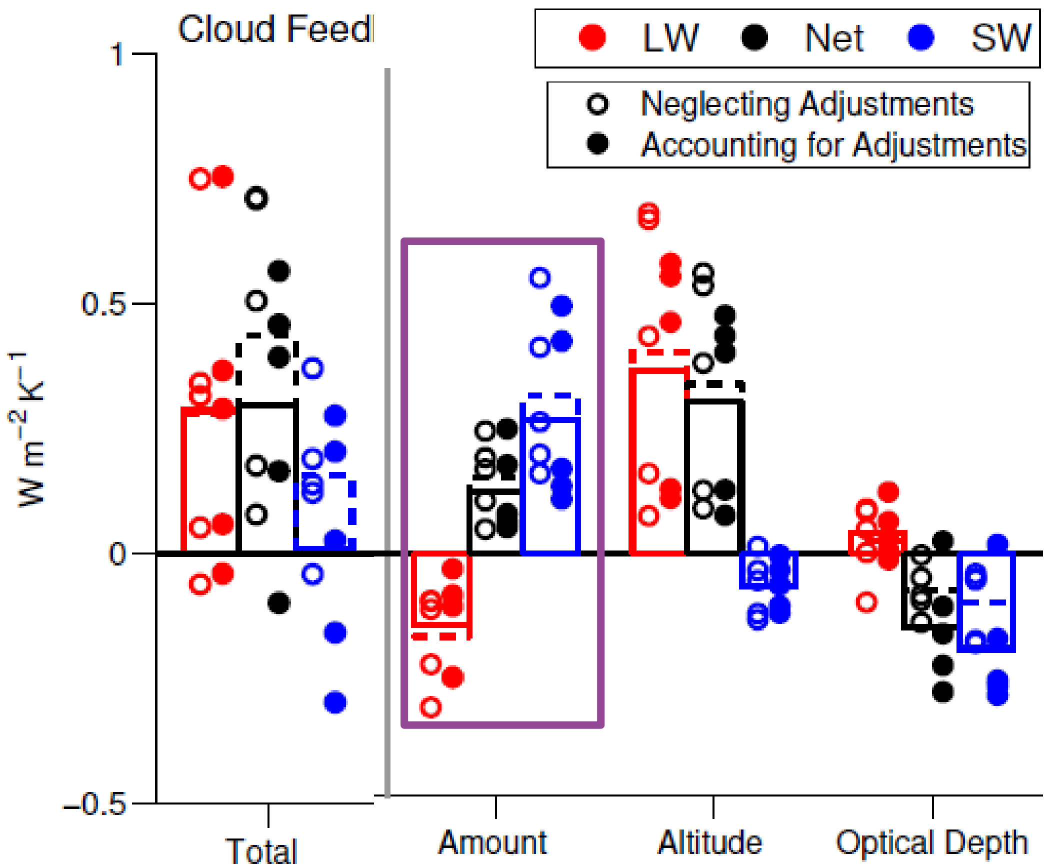


Positive cloud feedback associated with higher clouds

However, still some spread in the magnitude of this feedback..

Zelinka et al., J. Climate, 2013

CMIP5 Cloud Feedbacks

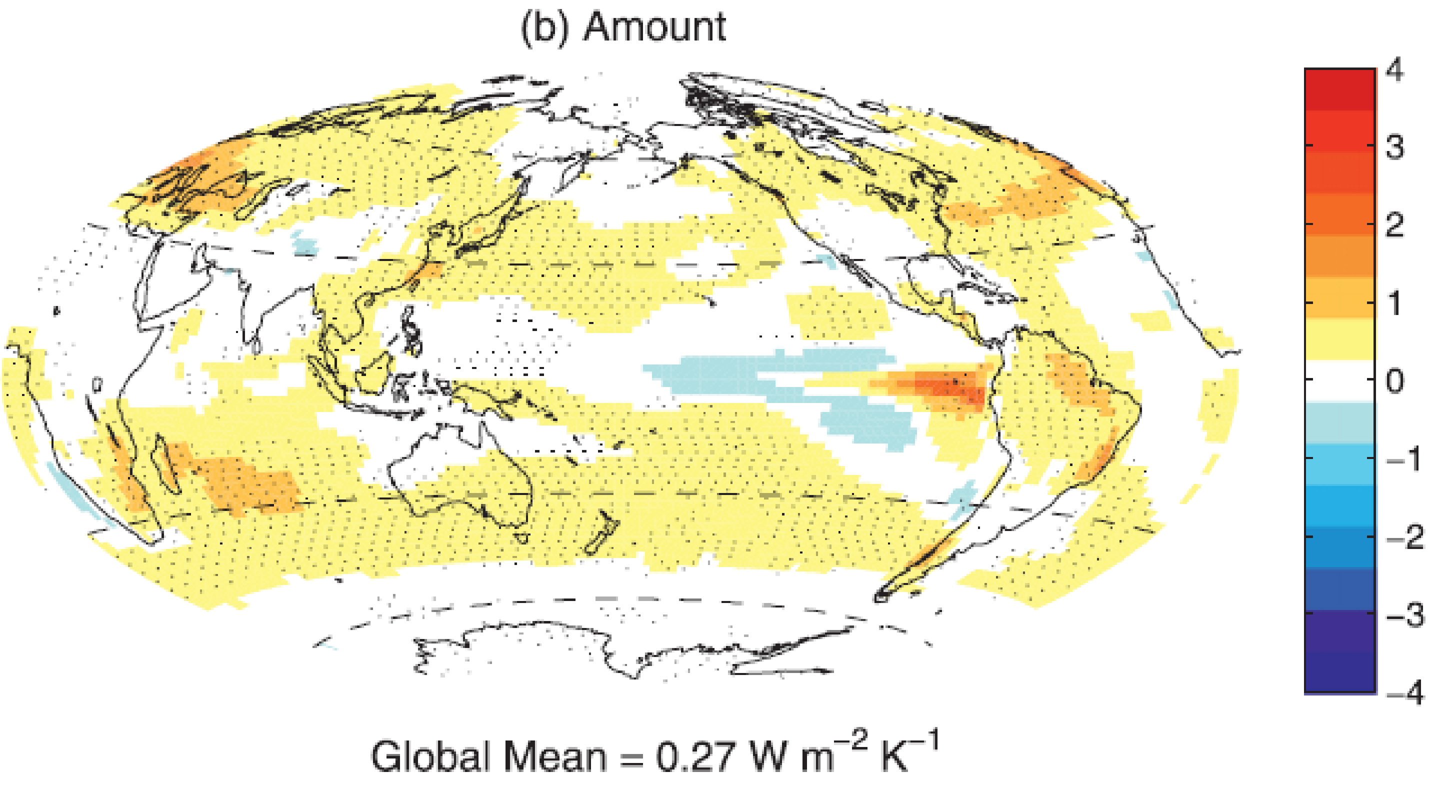


Positive cloud feedback associated with decreased cloud fraction

(Rq : would need to consider a wider ensemble of models)

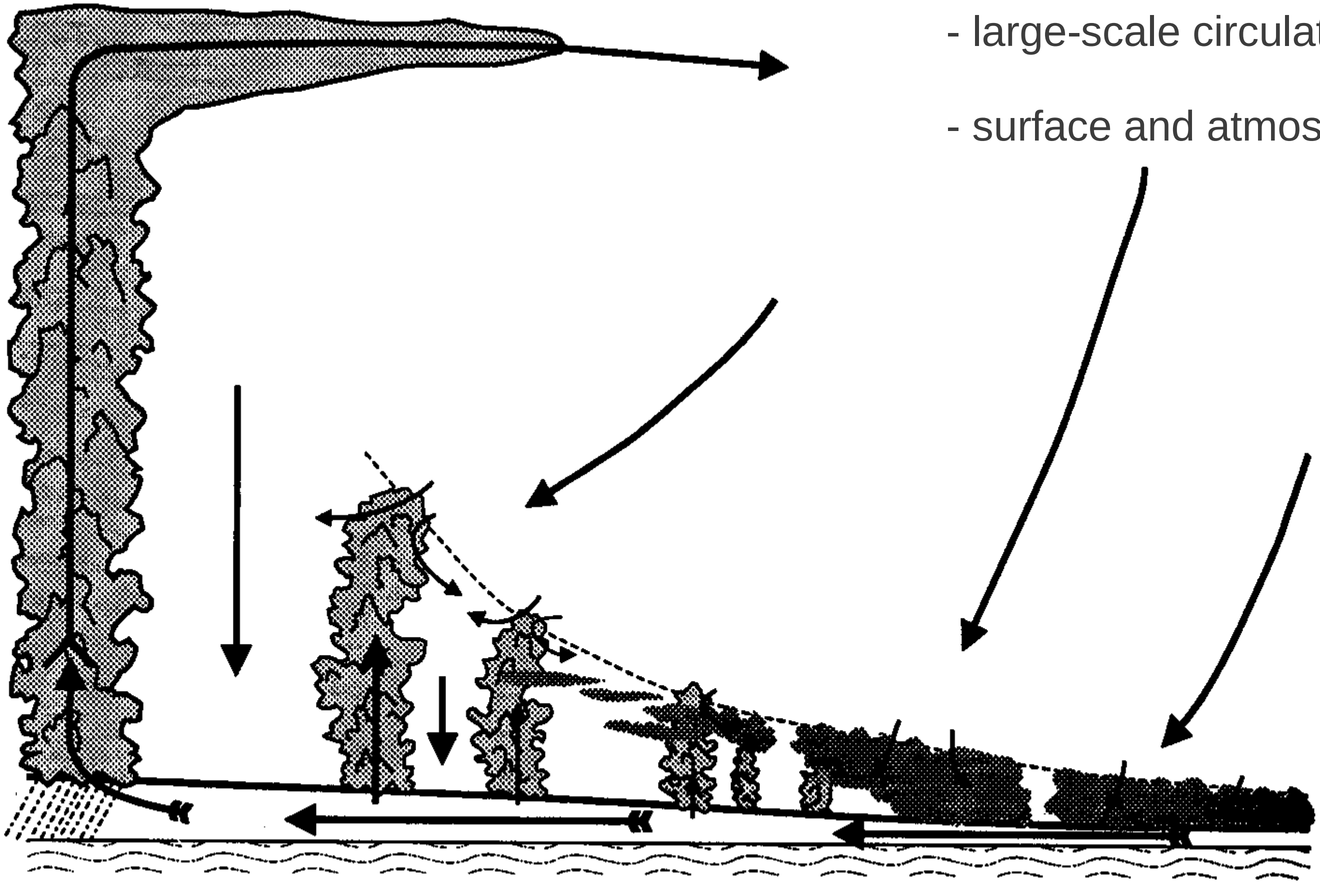
Zelinka et al., J. Climate, 2013

In many regions, the cloud amount feedback is not from robust



Especially in the Tropics...

What controls the tropical cloud amount and its radiative impact ?

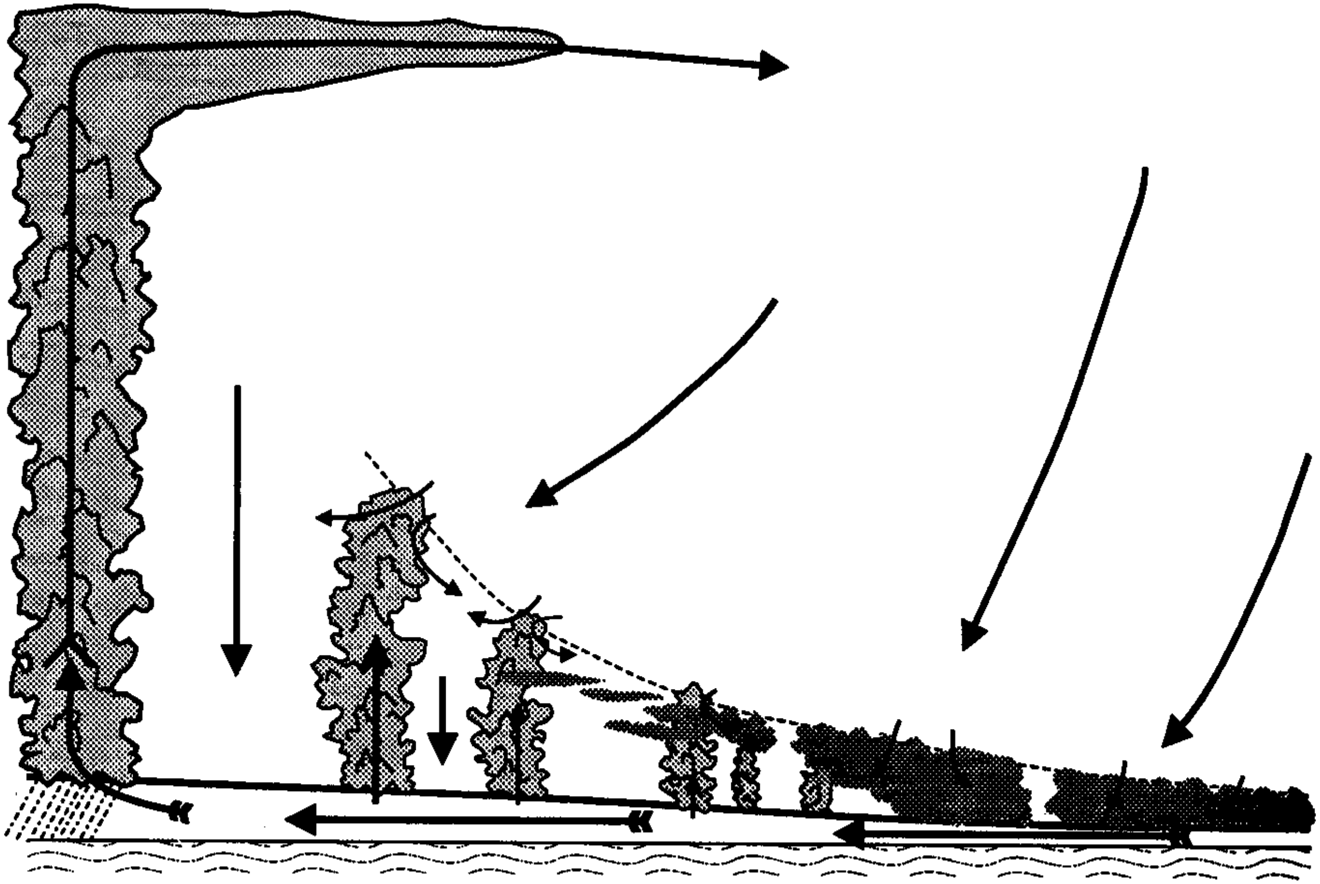


- large-scale circulation

- surface and atmospheric properties

Emanuel 1994

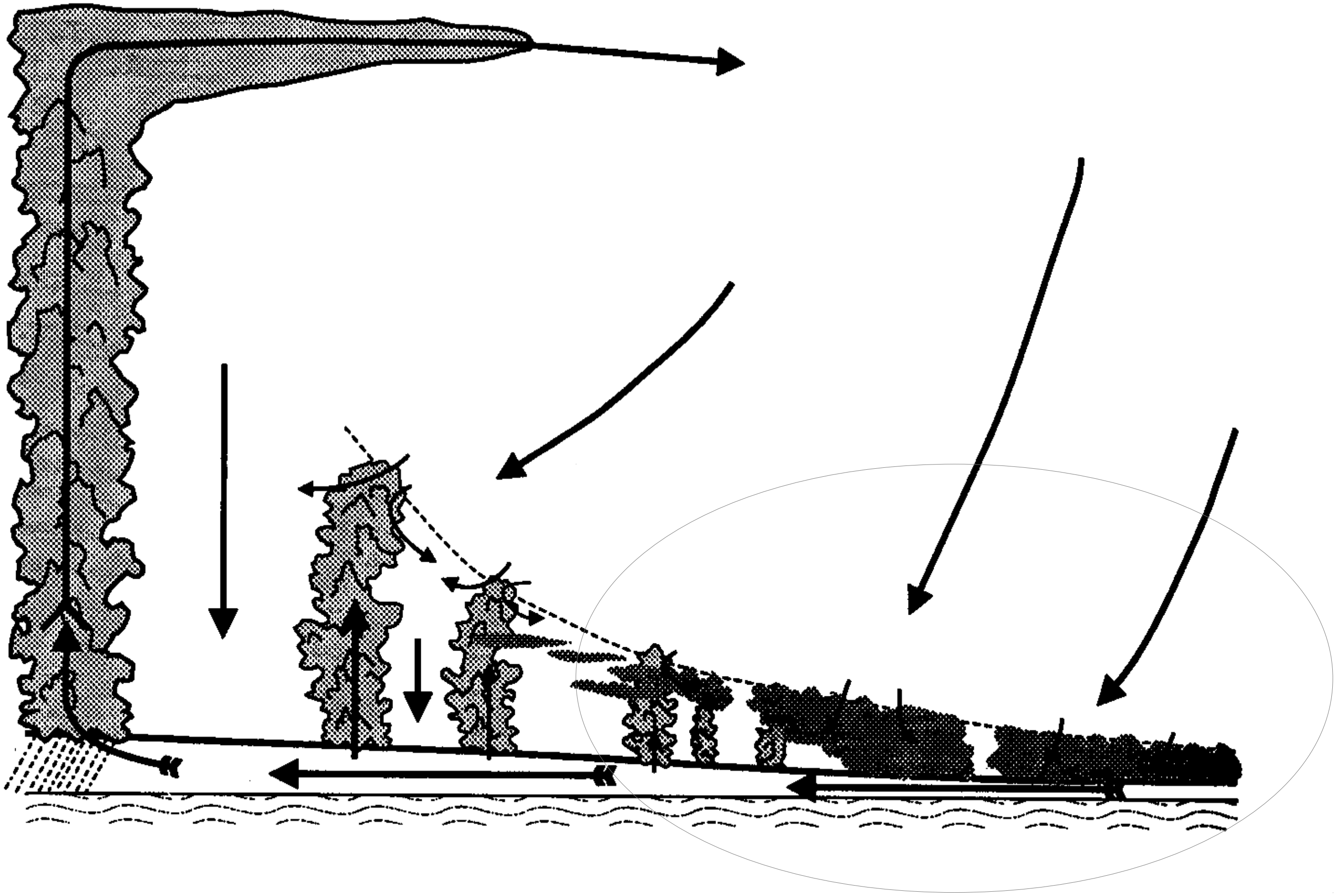
What controls the tropical cloud amount and its radiative impact ?



A change in the large-scale atmospheric circulation and/or convective/subsiding areas could be powerful
... but numerical investigations suggest otherwise (so far)

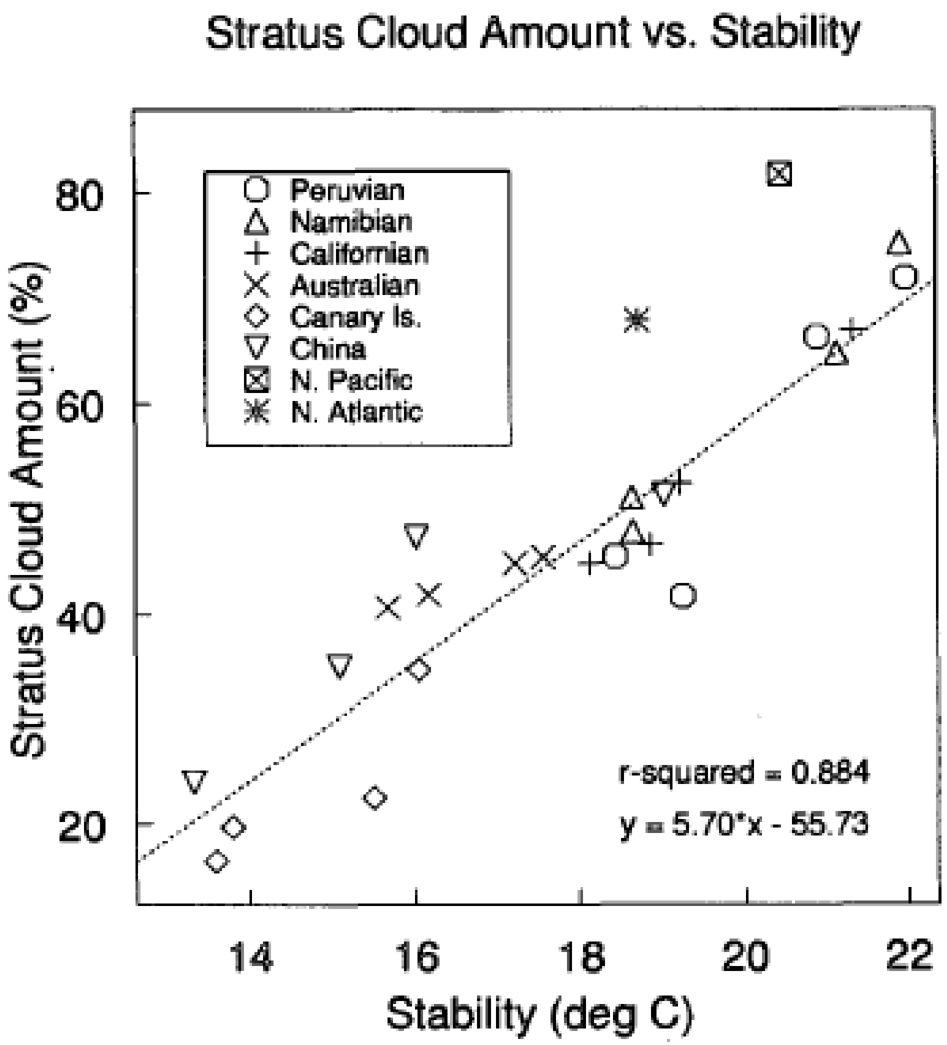
Pierrehumbert, JAS, 1995 ; Bony et al., Clim. Dyn, 2004
Bony and Dufresne, GRL, 2005 ; Clement and Soden, J. Climate, 2005, etc

What controls the tropical cloud amount and its radiative impact ?



Emanuel 1994

Relationship between low-cloud fraction and stability



LTS = θ(700mb)-θ(1000mb)

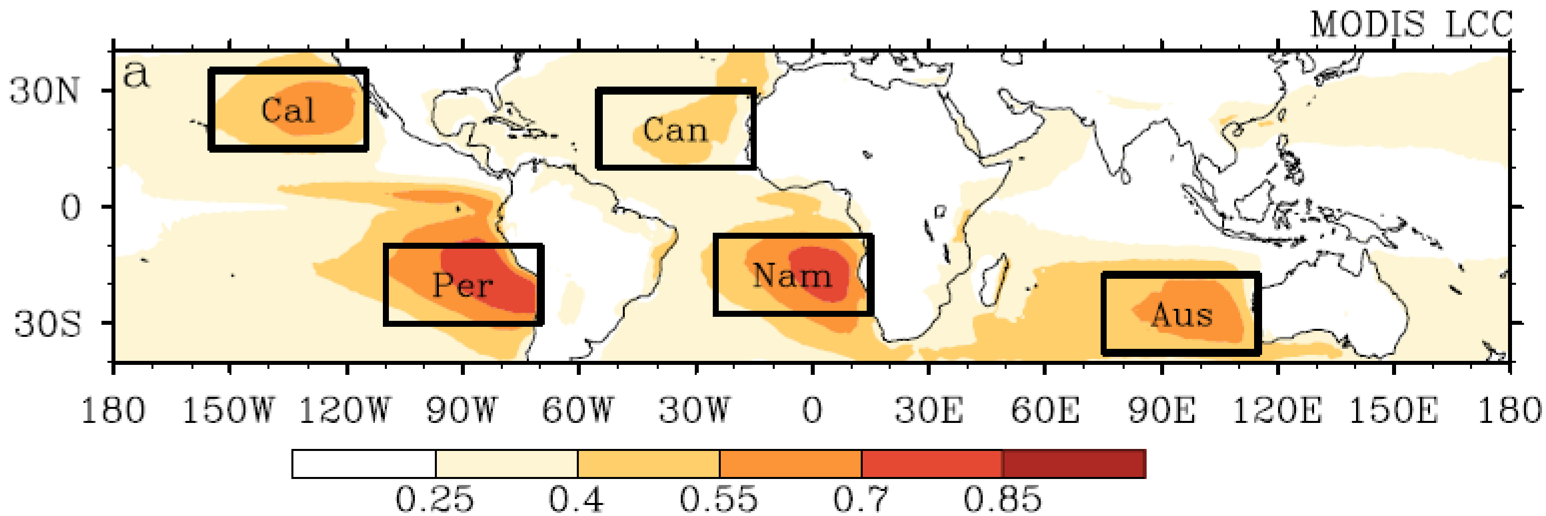
- Strong relationship in present-day climate

- LTS expected to increase in a warmer climate

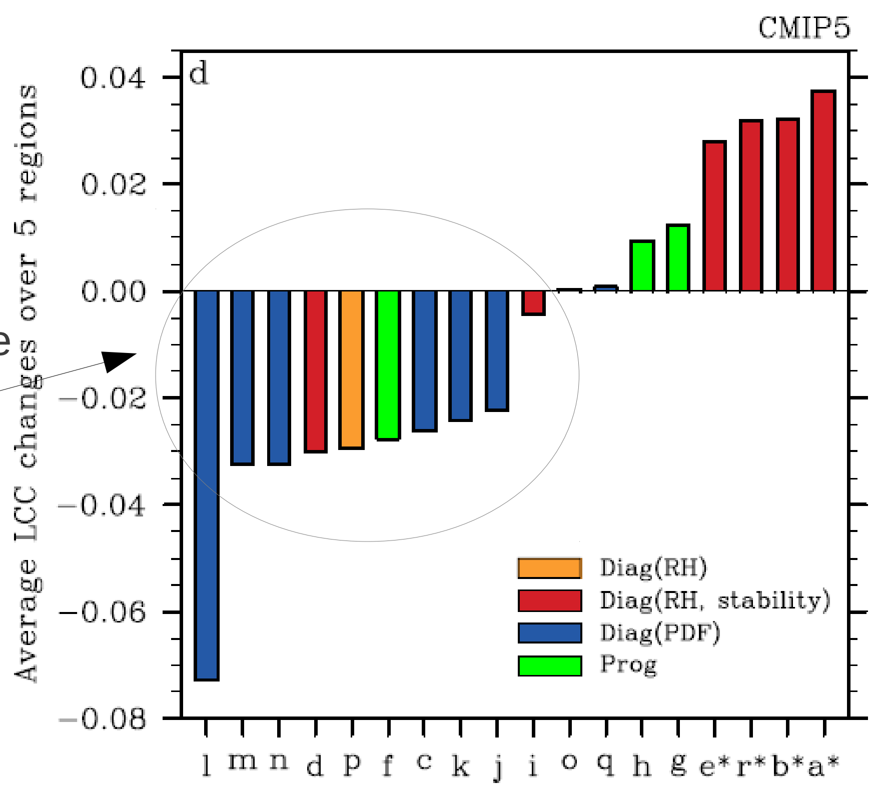
-> A low-cloud thermostat mechanism ?
(e.g. Miller 1997, Larson et al. 1999)

Klein and Hartmann, J. Climate, 1993

Dependence of predicted cloud changes on parameterization



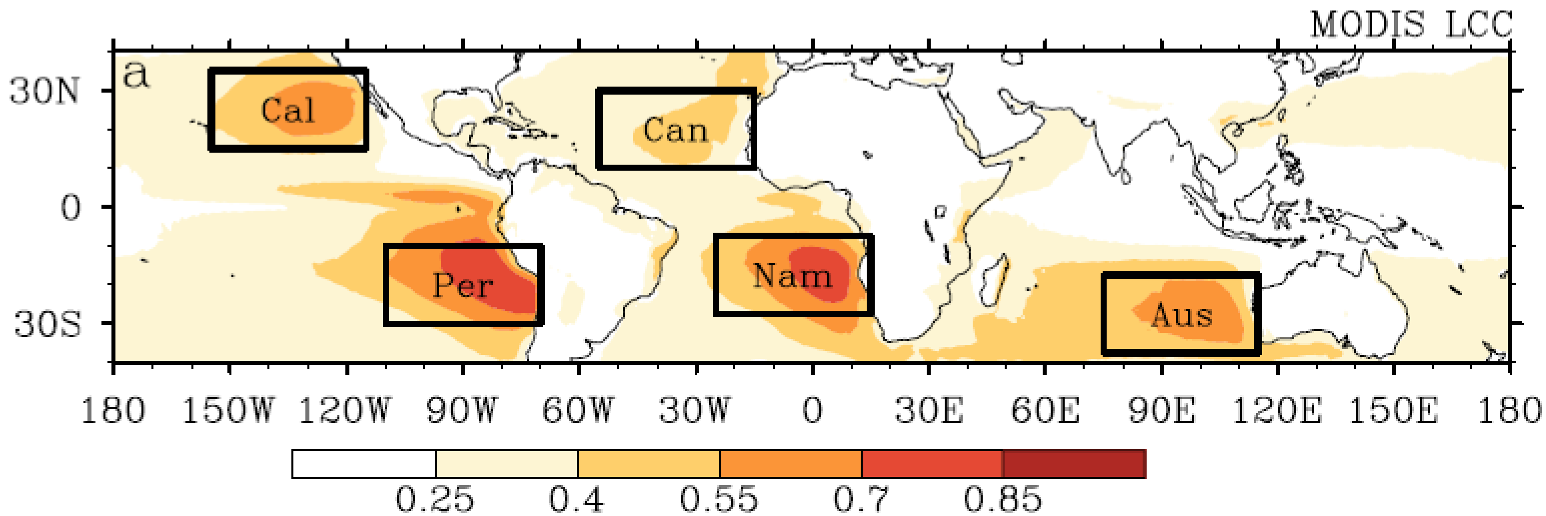
Even models that reproduce the f-LTS relationship in present-day climate can predict a decrease of low-level cloud amount in climate change

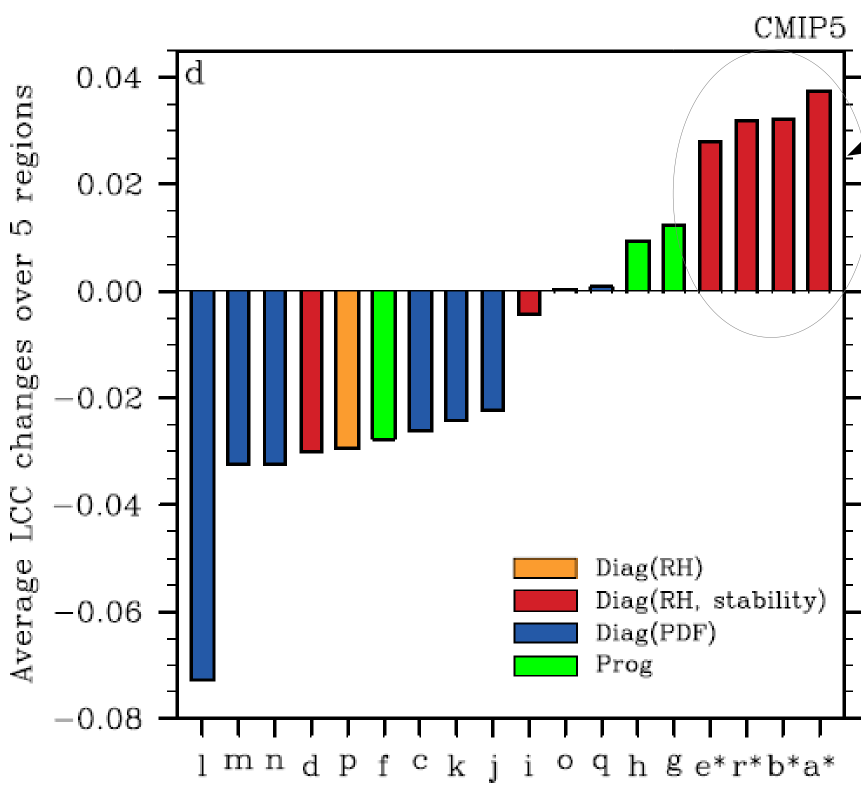


Courtesy Xin Qu (UCLA)

Qu et al, Clim. Dyn., submitted

Dependence of predicted cloud changes on parameterization





Dependence of
cloud amount parameterization
on tropospheric stability
(e.g. Slingo 1987)

Courtesy Xin Qu (UCLA)

Qu et al, Clim. Dyn., submitted

Unless there is a strong theoretical basis and/or numerical evidence..

Extrapolations of present-day relationships to climate change
can be misleading !

(many examples)

Unless there is a strong theoretical basis and/or numerical evidence..

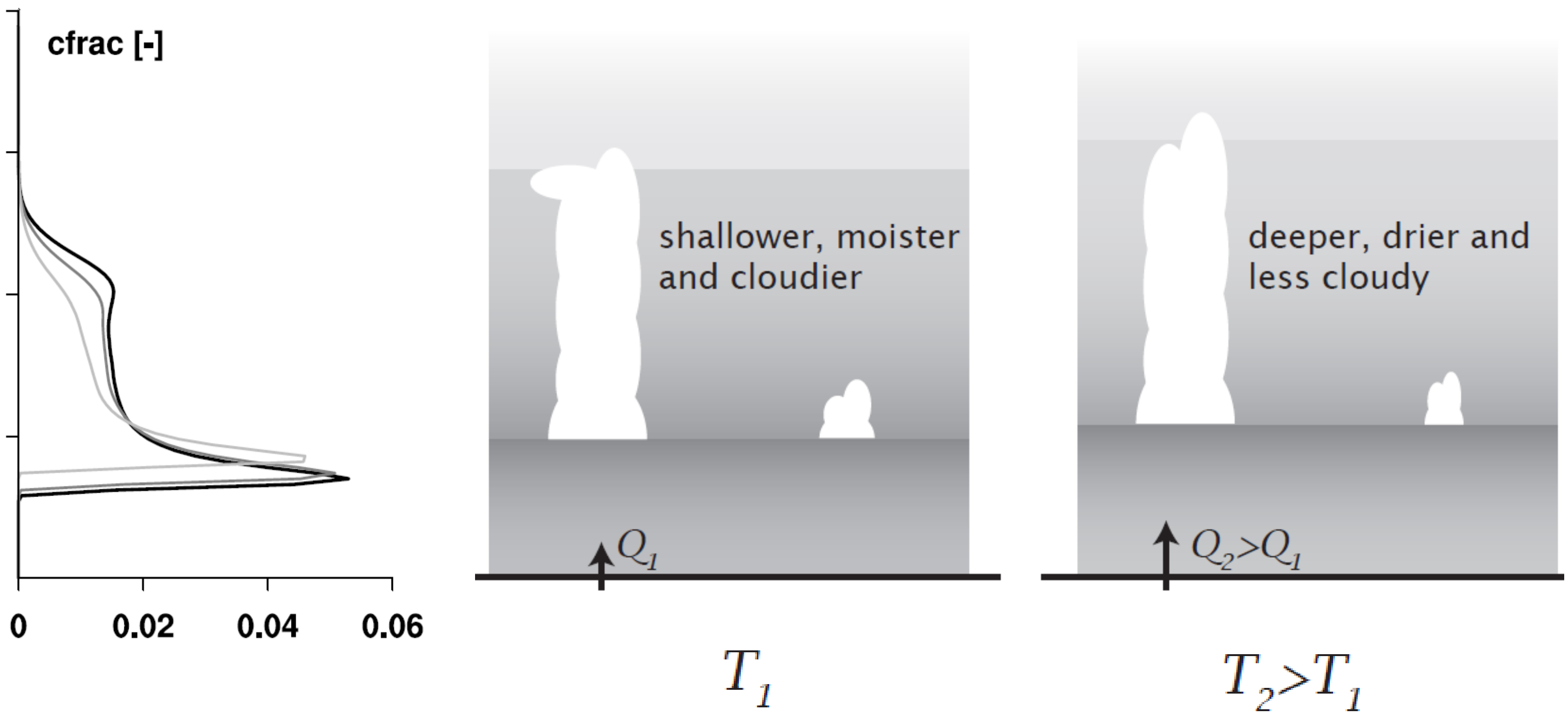
Extrapolations of present-day relationships to climate change can be misleading !

(many examples)

... So let's think in a climate change context

How would shallow cumulus clouds respond to global warming in a nearly unchanged RH atmosphere ?

Idealized LES idealized experiments



Let's assume an environment in which RH remains approximately constant during global warming.

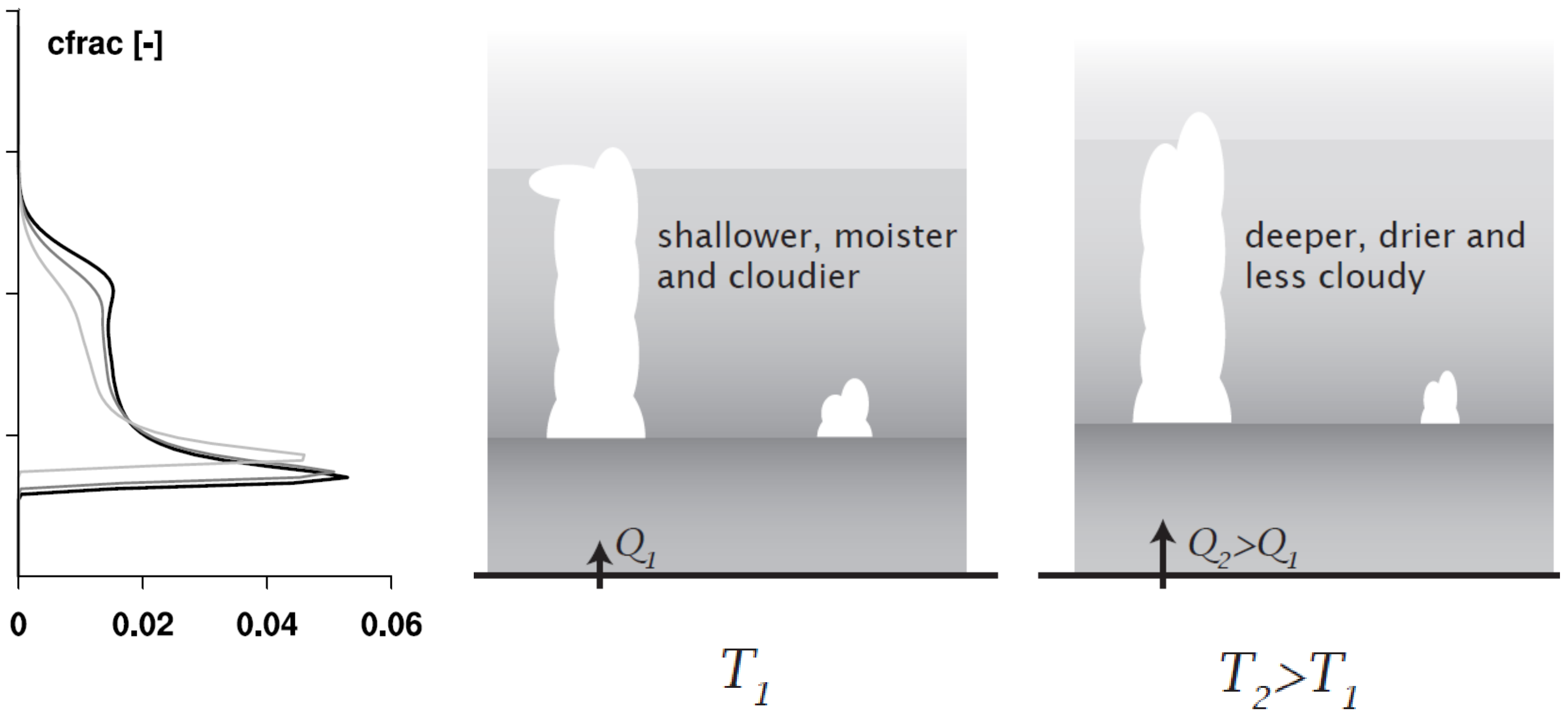
Optical depth feedback at work...

... but more than compensated by the effect of decreased cloud fraction. Why ?

Rieck, Nuijens and Stevens, JAS, 2012

How would shallow cumulus clouds respond to global warming in a nearly unchanged RH atmosphere ?

Idealized LES idealized experiments



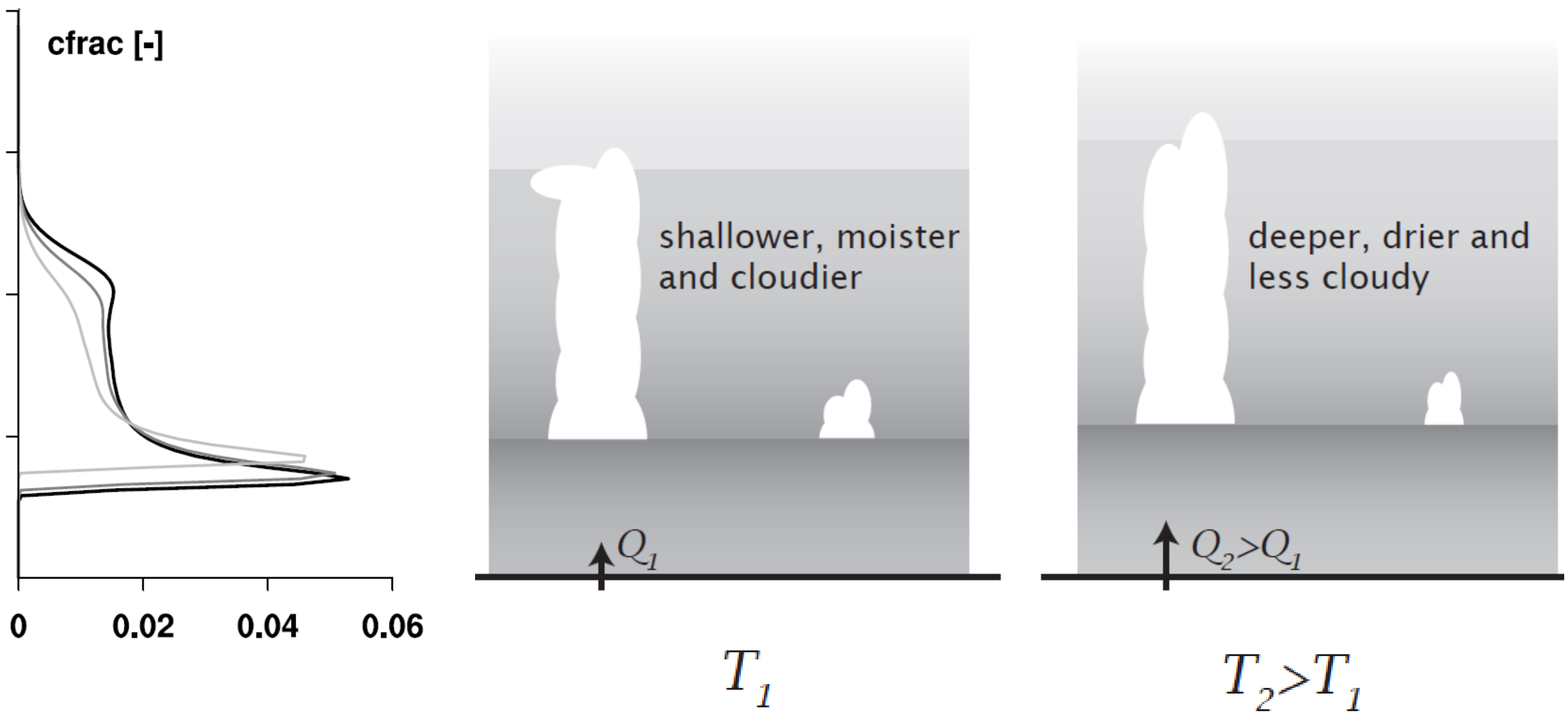
As Ts increases and RH constant : enhanced surface moisture flux

$$Q = V[q_s(T_0) - q_{2m}] \simeq Vq_s(T_0)(1 - \mathcal{H})$$

Rieck, Nuijens and Stevens, JAS, 2012

How would shallow cumulus clouds respond to global warming in a nearly unchanged RH atmosphere ?

Idealized LES idealized experiments



Enhanced surface moisture flux enhance surface buyancy flux
+ more liquid water carried by clouds.

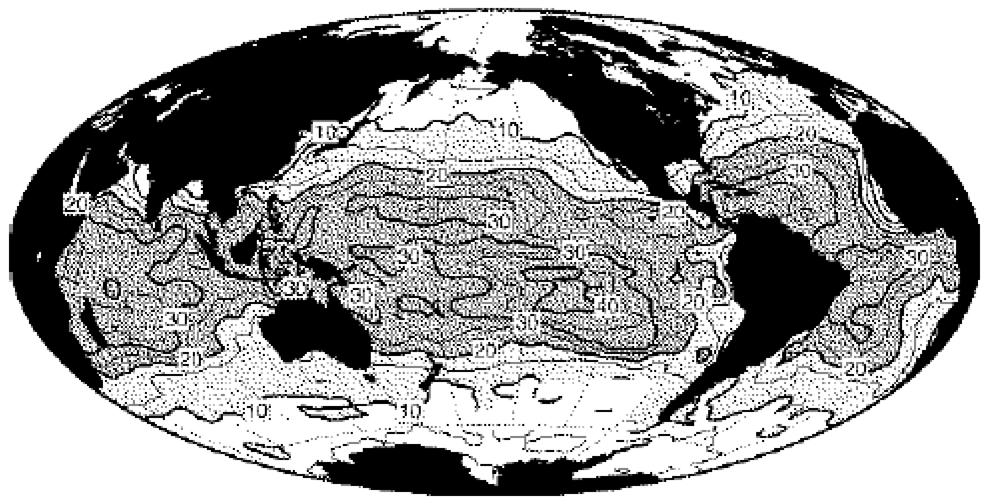
This drives a deeper boundary layer ...and hence mix more dry and warm air to the surface

..leading to a decreased cloudiness as climate warms.

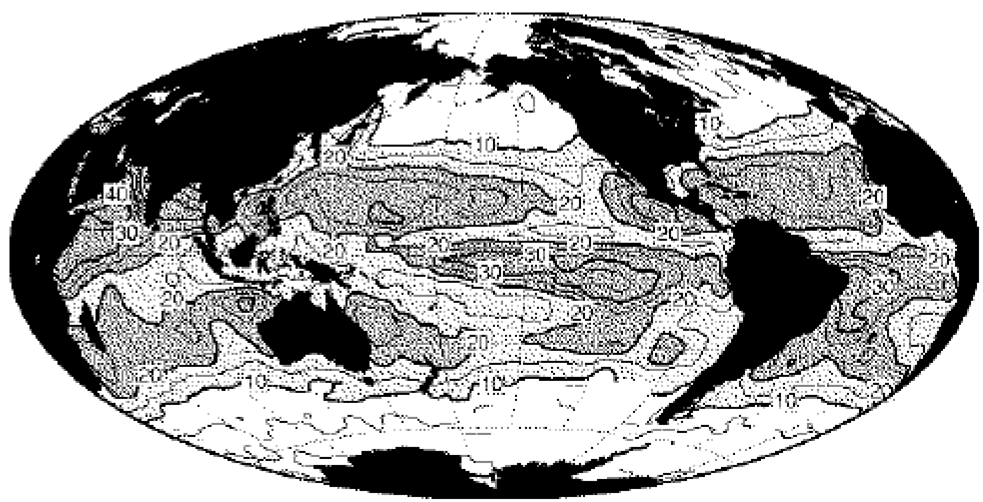
Rieck, Nuijens and Stevens, JAS, 2012

Shallow cumulus clouds are ubiquitous over ocean

Climatological frequency of occurrence of
moderate and large cumulus



Small cumulus



A positive cloud
feedback associated
with shallow cumulus clouds
?

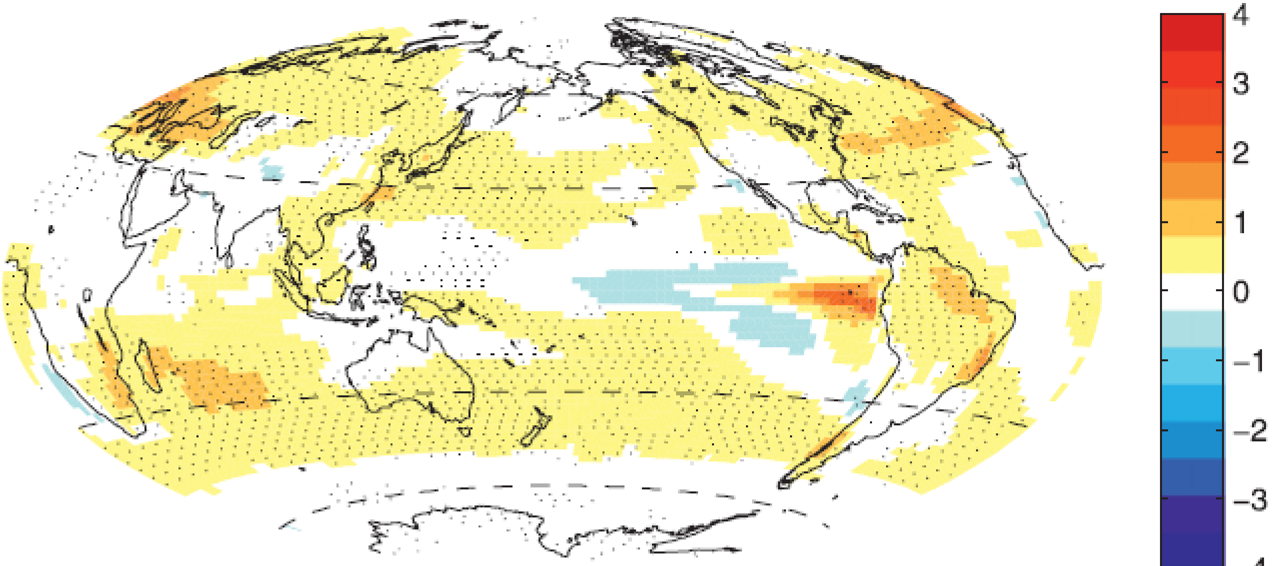
Norris, J. Climate, 1998b

Is this mechanism at work in GCMs ?

Does it explain the widespread reduction in low cloud amount ?

The spread of low-cloud feedback ?

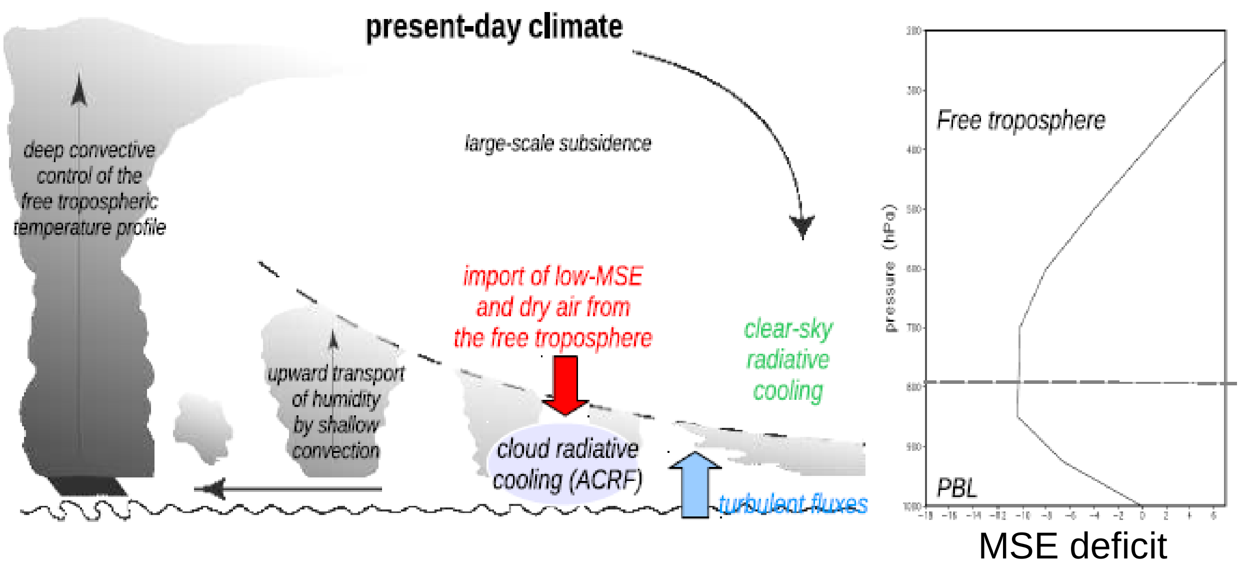
(b) Amount feedback



Global Mean = 0.27 W m^{-2} K^{-1}

Can we understand cloud feedbacks through a more integral approach ?

Energetic analysis of the low-cloud response to climate change



- Low-level clouds *cool* the troposphere radiatively (ACRF)

- Moist Static Energy budget (h = CpT + Lq + gz) :

$$[ACRF] = -[R_0] - (LH + SH) + [\vec{V}.\vec{\nabla} h] + [\omega \frac{\partial h}{\partial P}]$$

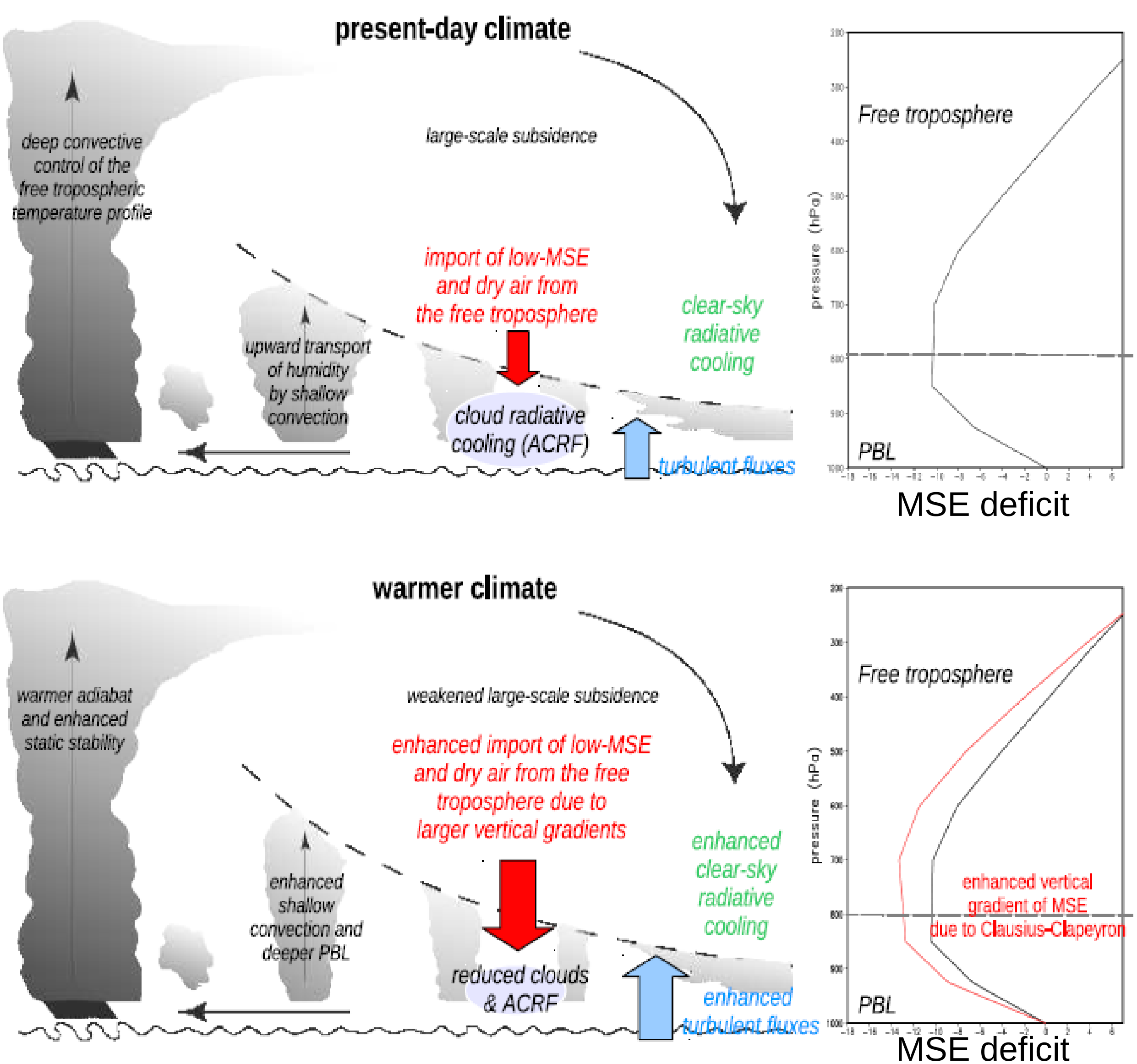
- Surface heat fluxes increase the MSE of the PBL, clear-sky rad cooling, clouds, and the vertical advection term decrease it.

Brient & Bony, Clim. Dyn, 2012

Energetic analysis of the low-cloud response to climate change

In a warmer climate :

- Enhanced vertical gradients of moist static energy (Clausius-Clapeyron)
- Enhanced import by large-scale subsidence of low-MSE from the free troposphere down to the PBL
- Increase of surface fluxes not sufficient to compensate
- Less ACRF needed to close the budget, i.e. less clouds

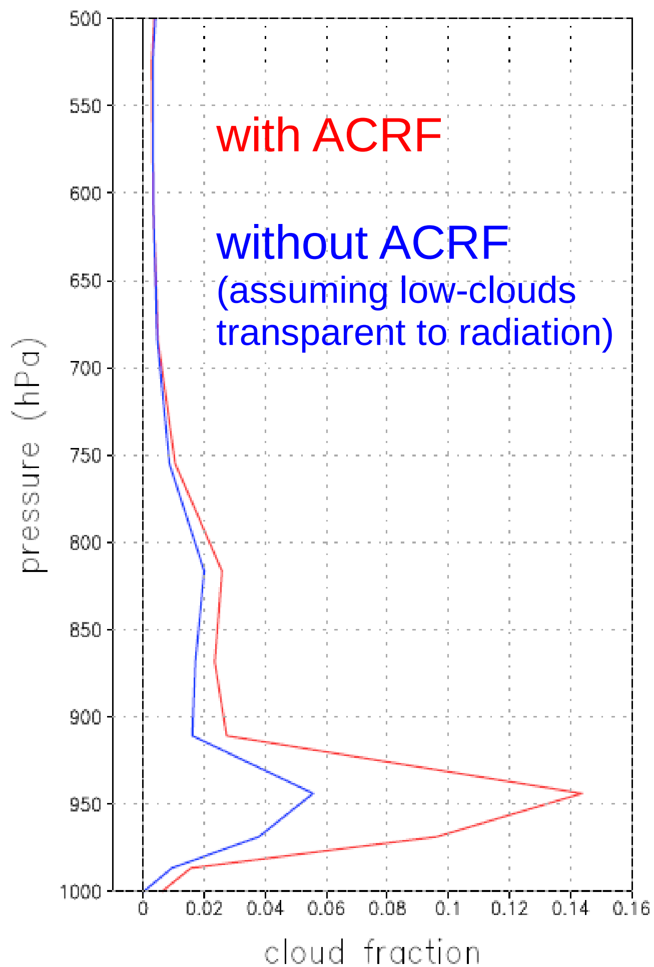


Brient & Bony, Clim. Dyn, 2012

Why is there such a large spread in the magnitude of the low-cloud response to climate change ?

A candidate :

Present-day cloud fraction



Low-level clouds contribute to their own maintenance through their radiative effects (local cooling)

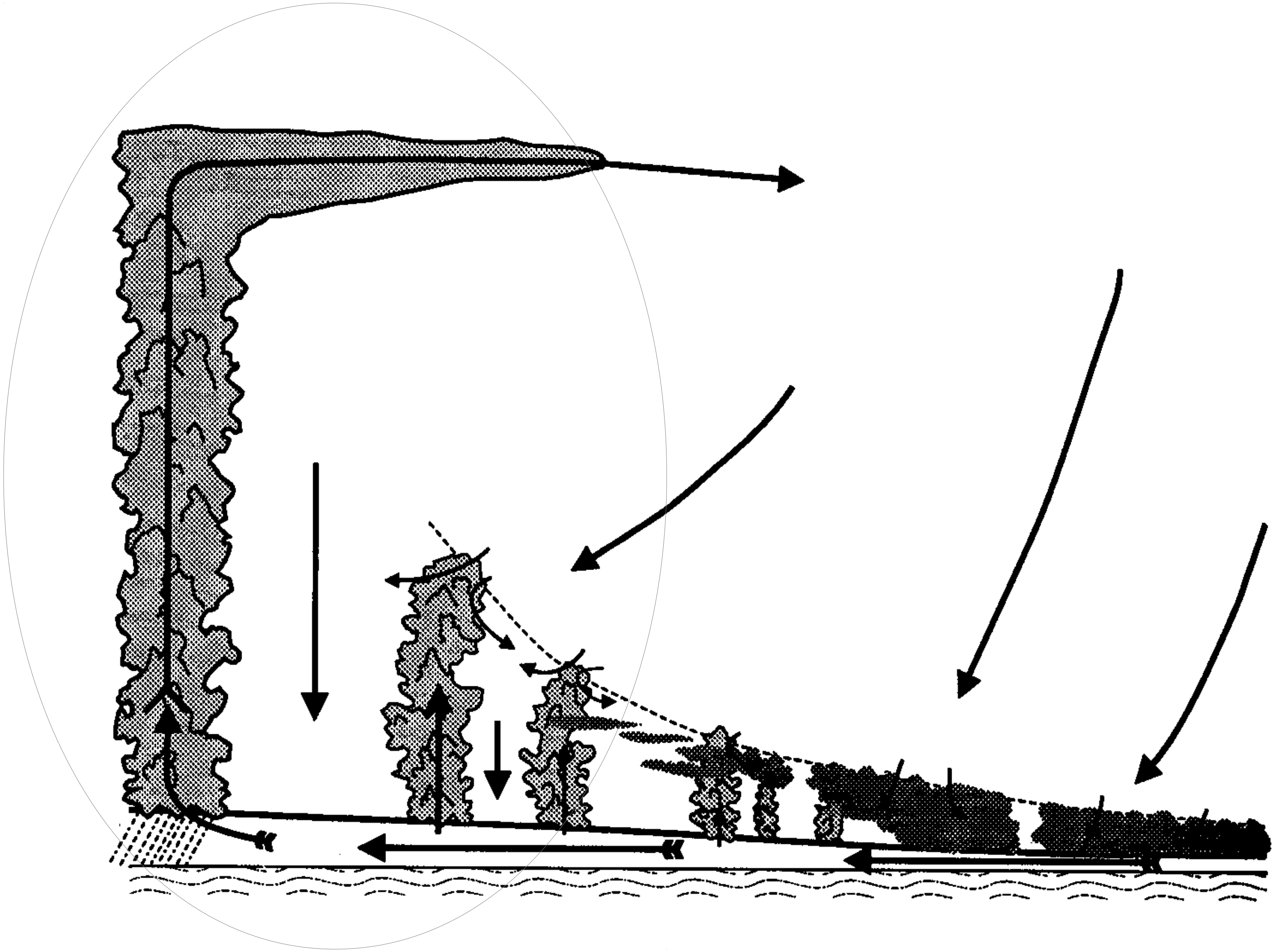
Less low-level clouds
→ less ACRF
→ less low-level clouds

Local positive feedback between ACRF and low-cloud fraction, both in the current climate and in climate change ("β feedback")

Enhances the spread of low-cloud feedbacks

Brient and Bony, GRL, 2012

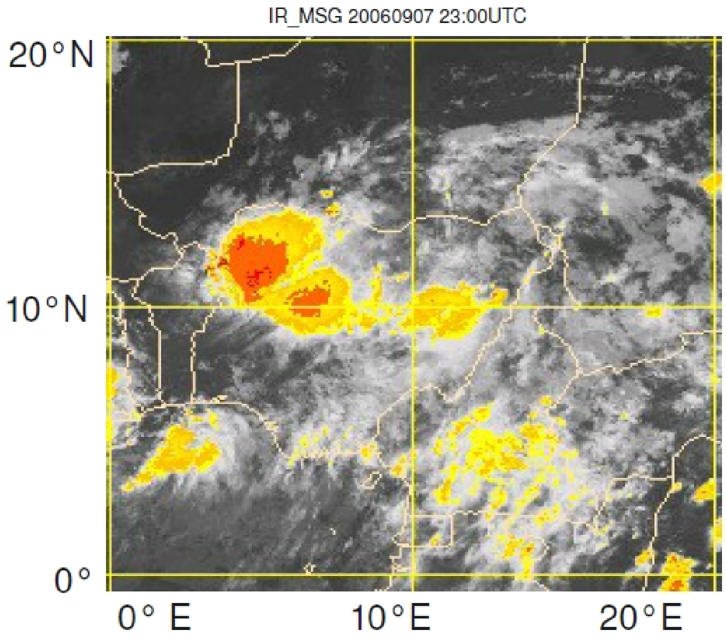
What controls the tropical cloud amount and its radiative impact ?

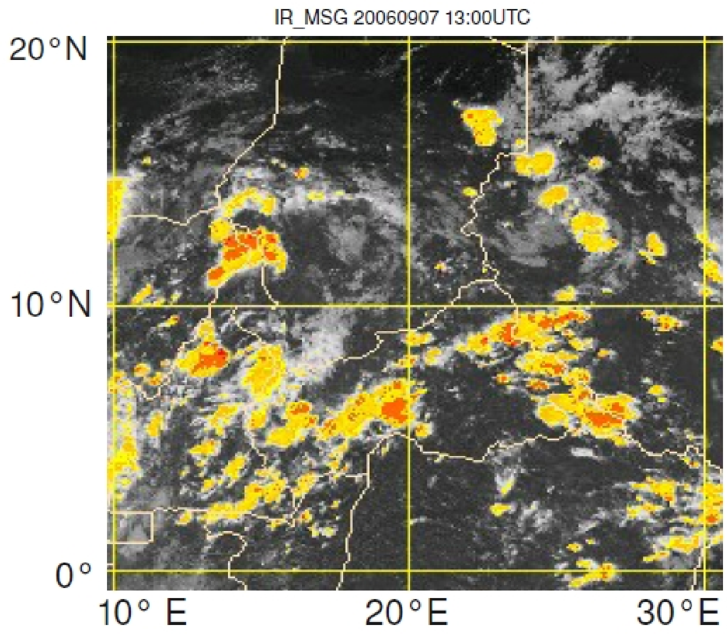


FAT doesn't say anything about the change in cloud amount

Still very much an open issue

Impact of convective aggregation ?





Observations and CRMs suggest that when tropical convection is in a more aggregated state :

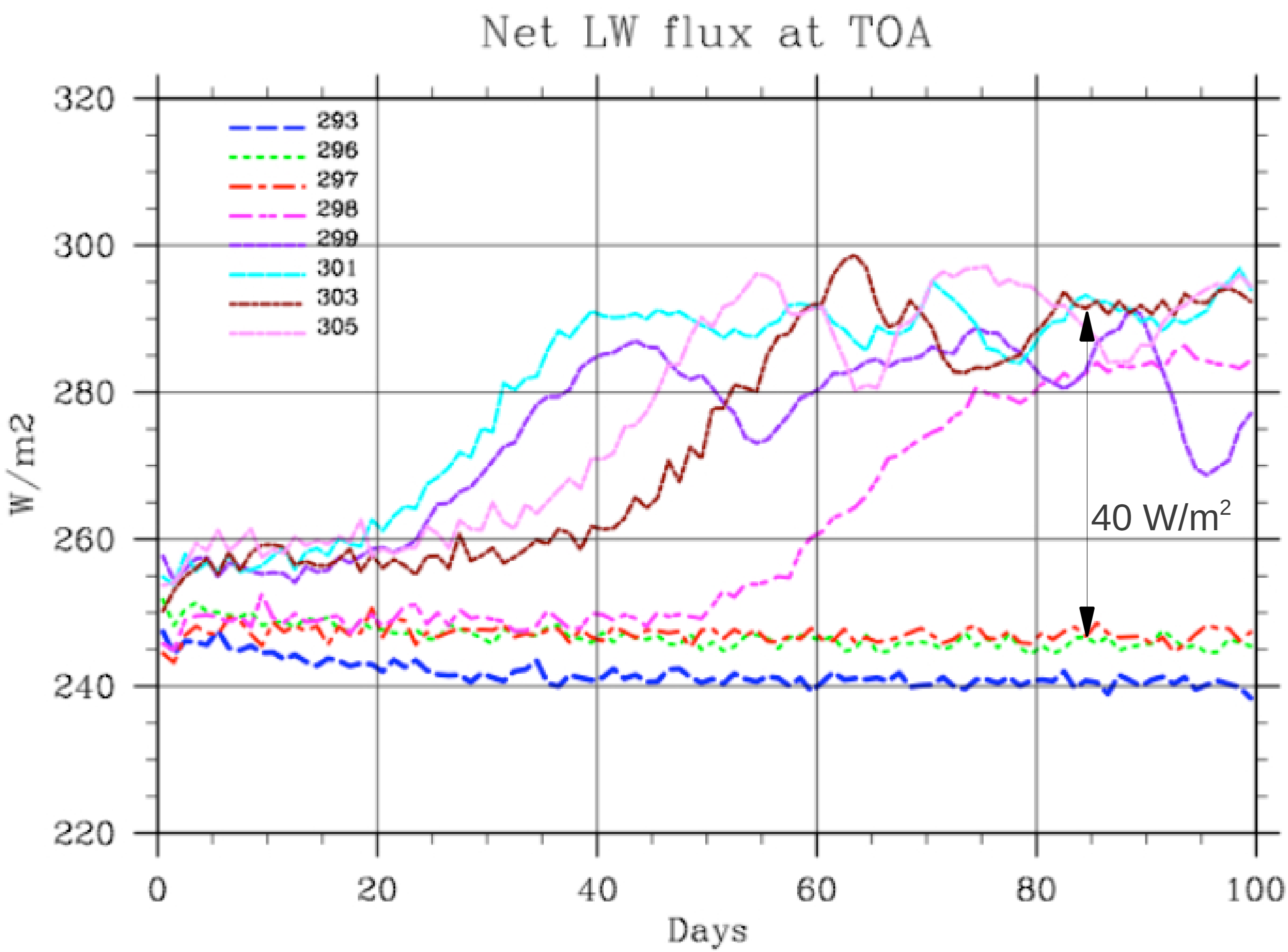
- troposphere drier and less cloudy

- higher OLR, lower planetary albedo

Bretherton et al., JAS, 2005
Tobin et al., J. Climate, 2012
Tobin et al., JAMES, 2013

Impact of convective aggregation ?

Idealized simulations of radiative-convective equilibrium



easier aggregation at higher SSTs

higher OLR

potential negative feedback on Climate Sensitivity

However, SW effects should be considered as well

Khairoutdinov & Emanuel, AMS, 2010

Summary

- **Some robust cloud feedback mechanisms have been identified**
  e.g. Negative cloud optical depth feedback (high latitudes)
  Positive LW cloud feedback associated with FAT (tropics)

- Several other feedback processes have been proposed,
  whose robustness has now to be assessed

- **Cloud feedback processes can now be studied using a spectrum of models,**
  including LES and CRMs (e.g. Sarah Del Sasso's poster)

- **Still many open questions !**
  e.g.
  * Cloud amount feedback processes in the tropics (low clouds, high clouds)
  * Dependence of cloud feedbacks upon model formulation
  * Potential impact of missing processes

- **Cloud feedbacks may be studied through a wider range of approaches !**

Next

Precipitation in a changing climate